How to apply a turbulent transport model based on a gyrokinetic simulation for the ion temperature gradient mode in helical plasmas

S Toda\(^1\), M Nunami\(^1\), A Ishizawa\(^1\), T -H Watanabe\(^2\) and H Sugama\(^1\)

\(^1\)National Institute for Fusion Science, Oroshi 322-6, Toki, Gifu, 509-5292, Japan
\(^2\)Department of Physics, Nagoya University, Furo-cho, Nagoya, Aichi, 464-8602, Japan

E-mail: toda@nifs.ac.jp

Abstract. How to apply a reduced model for the turbulent ion heat diffusivity [Nunami M \it et al. 2013 Phys. Plasmas, 20 092307] derived from a gyrokinetic code to a transport simulation is proposed. The reduced model is given by the function of the linear growth rate of the ion temperature gradient (ITG) mode and the decay time of zonal flows. The ion temperature gradient scale length is chosen for the additional modeling to include the linear growth rate of the ITG mode from a gyrokinetic code. The formula for the zonal flow decay time is derived at the given magnetic field configuration. The calculation of an extremely low computational cost in this article reproduces the results of the reduced model for the turbulent ion heat diffusivity within allowable errors.

1. Introduction
Turbulent transport is one of the most critical issues for plasma confinement in magnetic fusion devices. This is because the turbulent transport induces a large amount of the particle and heat loss in toroidal plasmas. Theoretical expressions for the turbulent transport coefficients due to various instabilities were reviewed [1, 2]. Recently, a large number of the gyrokinetic simulations have been done in toroidal plasmas [3]. The results in tokamak [4, 5, 6, 7, 8, 9] and helical [10, 11] plasmas from the gyrokinetic simulations have been studied with the experimental observations. The GKV-X code solving the gyro-kinetic equation has been used to examine the ITG mode and zonal flows in the LHD for studying the turbulent transport in helical plasmas [12], where the ITG mode is assumed to be the main underlying microinstability. The reduced model of \(\chi_i \sim \rho_i^2 v_{ti} f(\mathcal{L}, \bar{\tau}_{ZF})/R\) is taken [13, 14] using the GKV-X code for the high-\(T_i\) LHD discharge of the shot number 88343, where \(f\) is a function of \(\mathcal{L}\) and \(\bar{\tau}_{ZF}\), \(v_{ti}\) is the ion thermal velocity, \(\rho_i\) is the ion gyroradius and \(R\) is the major radius. Here, \(\mathcal{L}\) is the mixing length estimate \(\bar{\gamma}_{k_y}/\bar{k}_y^2\) integrated over the \(k_y\) space, where \(\bar{\gamma}_{k_y}\) is the normalized linear growth rate of the ITG mode for the normalized poloidal wavenumber \(\bar{k}_y\) and \(\bar{\tau}_{ZF}\) is the normalized decay time of zonal flows [15, 16]. The nonlinear gyrokinetic simulation results are quantitatively reproduced by the reduced model calculations. However, it is costly to carry out linear calculations of the growth rate by the gyrokinetic simulation at each time step of the dynamical transport code such as TASK3D [17], because the transport analysis of helical plasmas demands a high radial resolution so as to accurately evaluate the radial electric field, which strongly affects...
the neoclassical transport, and the field configuration. It is needed to speed up the predictive transport simulation, which proposes the experimental scenario to realize the favorable plasma state such as the improved confinement plasma mode, for performing the transport simulation in the wide plasma parameter regime. (In tokamak plasmas, the gyrokinetic simulations at each time step are globally done in the dynamical transport simulation [18, 19].)

