Integrated Transport Simulation of LHD Plasmas Using TASK3D

A. Wakasa 1), A. Fukuyama 1), S. Murakami 1), M. Miki 1), M. Yokoyama 2), M. Sato 2), S. Toda 2), H. Funaba 2), K. Tanaka 2), K. Ida 2), H. Yamada 2), M. Honda 3), N. Nakajima 2)

1) Department of Nuclear Engineering, Kyoto University, Kyoto, 606-8501, Japan
2) National Institute for Fusion Science, Toki, 509-5292, Japan
3) Japan Atomic Energy Agency, Naka, Ibaraki 311-0193, Japan

E-mail contact of main author: wakasa@p-grp.nucleng.kyoto-u.ac.jp

Abstract. An integrated transport simulation code for the helical plasma, TASK3D, is developed and applied to the LHD plasma. The neoclassical transport in the helical plasma is evaluated by the neoclassical transport database, DGN/LHD, which is constructed using a neural network technique. In addition to the neoclassical transport, five anomalous transport models (the Bohm and edge Bohm models, Gyro-Bohm and Gyro-Bohm like models, and Alcator model) are included and compared the temperature profiles with experimentally observed plasmas. We also take into account the differential equation for the radial electric field into TASK3D. The obtained electron and ion thermal diffusivities with the Alcator, Bohm, and gyro-Bohm models indicate the anomalous transport dominates in the electron thermal transport, while the neoclassical transport plays a crucial role in the ion thermal transport. The TASK/TX module, which solves the flux-surface averaged multi-fluid equation, is also applied to the LHD plasma to describe the time evolution of the radial electric field and the plasma rotation as well as the density and the temperature. The transition between the electron and ion roots, and the radial structure of the electric field have been demonstrated self-consistently.

1. Introduction

In order to obtain high temperature plasmas, it is necessary to understand the heat and particles transport process. In an axisymmetric plasma, the anomalous transport due to plasma turbulence plays a dominant role in the transport process. In a non-axisymmetric plasma, in the long-mean-free-path regime, helical ripples increase the neoclassical transport, which significantly modifies the transport process. As a result, in order to understand the anomalous transport in a helical system, it is important to accurately evaluate the neoclassical transport. Moreover, in non-axisymmetric systems, neoclassical transport has a strong dependence on the radial electric field. In helical devices, the fluxes are not intrinsically ambipolar as in a tokamak. The radial electric field is determined by the constraint that the ion and electron fluxes be equal. To evaluate the neoclassical transport, we have constructed the neoclassical transport database, DGN/LHD [1]. The diffusion coefficients in Large Helical Device (LHD) were evaluated by the DCOM and GSRAKE codes, and the database was constructed using a neural network technique.

In addition, the integrated transport simulation that connects a variety of physical models describing the different time scale phenomena self-consistently is essential to a systematical elucidation of the confinement physics in toroidal plasma. TASK3D [2] is an integrated transport simulation code for the helical plasma based on TASK [3] which is applicable for 2D tokamak configurations. TASK3D is under development in collaboration with Kyoto University and NIFS. DGN/LHD was incorporated into TASK3D. Based on accurate evaluation of the neoclassical transport including the radial electric field by DGN/LHD, several anomalous transport models were tested using experimental density and temperature profiles. In this study, we used the TR and the TX modules of TASK3D for transport simulation. The TR module [1] solves one-dimensional diffusive equations for densities, temperatures and a poloidal magnetic flux. The TX module [4] solves the flux-surface averaged multi-fluid equation and has been extended to include the neoclassical toroidal viscosity in a non-axisymmetric system.

2. Integrated Simulation Code, TASK3D

TASK3D is an integrated simulation code for non-axisymmetric systems. TASK3D has a modular structure as shown in Fig. 1 and each module describes different physical phenomena. Through the data exchange interface, each module is connected and plasma is described self-consistently.

