Comparison of carbon density distribution in \textit{L}-mode plasma discharges in TFTR tokamak using the Mixed Bohm/gyro-Bohm and Multi-Mode-95 transport models

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Abstract. The behaviors of carbon density distribution in low confinement mode (\textit{L}-mode) plasma in TFTR Tokamak are investigated using 1.5D BALDUR integrated predictive modeling code. In each simulation, either turbulent transport either Mixed Bohm/gyro-Bohm (Mixed B/gB) turbulent transport model or Multi-Mode (MMM95) turbulent transport model is used to describe thermal, particle, and impurity transports in the core region of the tokamak. It is found that, the simulations using both turbulent transport models agree equally well with experimental results, with an average RMS of 7-20\% for the simulations with Mixed B/gB model and 9-16\% for the simulations with MMM95 model.

1. Introduction
Although plasma in Low Confinement mode (\textit{L}-mode) has lower performance than that of High Confinement mode (\textit{H}-mode), it has better plasma stability and simplicity in operation [1]. If the understanding of \textit{L}-mode plasma is improved, it could potentially enhance the \textit{L}-mode performance. One of the important issues for an \textit{L}-mode plasma experiment is the accumulation of impurity in tokamak. The presence of impurity can result in radiation losses and fuel dilution, which leads to a degradation of fusion performance [2]. As a result, it is important to investigate impurity density distribution in \textit{L}-mode plasma.

In previous study by D.R. Baker \textit{et al.} [3], there was an accumulation and peaking of impurities in the core in DIII–D discharges with centrally enhanced confinement and peaked density profiles, as was predicted by neoclassical theory. The work of G. Bateman \textit{et al.} [4] used BALDUR code together with the Multi-mode (MMM95) core transport model to predict temperature and density profiles. It was found that those predicted profiles agreed with experimental data with an RMS deviation less than 15\% for 41 \textit{L}-mode and \textit{H}-mode discharges from the Tokamak Fusion Test Reactor (TFTR), the Doublet III-D tokamak (DIII-D) and the Joint Europian Torus (JET). In Ref [5], T. Onjun \textit{et al.} used BALDUR code with either the MMM95 or the Mixed B/gB core transport model to simulate plasma behaviours in tokamak for \textit{L}-mode regime. Electron temperature and electron density profiles from these simulations were compared with experimental data from DIII-D and TFTR but they neglected to observe the impurity density profiles.

In this work, it aims to study the behaviors of carbon density distribution and impurity transport in \textit{L}-mode tokamak in TFTR Tokamak by using BALDUR code. This work is organized as follows: brief descriptions of relevant components of the BALDUR code, including the MMM95 model and the Mixed B/gB model are presented in section 2; simulation results are described in section 3; and the conclusion is given in section 4.

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2. BALDUR integrated predictive modeling code

The BALDUR code is an integrated predictive modeling code [6] developed for self-consistency simulating time evolution of various plasma properties, including electron and ion temperatures, electron and ion densities, helium and impurity densities. The BALDUR code combines various modules, in which each module is responsible for computing different physical phenomena, such as transport, heating and instability. It was shown in many reports that BALDUR code is capable to predict electron and ion temperatures, and electron density profiles within 10% relative RMS of experimental data [5, 7].

2.1. Multimode Core Transport Model (MMM95)

The Multi-Mode Model version 1995 (MMM95) [4] is a transport model based on a combination of transport due to different kinds of physics. It consists of the Weiland model for the ion temperature gradient (ITG) and trapped electron modes (TEM), the Guzdar–Drake model for drift-resistive ballooning (RB) modes, and modified kinetic ballooning (KB) modes. The thermal and particle transport coefficients can be expressed as:

\[ \chi_i = 0.8 \chi_{i,ITG} + 0.65 \chi_{i,KB}, \]  
\[ \chi_e = 0.8 \chi_{e,ITG} + \chi_{e,RR} + 0.65 \chi_{e,KB}, \]  
\[ D_H = 0.8 D_{H,ITG} + D_{H,RR} + D_{H,KB}, \]  
\[ D_z = 0.8 D_{z,ITG} + D_{z,RR} + D_{z,KB}, \]

where \( \chi_i \) is ion thermal diffusion coefficient in \( \text{m}^2/\text{s} \), \( \chi_e \) is electron thermal diffusion coefficient in \( \text{m}^2/\text{s} \), \( D_H \) is hydrogenic particle diffusion coefficient in \( \text{m}^2/\text{s} \) and \( D_z \) is impurity particle diffusion coefficient in \( \text{m}^2/\text{s} \).