In this study, how to apply the reduced model of the turbulent heat diffusivity for the ITG mode derived from the gyrokinetic simulation to the transport code is shown with a low computational cost, while the accuracy of the gyrokinetic simulation is maintained. Modeling of the term $L$ in the reduced model for the ITG mode is necessary to be involved with a parameter dependence of the plasma instability in the dynamical transport code. The ion temperature gradient scale length $L_{T_i} (= -T_i/ (∂T_i/∂r))$ is chosen for the parameter to apply $L$ to avoid the calculations of the linear growth rate by the gyrokinetic code at each time step of the transport simulation. The field configuration is fixed at the initial state in the transport simulation. The linear gyrokinetic analysis is performed using the GKV-X code at this magnetic field configuration before the dynamical transport simulation. The dependence of $L$ on the ion temperature gradient scale length is examined at the different radial points. We have newly developed the formula for $L$ in terms of the ion temperature gradient scale length. The decay time of zonal flows depends on the magnetic field configuration and is independent of the the density and temperature profiles. The formula of the zonal flow decay time is needed to be calculated only at the initial state in the transport simulation, because the magnetic field configuration is dynamically fixed in this study. The calculation by substituting these formulae for $L$ and $τ_{ZF}$ to the reduced model [13] reproduces the results of the reduced model itself within allowable errors. The computational cost to obtain the value of the turbulent ion heat diffusivity by this modeling at each time step of the transport simulation is much smaller than that of the linear gyrokinetic simulation. This additional modeling for the turbulent ion heat diffusivity is applied to the transport code and enables us to study the simulation results with the experimental results in LHD.

2. The additional modeling of the turbulent ion heat diffusivity

This section addresses the adoption of the reduced transport model to a transport simulation for reducing a computational cost. Firstly, the linear analysis is done using the GKV-X code for the additional modeling of the turbulent ion heat diffusivity, before the dynamical transport simulation. The ITG instability is examined in the high-$T_i$ LHD discharge #88343 [20]. The saturation level of the linear growth rate for the perturbation of the electrostatic potential is calculated. The value of the turbulent ion heat diffusivity $χ_{i1}/χ^{GB}_i$ was fitted [13] only by the function $L \left( \equiv \int (k_y^2/ k_y^2) d\tilde{k}_y \right)$ as $χ_{i1}/χ^{GB}_i = C_0 \left( C_T L \right)^{δ}$, where $χ^{GB}_i$ is the gyroBohm diffusivity, $\chi_{i1}^{GB} = \rho_{ii}\tilde{v}_{ii}/R$, $\tilde{g}_i = \gamma/v_{ii}/R$ and $\tilde{k}_y = k_y\rho_{ii}$ with $C_0 = 0.11$, $C_T = 9.8 \times 10$ and $δ = 0.83$. A reduced model for the ITG turbulent heat diffusivity in terms of the functions $L$ and $τ_{ZF}(= τ_{ZF}/(R/v_{ii}))$ was obtained as $χ_{i2}/χ^{GB}_i = A_1 L^{α}/(A_2 + τ_{ZF}/L^{1/2})$. The numerical coefficients are given by $A_1 = C_1 C_T^{α+1/2} C_Z^{-1}$ and $A_2 = C_2 C_T^{1/2} C_Z^{-1}$, where $α = 0.38$, $C_Z = 0.202$, $C_1 = 6.3 \times 10^{-2}$ and $C_2 = 1.1 \times 10^{-2}$. For reducing a computational cost, the additional modeling is needed for $L$ in terms of the physical parameter which is included in the transport codes. The characteristic length of the ion temperature gradient is considered to be the important parameter for the ITG instability. The parameter $L_{T_i}$ is considered to be more sensitive to the ion heat flux than the electron temperature gradient scale length for the ITG mode examined here. The radial profiles of the density and the electron temperature are fixed in the dynamical transport simulation. Therefore, the parameters, $L_n(= -n/ (∂n/∂r))$ and $L_{T_e}(= -T_e/ (∂T_e/∂r))$ do not change at each radial point. As the function of the ion temperature gradient scale length $L_{T_i}$,
Figure 1. Radial profiles of (a) the density, (b) the electron temperature and (c) the safety factor.

Figure 2. The radial dependence of (a) $R/L_{T_i}$ and (b) $a(\rho)$ is shown with filled circles. The red curve shows the fitting function with respect to the radial position $\rho$. These are results from the GKV gyrokinetic linear code.

The parameter $\mathcal{L}$ is modeled by

$$\mathcal{L} = a(\rho) \left( \frac{R}{L_{T_i}} - \frac{R}{L_{T_i}} \right),$$

where $L_{T_c}$ is the normalized critical ion temperature gradient for the ITG instability and $\rho$ is the radial axis normalized by the minor radius.