In this study, we mainly use three modules: the TR module, the ER module and the DGN/NNW module. The TR module solves the 1D diffusive transport equation for the density, the temperature and the toroidal angular momentum of each plasma species and the poloidal magnetic field. In this study, only following heat transport equation is solved;

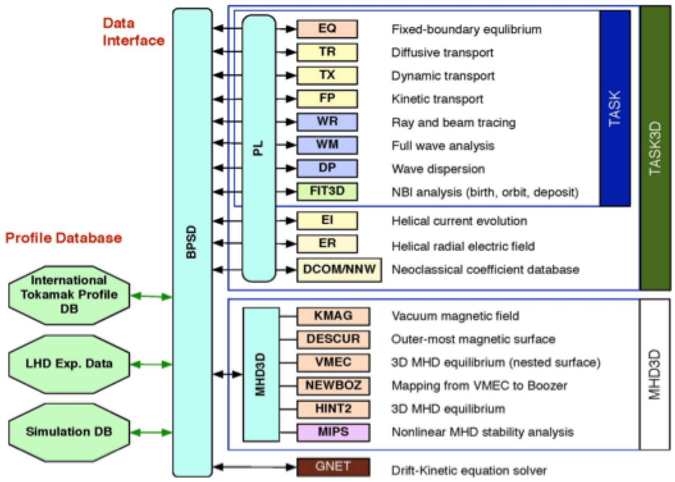

FIG. 1. Module structure of the core code of the integrated simulation code TASK with the extensions; TASK3D and MHD3D and GNET.

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_sT_sV'^{5/3}\right)=$$
$$-V'^{2/3}\frac{\partial}{\partial\rho}\left(V'\left\langle\left|\nabla\rho\right|\right\rangle\frac{3}{2}n_sT_sV_{Es}-V'\left\langle\left|\nabla\rho\right|^2\right\rangle\frac{3}{2}D_sT_s\frac{\partial n_s}{\partial\rho}-V'\left\langle\left|\nabla\rho\right|^2\right\rangle n_s\chi_s\frac{\partial n_s}{\partial\rho}\right)+P_sV'^{5/3}, \tag{1}$$

where n_s is the density, T_s is the temperature and s specifies the particle species. V is the plasma volume, ρ is the normalized minor radius, $V'=dV/d\rho$, $V_{Es} = V_{Ks} + (3/2)V_s$, V_{Ks} is the heat pinch velocity, V_s is particle pinch velocity and D_s and χ_s are the particle diffusion coefficient and thermal diffusion coefficient, respectively. P_s is the power source. $< >$ represents the magnetic surface average. We assume that the thermal diffusion coefficients are given as the sum of a turbulent term χ^{TB} and a neoclassical term χ^{NC}, $\chi = \chi^{TB+}\chi^{NC}$. The particle diffusion coefficient, heat pinch velocity, and particle pinch velocity are assumed only neoclassical components. V_s and V_{Ks} is determined by

$$V_s=\left[\Gamma_s^{\mathrm{NC}}+\frac{\partial n_s}{\partial r}\right]\Big/n_s,\ V_{Ks}=\left[Q_s^{\mathrm{NC}}+n_s\frac{\partial T_s}{\partial r}\left(\frac{D_3}{D_2}-\frac{3}{2}\right)\right]\Big/n_sT_s, \tag{2}$$

where

$$\Gamma_s^{\mathrm{NC}}=-n_sD_1^s\left\{\frac{1}{n_s}\frac{\partial n_s}{\partial r}-\frac{q_sE_{\mathrm{r}}}{T_s}+\left(\frac{D_2^s}{D_1^s}-\frac{3}{2}\right)\frac{1}{T_s}\frac{\partial T_s}{\partial r}\right\}, \tag{3}$$

$$Q_{\mathrm{s}}^{\mathrm{NC}}=-n_sT_sD_2^s\left\{\frac{1}{n_s}\frac{\partial n_s}{\partial r}-\frac{q_sE_{\mathrm{r}}}{T_s}+\left(\frac{D_3^s}{D_2^s}-\frac{3}{2}\right)\frac{1}{T_s}\frac{\partial T_s}{\partial r}\right\}, \tag{4}$$

are the neoclassical particle flux and heat flux and D_1, D_2, and D_3 are the neoclassical particle diffusion coefficient, off-diagonal term, and thermal diffusion coefficient, respectively, and are determined by the DGN/LHD module. The DGN/LHD is the neoclassical transport database and can evaluate the neoclassical transport coefficient accurately even in high-temperature plasma and finite beta plasma.