2.2. Mixed B/gB model

The Mixed B/gB core transport model [9] is a semi-empirical transport model, which is a combination of Bohm (B) and gyro-Bohm (gB) terms. The transport diffusivity in Bohm model is proportional to the gyro-radius times the thermal velocity, while the transport diffusivity in gyro-Bohm model is proportional to the square of the gyro-radius times the thermal velocity divided by the plasma major radius. The expressions of transport coefficients in this model are:

\[ \chi_i = 0.5 \chi_{gB} + 4.0 \chi_B, \]  
\[ \chi_e = 1.0 \chi_{gB} + 2.0 \chi_B, \]  
\[ D_H = D_z = \left( 0.3 + 0.7 \frac{r}{a} \right) \frac{\chi_e \chi_i}{\chi_e + \chi_i}, \]  
\[ \chi_{gB} = 5 \times 10^{-6} \sqrt{T_e} \left( \frac{\nabla (T_e)}{B_T^2} \right), \]  
\[ \chi_B = 4 \times 10^{-5} R \left( \frac{\nabla (n_e T_e)}{n_e B_T} \right) q^2 \left( \frac{T_e \left( \frac{r}{a} = 0.8 \right)}{T_e \left( \frac{r}{a} = 1 \right)} - T_e \left( \frac{r}{a} = 1 \right) \right), \]

where \( r/a \) is the normalized minor radius of the plasma, \( \chi_{gB} \) is the gyro-Bohm contribution in \( \text{m}^2/\text{s} \), \( \chi_B \) is the Bohm contribution in \( \text{m}^2/\text{s} \), \( T_e \) is the local electron temperature in keV, \( B_T \) is the toroidal magnetic field in Tesla, and \( n_e \) is the local electron density in \( 10^{19} \text{m}^{-3} \).
3. Simulation results
In this work, the BALDUR integrated predictive modeling code is used to simulate the radial profiles of impurity density in L-mode scenario from 4-different auxiliary heating power discharges of TFTR tokamaks. Some important engineering parameters of these discharges are listed in table 1.

For each simulation, either MMM95 anomalous transport or Mixed B/gB anomalous transport model is used to describe both thermal and particle transports. It is assumed that pedestal impurity density in the simulation is the same as that in the experiment.

### Table 1. List of engineering parameters in TFTR discharges.

| Tokamak Shot No. | Unit | 45966 | 50911 | 50921 | 62270 |
|------------------|------|-------|-------|-------|-------|
| Major radius \(R\) | m    | 2.45  | 2.45  | 2.45  | 2.45  |
| Minor radius \(a\) | m    | 0.80  | 0.798 | 0.797 | 0.80  |
| Plasma current \(I_p\) | MA   | 2.00  | 1.78  | 0.89  | 1.78  |
| Magnetic field \(B_t\) | T     | 4.76  | 4.23  | 2.14  | 4.77  |
| Elongation \(\kappa_{95}\) | -    | 1.00  | 1.00  | 1.00  | 1.00  |
| Line average electron density \(\bar{n}_e\) | \(10^{19}\) m\(^{-3}\) | 3.44  | 4.37  | 1.77  | 3.23  |
| Auxiliary heating power \(P_{aux}\) | MW   | 11.30 | 17.72 | 4.66  | 19.20 |
| Diagnostic time \(t_{diag}\) | s    | 3.47  | 3.93  | 3.95  | 4.17  |

3.1. Profile comparison
Figure 1 shows the radial profiles of the ion thermal diffusion coefficient \(\chi_i\) from the MMM95 model and the Mixed B/gB model for discharges no. 45966 and 50921. It is found that \(\chi_i\) from Mixed B/gB is higher than that from MMM95 model. Figure 2 shows the radial profiles of the electron thermal diffusion coefficient \(\chi_e\) from the MMM95 model and the Mixed B/gB model for discharges no. 45966 and 50921. \(\chi_e\) of Mixed B/gB tends to be higher than that of MMM95 model in most of the region for both discharges, except at the edge of the plasma. It is also found that the ion temperature gradient term (ITG) provides the largest contribution in the center of the plasma as shown in figure 4. Note that, the
peak in figure 3 of MMM95 come from the error of the model because this model consists of many models to predict the simulation. Figure 5 shows the radial profiles of the impurity (carbon) diffusion coefficient \( \chi_i \) as a function of normalized minor radius for TFTR discharge 45966 (left) and TFTR discharge 50921 (right). The solid lines represent Mixed B/gB model while the dotted lines represent MMM95 model.

Figure 2. Electron thermal diffusion coefficient \( \chi_e \) as a function of normalized minor radius for TFTR discharge 45966 (left) and TFTR discharge 50921 (right). The solid lines represent Mixed B/gB model while the dotted lines represent MMM95 model.

Figure 3. Hydrogenic particle diffusion coefficient \( D_{HH} \) as a function of normalized minor radius for TFTR discharge 45966 (left) and TFTR discharge 50921 (right). The solid lines represent Mixed B/gB model while the dotted lines represent MMM95 model.

Figure 4. Contributions of hydrogenic particle diffusion coefficient \( D_{HH} \) of MMM95 model as a function of normalized minor radius for TFTR discharge 45966 (left) and TFTR discharge 50921 (right). The dotted lines show the (ITG) contribution, the resistive-dotted lines show the resistive ballooning (RB) contribution, the dashed lines show the kinetic ballooning (KB) contribution, and the solid lines show the total effective diffusivity (tot MMM95).
coefficient ($D_z$) from either the MMM95 model or the Mixed B/gB model for discharges no. 45966 and 50921. $D_z$ of Mixed B/gB model is higher than MMM95 model in the core of plasma but kinetic ballooning term (KB) provides the largest contribution in the center of the plasma while the resistive ballooning contribution term (RB) provides the largest contribution near the edge of the plasma. Figure 7 shows impurity (carbon) density profiles for discharges no. 45966 and 50921 from TFTR.