To find the critical ion temperature gradient for the ITG mode, the dependence of $\mathcal{L}$ on $R/L_{T_i}$ is examined [21] with all plasma parameters fixed except the ion temperature gradient at forty five radial points in the radial region $0.00 \leq \rho \leq 0.88$. When we examine the linear growth rate of the ITG mode, the radial profiles of the density ($n$), the electron temperature ($T_e$) and the safety factor ($q$) are used in figure 1. The density and ion temperature profiles are obtained from the experimental results at $t = 2.233s$ in the high-$T_i$ LHD discharge #88343. The $T_e$ profile is set as $T_e = T_i$ in a gyrokinetic simulation. This simulation is performed for the three dimensional equilibrium field configuration with $R = 3.75m$, using the plasma profiles explained here in the VMEC calculation. The slope $a(\rho)$ and the critical ion temperature...
gradient $L_{Te}$ depend on the values of $L_{Te}$, $L_n$ and the safety factor, which change due to the radial positions. We calculate the linear fitting function (1) at each radial point and obtain the critical values of $R/L_{Te}$, $R/L_{Te}$, where $\mathcal{L}$ becomes zero. The critical ion temperature gradient for the ITG mode, (a) $R/L_{Te}$ and the slope (b) $a(\rho)$ in terms of $R/L_{Te}$ are obtained in figure 2, when the GKV gyrokinetic linear simulation is performed. When we calculate the value of the ion heat diffusivity in the integrated transport code, the fitting polynomials of $R/L_{Te}$ and $a(\rho)$ are used as $R/L_{Te} = 4.0929 - 3.7681\rho + 19.712\rho^2 + 11.087\rho^3 - 14.272\rho^4$ and $a(\rho) = 0.38661 - 0.070919\rho + 0.2571\rho^2 + 0.95949\rho^3 - 0.92978\rho^4$. If the degree of the fitting polynomial increases, the accuracy of the fitting gets better. Figure 3 shows the comparison between the right hand side ($a(\rho) (R/L_{Te} - R/L_{Te})$) and the left hand side ($\mathcal{L}$) in (1) with the root mean square of $((a(\rho) (R/L_{Te} - R/L_{Te}))/\mathcal{L} - 1$ given by $\sigma = 0.13$, when the fourth degree fitting polynomial is used. The zonal flow decay time $\tau_{ZF}$ [16], which only depends on the magnetic field structure, is examined at forty four points in the radial region $0.02 \leq \rho \leq 0.88$.

**Figure 3.** Comparison between the modeled function in terms of the ion temperature gradient scale length and the integral of the linear growth rate divided by the square of the poloidal wavenumber over the $k_y$ space.

**Figure 4.** The radial profile of $\tau_{ZF}$ is shown with filled circles. The red curve shows the fitting function for the zonal flow decay time with respect to the radial position $\rho$. 


The radial profile of the zonal flow decay time $\tau_{ZF}$ is shown in figure 4. The fitting function for the zonal flow decay time: $\tau_{ZF}(fit) = 0.98565 - 0.65943\rho + 2.4471\rho^2 + 3.2337\rho^3 - 2.8382\rho^4$ is used throughout the transport simulation, because the field configuration is dynamically fixed. The first modeled turbulent ion heat diffusivity, where the term $a(\rho)(R/L_{T_i} - R/L_{T_c})$ is substituted for $L$ in $\chi_i^{(1)}/\chi_i^{GB}$, is shown as

$$\frac{\chi_i^{FTS(1)}}{\chi_i^{GB}} = C_0 \left( C_T a(\rho) \left( \frac{R}{L_{T_i}} - \frac{R}{L_{T_c}} \right) \right)^{\delta},$$