The radial electric field, E_r, is determined by the ambipolar condition, $e\Gamma_e^{\mathrm{NC}} - Ze\Gamma_i^{\mathrm{NC}} = 0$. In this algebraic equation, neighboring points are independent and unphysical change of the radial electric field profile appears in some case. Also the effect of the boundary conditions cannot be considered. Because various physical mechanisms are involved in the edge region, it is necessary to consider the boundary condition. In order to solve this problem, the differential equation for the radial electric field should be solved. The differential equation in non-axisymmetric systems are formulated as follows [5],

$$\frac{\partial E_r}{\partial t}=-\frac{e}{\varepsilon_\perp}\sum_j Z_j\Gamma_j+\frac{1}{V'(\rho)}\left(\frac{\partial}{\partial\rho}V'(\rho)D_{E_r}\frac{\partial E_r}{\partial\rho}\right) \tag{5}$$

where D_{E_r} is the electric diffusion coefficient and $\varepsilon_\perp$ is the perpendicular dielectric coefficient. In the differential equation, neighboring points are coupled, and the boundary condition can be considered.

3. Thermal Transport Simulation in LHD Plasmas Using TASK3D

We applied the TASK3D to the LHD experimental data in Ufile format in the experimental profile database of Stellarator and Heliotoron. We assume that the turbulent diffusivities of the electron and the ion are same. We have implemented five turbulent transport models as follows;

$$\chi^{\mathrm{TB}}_{\mathrm{Alcator}} = \mathrm{C}_{\mathrm{Alcator}}\left(1/n\right) \tag{6}$$

$$\chi^{\mathrm{TB}}_{\mathrm{Bohm}} = \mathrm{C}_{\mathrm{Bohm}}\left(T/eB\right) \tag{7}$$

$$\chi^{\mathrm{TB}}_{\mathrm{edgeBohm}} = \mathrm{C}_{\mathrm{edgeBohm}}\left(T/eB\right)\left(r/a\right)^2 \tag{8}$$

$$\chi^{\mathrm{TB}}_{\mathrm{gyroBohm}} = \mathrm{C}_{\mathrm{gyroBohm}}\left(T/eB\right)\left(\rho/L\right) \tag{9}$$

$$\chi^{\mathrm{TB}}_{\mathrm{gyroBohm+gradT}} = \mathrm{C}_{\mathrm{gyroBohm+gradT}}\left(T/eB\right)\left(\rho/L\right)\left(aT'/T\right) \tag{10}$$

(6) the Alcator scaling model [6], (7) the Bohm model, (8) the Bohm model emphasized on the edge region, (9) the gyro-Bohm model, (10) the gyro-Bohm multiplied by gradient T term model. In each models, the $\mathrm{C}_{\mathrm{model}}$ is a constant factor to match the simulation results with experimental results.

First, we determine the values of $\mathrm{C}_{\mathrm{model}}$ so as to properly fit the simulation results to experimental results; T_{e} and T_{i} reported in reference (#88343, shown in Fig. 2(a)). The characteristic parameters of this plasma are R_{axis} is 3.6m , B_0 = 2.75T and β_0 = 0.11%. In this study, LHD experimental data is used for initial profiles of the simulation; density profiles are fixed to the experimental values (fixed); electron and ion temperature profiles are calculated until the stationary state is obtained; initial MHD equilibrium is calculated by VMEC code; and the radial electric field E_{r} is determined by the ambipolar condition with the experimentally obtained density and temperature profiles.

Figure 2(b)-(d) show the radial profiles of T_{e} and T_{i} calculated using TASK3D with (b) Alcator model, (c) Bohm model, (d) edge Bohm model, (e) gyro-Bohm model, and (f) gyro-Bohm multiplied by gradient T model Here, each $\mathrm{C}_{\mathrm{model}}$ is determined as $\mathrm{C}_{\mathrm{Alcator}}$=1.61,