It is found that the impurity density profiles simulated using MMM95 model and Mixed B/gB model are lower than the impurity density profiles from the experimental data, which can be explained by the hydrogenic particle diffusion ($D_H$) and the impurity diffusion coefficient ($D_z$) of the simulation being higher than that of the experiment. If the transport is higher, the lower the impurity density profiles will be lower. In addition, the impurity density profiles for the simulations using MMM95 model are higher than those using Mixed B/gB model for both discharges.

3.2. Statistical analysis

Two statistical quantities: the relative root-mean-square deviation (RMSD) and the relative offset are used to quantify the comparison between the simulations and the experiments. Both are computed based
on the difference between simulation profiles and experimental data. The RMS deviation for impurity (carbon) density is defined as

\[
\sigma_X = \frac{1}{N} \sum_{j=1}^{N} \left( \frac{X_j^{\exp} - X_j^{\sim}}{X_{\max}^{\exp}} \right)^2
\]

(10)

where \(X_j^{\exp}\) and \(X_j^{\sim}\) are the \(j\)th data point of the simulation and experimental profiles, respectively, while \(X_{\max}^{\exp}\) is the maximum data point of the experimental profile of \(X\) as a function of radius which has \(N\) points in total. The RMS deviation of impurity (carbon) density profile is designated by \(\sigma_i\), then the distribution of the RMS deviation over all the discharges can be characterized by the average RMS deviation as

\[
\overline{\sigma} = \frac{1}{N_s} \sum_{i=1}^{N_s} \sigma_i
\]

(11)

and the RMS deviation is defined as

\[
\sigma_{\sigma} = \sqrt{\frac{1}{N_s-1} \sum_{i=1}^{N_s} (\sigma_i - \overline{\sigma})^2}
\]

(12)

where \(N_s\) is the number of all discharges. The relative offset of impurity (carbon) density is defined as

\[
\mathcal{f} = \frac{1}{N} \sum_{j=1}^{N} \left( \frac{X_j^{\exp} - X_j^{\sim}}{X_{\max}^{\exp}} \right)
\]

(13)

This statistical analysis is used for comparing the simulation profiles and experimental profiles. The results of the statistical analyses for simulations are presented in figures 8 and 9. The RMS deviation for each discharge using the Mixed B/gB model varies from 7.76\% to 20.35\% while that using the MMM95 model varies from 9.73\% to 16.94\%. The offsets shown in figure 9 vary from about -1.77\% to 13.93\% by using the Mixed B/gB model and vary from about 4.52\% to 12.25\% by using the MMM95 model. The main reason that makes the results of RMS deviation and offset significantly different between some discharges is auxiliary heating power. The higher auxiliary heating power discharge yields the lower of RMS deviation and offset except for discharge no. 50921. The lowest auxiliary heating power for discharge no. 50921 gives the lowest of RMS deviation and offset; this may be explain by the others engineering parameters. The average RMS deviation (\(\overline{\sigma}\)) and the RMS deviation of the RMS deviation (\(\sigma_{\sigma}\)) for impurity (carbon) density profiles are summarized in table 2. It can be seen that the magnitude of the average RMS deviations of the MMM95 model is smaller than the Mixed B/gB model. However, the two models match experiment data equally well except for one case (discharge 50911).

Table 2. The average RMS deviation (\(\overline{\sigma}\)) and the RMS deviation of the RMS deviation (\(\sigma_{\sigma}\)) for impurity (carbon) density profiles produced by simulations using the Mixed B/gB model and MMM95 model.

| Profile | Mixed B/gB | MMM95 | \(|\overline{\sigma}_{\text{Mixed}} - \overline{\sigma}_{\text{MMM95}}|\) | \(\sigma_{\sigma, \text{Mixed}} + \sigma_{\sigma, \text{MMM95}}\) |
|---------|------------|--------|---------------------------------|---------------------------------|
| C density | 15.53      | 5.54   | 13.66                           | 3.37                            |
|          |            |        | 1.87                            | 8.91                            |
4. Conclusion
The carbon density distribution in the L-mode of TFTR tokamak are carried out using BALDUR code with two choices of turbulent transport models, Mixed B/gB and MMM95 models. It is found that the both turbulent transport models match with the experiment data for carbon density profiles equally well.

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Figure 8. RMS deviation for impurity (carbon) density profiles produced by simulations using the Mixed B/gB model and MMM95 model compared with experimental data for TFTR discharge 45966, 50921, 50911 and 62270.

Figure 9. Offset from impurity (carbon) density profiles produced by simulations using the Mixed B/gB model and MMM95 model compared with experimental data for TFTR discharge 45966, 50921, 50911 and 62270.