(2)

which is the function of only the ion temperature gradient scale length. The second modeled turbulent ion heat diffusivity, where the term $a(\rho)(R/L_{T_i} - R/L_{T_c})$ is substituted for $L$ and the fitting function $\tau_{ZF}(fit)$ is used for $\tau_{ZF}$ in $\chi_i^{(2)}/\chi_i^{GB}$, is also shown as

$$\frac{\chi_i^{FTS(2)}}{\chi_i^{GB}} = \frac{A_1 \left( a(\rho) \left( \frac{R}{L_{T_i}} - \frac{R}{L_{T_c}} \right) \right)^{\alpha}}{A_2 + \tau_{ZF}(fit) / \left( a(\rho) \left( \frac{R}{L_{T_i}} - \frac{R}{L_{T_c}} \right) \right)^{1/2}},$$

(3)

which is the function of $L_{T_i}$ and the zonal flow decay time. The values for the root mean square of $(\chi_i^{FTS(1)}/\chi_i^{(1)} - 1)$ and $(\chi_i^{FTS(2)}/\chi_i^{(2)} - 1)$ are 0.13 and 0.12, respectively. Therefore, the present modeling (1) reproduces the results of the reduced model, while the accuracy of the linear gyrokinetic simulation is maintained. To obtain the value of the turbulent ion heat diffusivity at each time step in the integrated transport code, the values of (2) and (3) are calculated instead of the reduced model calculation by the linear gyrokinetic simulation. Note that this modeling for $L$ and the fitting function for the zonal flow decay time is applicable to the magnetic field structure used here and the fixed profiles of the density and the electron temperature.

3. Transport analysis using the additional modeled turbulent diffusivity

In section 2, we have modeled the turbulent ion heat diffusivity, (2) and (3) to reduce a computational cost. The modeled turbulent ion heat diffusivities expressed in terms of the ion temperature gradient scale length for the ITG mode are useful in a transport simulation.

Now, the transport dynamics is examined using the modeled turbulent ion heat diffusivity, when the integrated transport code, e.g., TASK3D [17] is performed. The radial profiles of the density and the electron temperature are fixed, which are shown in figure 1(a) and (b). This is because the radial profiles of the density and the electron temperature are considered to be almost stationary in the experimental results [20]. The $T_i$ profile of the experimental results at $t = 2.233$s in the high-$T_i$ LHD discharge #88343 is used as an initial state for the transport simulation. At the initial state, we set $T_e = T_i$ and use the dynamically fixed $q$ profile in figure 1(c). The dynamics of the radial $T_i$ profile is simulated by solving the diffusion equation as

$$\frac{\partial}{\partial r} \left( \frac{3}{2} n T_i \right) = - \frac{1}{V'} \frac{\partial}{\partial \rho} \left( V' Q_i \right) + P_{hx} + P_{hi},$$

(4)

where $V'$ is the plasma volume, $V' = dV/d\rho$, $P_{hx}$ is the heat exchange term and $P_{hi}$ is the absorbed power of ions. The ion heat flux $Q_i$ is set as $Q_i = -\langle \nabla n \rho^2 \rangle \left( \chi_i^{FTS} + \chi_i^{NEO} \right) \partial \rho \nabla T_i / \partial \rho$, where $\chi_i^{NEO}$ is the neoclassical diffusion coefficient of ions and $<>$ represents the magnetic surface average. The flux $Q_i$ does not contain the convective part, because the core particle source is negligibly smaller than that in the edge region. The neoclassical diffusion coefficient is derived from DGN/LHD database with the low-$\beta$ limit ($\beta = 0$) [22]. The profile of the radial electric field $E_r$ is derived from the ambipolar condition at the initial plasma state. A
Figure 5. The radial profile of the electric field, which is dynamically fixed, is shown with filled circles. The (a) largest positive or (b) negative radial electric field is chosen from three ambipolar electric fields.