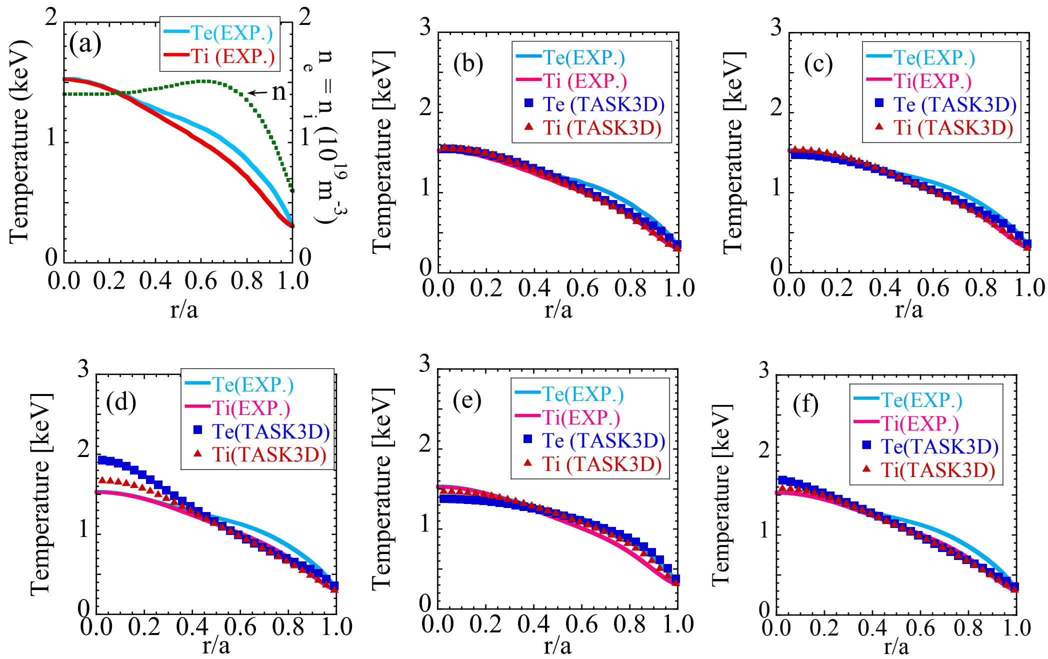

FIG. 2. (a) Initial profle of Te and Ti, and density (#88343). Comparison of the temperatures between experimentarl results and TASK3D results with (b) Alcator model, (c) Bohm model, (d) edge Bohm model, (e) gyro-Bohm model, and (f) gyro-Bohm multipld by gradT model.

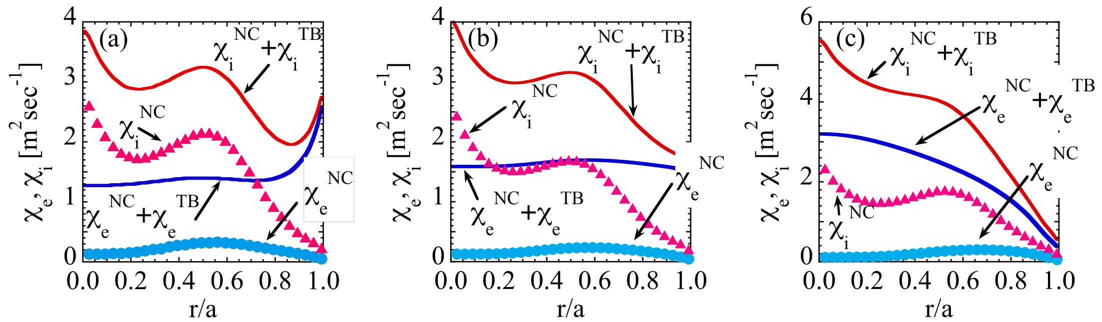

FIG. 3. The obtained thermal diffusivities of ion and electron with the turbulence (a) Alcator, (b) Bohm, and (c) gyro-Bohm model and the neoclassical transport.

C_{Bohm}=0.19, $C_{edgeBohm}$=0.24, $C_{edgeBohm}$=25, and $C_{gyroBohm+gradT}$=9.07 to minimize the relative mean square error between experimental and simulation results of the temperature profile. The obtained electron and ion thermal diffusivities with the Alcator, Bohm, and gyro-Bohm models are shown in Fig. 3. It is found that the turbulent transport dominates in the electron thermal transport, while the neoclassical transport plays an important role in the ion thermal transport except the edge region (r/a>0.8). By increasing the heating power, the heating power dependence of τ_E was evaluated and we obtained $\tau_E \propto P^{-0.6}$ in the case of gyro-Bohm model.