positive $E_r$ is observed in the region $0.8 < \rho < 1.0$ at $t = 2.24s$ in the high-$Ti$ LHD discharge of #88343 [20]. Three solutions of the ambipolar radial electric field are found in the radial region $0.265 < \rho < 0.785$. For the first case, the largest positive radial electric field, which is chosen from three solutions of the ambipolar conditions, is shown in figure 5(a). For the second case, the negative radial electric field is chosen in figure 5(b). The profiles of the radial electric field are dynamically fixed for two cases in this study. This is because the power balance is almost satisfied at the plasma initial state when the reduced model for the turbulent ion heat diffusivity [13] is used and therefore it is predicted that the profile of $T_i$ does not change much in the transport simulation. The turbulent heat diffusivity is calculated using (2) and (3) with the additional modeling (1). The value of the ion temperature is fixed at the initial state in the shaded region $0.785 \leq \rho \leq 1.000$ shown in figure 6 and 7, because the modeling for the turbulent ion diffusivity in section 2 is done in the region $0.00 \leq \rho \leq 0.88$ and in many studies the gyrokinetic analysis does not predict the results which agree with the experimental results especially in the edge region. At the initial state, the radial profile for the absorbed power of ions, $P_{hi}$ is calculated using TASK3D and is dynamically fixed. At first, the positive $E_r$ is chosen from the three ambipolar radial electric fields to calculate the value of $\chi_i^{NEO}$. We show the simulation results for the stationary ion temperature profile at $t = 0.1s$ with the solid line in figure 6. In figure 6(a), the simulation result for the ion temperature profile is obtained when we use $\chi_i^{FTS(1)}$ for the turbulent ion heat diffusivity. We show the simulation result of the $T_i$ profile in figure 6(b) when $\chi_i^{FTS(2)}$ is used. The dashed line indicates the radial profile of $T_i$ at $t = 2.233s$ in the LHD discharge #88343. In the figure 6 (a) and (b), the simulation results for the radial $T_i$ profile show a good agreement with the experimental results. Specially, in figure 6(b) when the turbulent ion heat diffusivity is given by the function of $\tau_{ZF}$ in addition to $L_{Ti}$, the better agreement between the experimental and the simulation results is obtained. The stationary profiles of the turbulent and neoclassical diffusivities are also shown in figure 7. The solid and dashed lines represent the turbulent and neoclassical ion diffusivities. In both cases, the ITG mode is destabilized in the radial region $0.135 \leq \rho \leq 1.00$. The turbulent transport is dominant compared with the neoclassical transport in the radial region where the positive electric field is chosen. Table 1 shows the comparison between the ion heat diffusivities calculated by the nonlinear gyrokinetic simulation at the initial state in the transport simulation $\chi_i^{NL}$ [13] and from the additional modeling in this study, $\chi_i^{FNS(1)}$ and $\chi_i^{FNS(2)}$. The values of $\chi_i^{FNS(1)}$ and $\chi_i^{FNS(2)}$ are estimated at the stationary state as the result of the transport simulation. The results of the additional modeling in this study (specially, the value of $\chi_i^{FNS(2)}$ ) quantitatively agree with the results of the nonlinear gyrokinetic simulation in the radial region $0.46 \leq \rho \leq 0.72,
Figure 6. Simulation results for the $T_i$ profile are shown with solid lines using (a) $\chi_i^{FTS(1)}$ and (b) $\chi_i^{FTS(2)}$ for the turbulent ion diffusivity, when the positive radial electric field is chosen. The dashed lines show the $T_i$ profile at $t = 2.233s$ in the LHD discharge #88343.

Figure 7. Simulation results for the neoclassical and turbulent diffusion coefficients are shown using (a) $\chi_i^{FTS(1)}$ and (b) $\chi_i^{FTS(2)}$ for the turbulent ion diffusivity, when the positive $E_r$ is chosen. The solid and dashed lines represent the radial profiles of the turbulent and neoclassical ion diffusivities.

even if the stationary profile of $T_i$ slightly changes from the initial state. For modeling $\mathcal{L}$ in terms of the ion temperature gradient scale length, three runs at the different values of $L_{T_i}$ are needed at a radial point before the dynamical transport simulation. It takes about one hour per one time of the program run. If the value of $\mathcal{L}$ is calculated at each time step in the transport simulation, TASK3D, about one hundred thousand times of the program run are necessary at a radial point. Therefore, the transport simulation of an extremely low computational cost can be achieved due to the additional modeling of the turbulent ion heat diffusivity based on the gyrokinetic simulation.