Next, we apply TASK3D to another experimental data of LHD (see table 1) assuming the Alcator and gyro-Bohm models with the same fitting factor evaluated for s88343 plasma. We obtain relatively good agreements between experimental results and simulation ones in the case of R_{ax}= 3.60m plasma (s11369) in Fig. 4. On the other hand, we find slight differences in the case of R_{ax}=3.75 m plasmas and the differences are smaller in the case of gyro-Bohm model than that in the Alcatrol model.

Table 1 Characteristic feature of the plasmas.

Shot num.	**time [sec]**	**feature**	**Rax [m]**	**B_0 [T]**	**T_{e0} [keV]**	**n_0 [$10^{19}m^{-3}$]**	**Heating**
81079	0.866	low density	3.75	1.5	2.01	0.189	NBI
11369	2.2	NBI plasmas (similar n and T profiles.)	3.60	1.52	0.83	2.2	NBI
16727	1.02		3.75	1.5	0.91	1.84	NBI
32940	2.003	Electron Root plasma	3.75	1.52	3.48	0.299	NBI+ECH

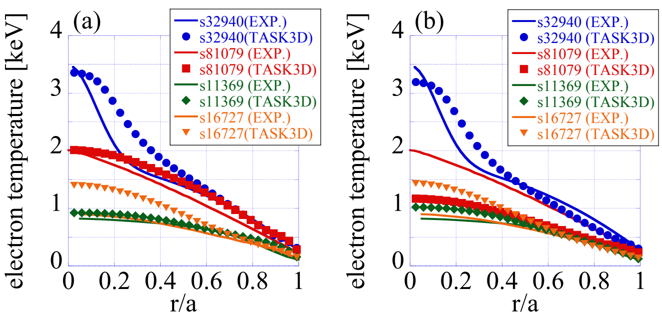

FIG. 4. *Experimentally obtained electron temperature and temperature obtained by TASK3D with (a) gyro-Bohm model and (b) Alcator model.*

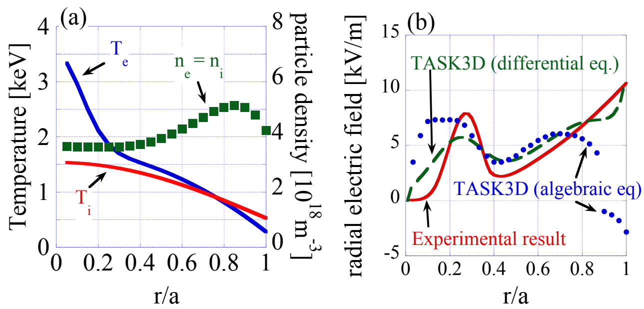

FIG. 5. *(a) experimental profiles of T_e, T_i and n, (b) experimental result of E_r (line) and simulation result solved by the algebraic equation (symbols) and by the differential equation (dashed line).*

We show a comparison between the simulation results using the algebraic equation and the differential equation for calculating the radial electric field. We apply TASK3D assuming the Alcator model to the electron root plasma (#32940, 2.003s, B = 1.5 T, R_{ax} = 3.75 m, β_0 = 0.00%, shown Fig. 5(a)) and assume that the electric diffusion coefficient is constant (D_{Er} =0.01). As shown in Fig. 5(b), the experimental results of E_r indicate the positive value all regions and the ion root appears in the edge region of the simulation result with the algebraic equation. The simulation results using the differential equation for the radial electric field are also shown in Fig. 5(b). We give the experimental value of E_r(r/a=1) as the boundary condition. The ion root in the edge region vanishes in the case the differential equation is solved, and the appropriate electric field is obtained.

4. Dynamic Transport Code, TASK/TX

The one-dimensional transport code, TASK/TX, was developed to self-consistently describe the plasma rotation and the radial electric field in tokamaks [4]. Surface-averaged multi-fluid equations including continuity equation, equations of motion, and energy transport equation, and Maxwell's equation including Gauss's law are solved simultaneously. In order to extend it to three-dimensional helical configurations, we have introduced neoclassical toroidal viscosity and radial diffusion due to magnetic braiding in the edge region [7]. In the present analysis of LHD plasmas, the radial electric field and the density profiles are self-consistently calculated with a simple model of anomalous transport coefficients, particle diffusivity D, thermal diffusivity χ, and viscosity μ.

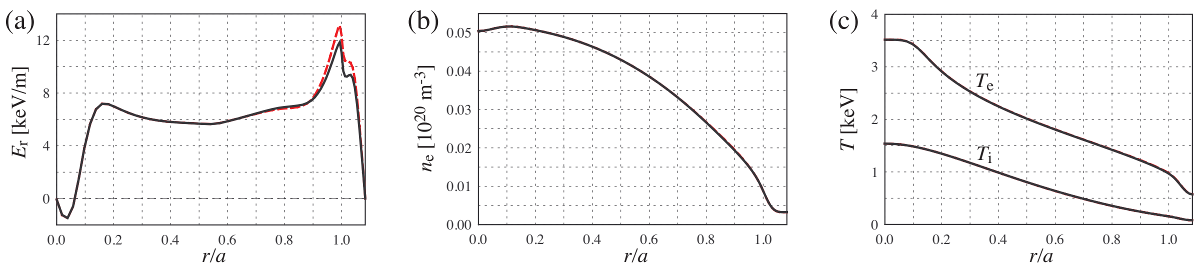

FIG. 6. Simulation results by TASK/TX for #32940, 2.003s; (a) radial profile of E_r, (b) n_e, (c) T_e, T_i; D_m=0 (solid black line) and D_m=10^{-9} m (dashed red).

Fig. 6 shows the results for #32940, 2.003s with NBI and EC heating and gas puffing. The anomalous transport coefficients are assumed to be parabolic with $D(0)$=0.09 m^2/s, $D(a)$=0.19 m^2/s, $\chi(0)=\mu(0)$=7 m^2/s, $\chi(a)=\mu(a)$=30m^2/s. The radial profile of the radial electric field has two peaks, near the plasma edge and r/a ~ 0.2, as observed in the experiment.

The density profile is broad, but not so flat as observed. The temperature profiles are well reproduced in the central region, while the difference between T_e and T_i in the outer region is larger than the experimental observation. Though we employed same values of χ and μ for electrons and ions in the present analysis, different transport coefficients for electrons and ions may improve the agreement with experimental results. The effect of magnetic braiding with magnetic diffusion coefficient D_m is small in the present case and appears only in E_r.

5. Summary and Future Plans

We have been developing the integrated simulation code TASK3D for non-axisymmetric plasma. The neoclassical transport database DGN/LHD and the differential equation determining the radial electric field have been incorporated. We have assumed several turbulent transport models. The obtained electron and ion thermal diffusivities with these tree models indicate the anomalous transport dominates in the electron thermal transport, while the neoclassical transport plays a crucial role in the ion thermal transport.

Acknowledgments

This work is supported in part by Grant-in-Aid for Scientific Research (S) (20226017) from JSPS and by the NIFS Collaboration Research program.

References

[1] A. Wakasa et. al., " Development of the Neoclassical Transport Module for the Integrated Simulation Code in Helical Plasmas", Contrib. Plasma Phys. 50, No. 6-7, 582 – 585 (2010)

[2] M. Sato et al., “Development of a Hierarchy-Integrated Simulation Code for Toroidal Helical Plasmas, TASK3D,” *Plasma Fusion Res.*, **3**, S1063 (2008)

[3] A. Fukuyama et al., “Advanced Transport Modeling of Toroidal Plasmas with Transport Barriers,” Proc. 20th Fusion Energy Conf., Villamoura, Portugal, 2004, IAEA-CSP-250CD/TH/P2-3, International Atomic Energy Agency (2004).

[4] M. Honda and A. Fukuyama, “Dynamic Transport Simulation Code Including Plasma Rotation and Radial Electric Field,” *J. Comp. Phys.*, **227**, 2808-2844 (2008).

[5] D.E. Hasting, *et al.*, "THE AMBIPOLAR ELECTRIC FIELD IN STELLARATORS", Nuclear Fusion, Vol. 25, No 4 (1985) 445.

[6] A. Gondhalekar et al. (1979) in Plasma Physics and Controlled Nuclear Fusion Research, Vol. I, IAEA, Vienna, 199.

[7] M. Miki, A. Fukuyama and M. Honda, "Transport simulation of helical plasmas using the TASK/TX code", *Plasma Fusion Res.,* in press.