Next, the negative radial electric field is chosen from the three radial electric fields which satisfy the ambipolar condition in figure 5(b). The stationary ion temperature profile at $t = 0.1s$ is obtained. When the turbulent heat diffusivities, (2) and (3) are used, the radial profile of the ion temperature does not agree with the experimental results. The ion temperature is found to
Table 1. The ion heat diffusivities by the nonlinear gyrokinetic simulation, $\chi_{i}^{NL}$ and from the additional modeling for transport simulation, $\chi_{i}^{FNS(1)}$ and $\chi_{i}^{FNS(2)}$

| $\rho$ | $\chi_{i}^{NL} (m^2/s)$ | $\chi_{i}^{FTS(1)} (m^2/s)$ | $\chi_{i}^{FTS(2)} (m^2/s)$ |
|-------|-----------------|-----------------|-----------------|
| 0.46  | 3.60            | 2.64            | 3.10            |
| 0.50  | 3.30            | 2.53            | 2.94            |
| 0.57  | 3.04            | 2.44            | 2.77            |
| 0.65  | 2.77            | 2.33            | 2.53            |
| 0.72  | 2.40            | 1.99            | 2.11            |
| 0.79  | 2.35            | 1.33            | 1.51            |
| 0.83  | 1.84            | 1.38            | 1.52            |

...become low from the initial $T_i$ profile and the lower ion temperature ($T_i \simeq 3.2$keV at $\rho = 0$) is obtained than the case when the positive radial electric field is chosen. The neoclassical transport is found to be dominant compared with the turbulent transport in the almost whole radial region. The neoclassical ion heat diffusivity in the region $0.265 \leq \rho \leq 0.785$ when the negative $E_r$ is chosen is much larger than those in figure 7. This is because the absolute value of $E_r$ when the positive radial electric field is chosen is larger than that when the negative $E_r$ is chosen. Therefore, the lower ion temperature is obtained due to the enhanced neoclassical transport, when the negative $E_r$ is chosen.

4. Summary

To reduce the simulation cost, how to apply the transport model based on a gyrokinetic simulation to a dynamical transport code is shown within the accuracy of the gyrokinetic simulation. Before the dynamical transport simulation, the GKV-X code is performed for the additional modeling in terms of the ion temperature gradient scale length instead of the linear growth rate term for the ITG mode. The formula of the zonal flow decay time in the reduced model is derived at the given magnetic field structure. The value of the reduced model is reproduced by those of the modeled turbulent ion heat diffusivity with an extremely low computational cost. The simulation results by applying the additional modeled turbulent ion heat diffusivity to the dynamical transport code are shown. In the dynamical transport simulation, the linear gyrokinetic simulation is not needed at all, because of the additional modeling in section 2. This simulation results agree with the experimental results of the ion temperature profile in the high-$T_i$ LHD discharge #88343, when the positive radial electric field is chosen. If the negative radial electric field is chosen, the less agreement of the simulation results with the experimental result of the ion temperature is shown. Therefore, the transport analysis including the neoclassical transport is important in helical plasmas. A critical temperature gradient model has been proposed in [23], which is similar to the models, (2) and (3) in this study. The value of the critical ion temperature gradient for the ITG stability in (2) and (3) is calculated with the GKV linear simulation. So far, we concentrate on the ITG turbulence in helical plasmas. Reduced model of the turbulent heat diffusivity in helical plasmas will be constructed in terms of the linear growth rate of the other modes, such as the trapped electron mode and the electron temperature gradient mode. To apply the reduced model of the turbulent diffusivity to a transport code, the similar method discussed in this study can be used, if we choose the parameters such as $L_{Te}$ and/or $L_{ne}$ in the transport simulation for the additional modeling. In this study, the promising technique of a low computational cost for adapting the gyrokinetic turbulent transport model to a transport code is proposed within allowable errors.

Note that the form for the turbulent ion heat diffusivity by this additional modeling is valid...
for the high-$T_i$ LHD discharge #88343. The dependence of the turbulent heat diffusivity on the field configuration and the plasma profiles for the LHD and different devices will be investigated. The effect of the radial electric field on the turbulent diffusivities should be examined for the future study.

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