การทดสอบโมเดลทำนายการเกิดเพเดสทัลสำหรับพลาสมาในโหมดประสิทธิภาพสูงด้วยวิธีการให้เหตุผลแบบไขว้กับโทคาแมคเจ็ต

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บทคัดย่อ

งานวิจัยนี้แบบจำลองที่ใจกลางและขอบของพลาสมา สำหรับใช้ในการทำนายการเกิดเพเดสทัลในโหมดประสิทธิภาพสูง ได้ถูกพัฒนาและทำการทดสอบในแบบจำลองทางคณิตศาสตร์แบบรวมที่ชื่อว่า BALDUR โดยแบบจำลองดังกล่าวได้รับการพัฒนาบนพื้นฐาน การใช้แบบจำลองการส่งผ่านพลังงานและอนุภาคแบบแปรปรวนของพลังงานและมวลในใจกลางพลาสมา ซึ่งเรียกว่า Mixed Bohm/gyro-Bohm ไปทำการขยายออกเพื่ออธิบายการเกิดเพเดสทัลที่บริเวณขอบของพลาสมา ด้วยการยับยั้งการส่งผ่านพลังงานและมวลของทุกอนุภาคในพลาสมา (ไอออน อิเล็กตรอน สปีชีส์ไฮโดรเจน และ สารปนเปื้อน) เนื่องมาจากผลการไหลแบบเฉือน และสนามแม่เหล็กแบบเฉือน นอกจากนั้นค่าคงที่ความมีเสถียรภาพได้ถูกใส่ในแบบจำลอง พร้อมทำการเปรียบเทียบวัดกับผลการทดลองของโทคาแมคดีทรี-ดี (DIII-D) แล้วใช้ค่าทางสถิติที่เรียกว่าค่ารากที่สองของกำลังสองเฉลี่ย (RMS%) ในการวิเคราะห์เพื่อหาจุดเหมาะสมของค่าดังกล่าว ทั้งนี้แบบจำลองใจกลางและขอบของพลาสมาที่สมบูรณ์แล้ว ได้ถูกนำมาทดสอบอีกครั้งด้วยวิธีการให้เหตุผลแบบไขว้ เพื่อเป็นการยืนยันความแม่นยำในการทำนายผลกับผลการทดลองของโทคาแมคเจ็ต (JET) ซึ่งพบว่าค่าเฉลี่ย RMS ที่ได้มีค่าน้อยกว่า 20.38% ในทุกตัวแปร เช่น อุณหภูมิไอออน อุณหภูมิอิเล็กตรอน ความหนาแน่นอิเล็กตรอน และ ความหนาแน่นดิวเทอเรียม

คำสำคัญ : พลาสมา โทคาแมค ฟิวชัน เอช-โหมด และ เพเดสทัล

Test of Core-Edge Modeling on *H*-mode Plasmas by Cross Validation Test in JET Tokamak

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Abstract

The core-edge model for predicting a pedestal formation in *H*-mode plasmas is developed and tested using BALDUR integrated predictive modeling code. This model expands on an anomalous core transport model (Mixed Bohm/gyro-Bohm) which is suitable for the edge of plasma by suppression due to the $\omega_{E\times B}$ flow shear and magnetic shear effects. Moreover, the stabilizer coefficients of every species (ion, electron, hydrogenic, and impurity) are calibrated with the experimental data of DIII-D tokamak. The root mean square (RMS%) analysis is used to validate the optimal point of the stabilizer coefficients in every channel. Thus, the complete core-edge model, used in predicting the pedestal formation, is confirmed accurately by cross validating with the experimental data of JET tokamak. The results show good agreement with experimental data, with the RMS average less than 20.38% in every channel (ion temperature, electron temperature, electron density, and deuterium density).

Keywords: plasma, Tokamak, fusion, H-mode, and pedestal

1. Introduction

High confinement mode (*H*-mode)[1] has been discovered in 1982 , this regime has been commonly operated in many experiments from different tokamaks around the world, because it extensively increases plasma temperature and density, and energy confinement time. The enhancement of plasma performance mainly results from the formation of transport barrier at the edge of the plasmas. This edge transport barrier (ETB) is usually referred as the “pedestal”. Usually, the energy content in an *H*-mode discharge is approximately twice the energy contained in low confinement mode (*L*-mode) discharge, for the similar plasma with the same input power [2]. Thus, to develop a better understanding of the physical processes and the interrelationships between those physical processes that occur in tokamak *H*-mode plasma experiments, advanced computer codes are developed to improve understanding of plasma behaviours. The integrated predictive modeling codes, such as BALDUR[3], TASK/TR[4], and JETTO[5] have played an important role in carrying out simulations in order to predict the time evolution of plasma current, temperature, and density profiles. The simulations from these integrated predictive modeling codes have advanced the field in various aspects. In fact, many of the simulations carried out with these integrated predictive modeling codes normally make use of boundary conditions usually been taken at the top of the pedestal from experimental data. It was found that their predictions depend sensitively on the choice of the pedestal conditions used. This indicates the need for reliable method for predicting boundary conditions of the integrated predictive modeling in order to advance the predictive capability, which is essential in designing future experiments for existing and future tokamaks. In the recent work, Y. Pianroj, *et.al.* used the core-edge model which composed of the anomalous core transport model, Mixed Bohm/gyro-Bohm (Mixed B/gB). It was extended for describing the transport in the pedestal region, so the anomalous transport was suppressed by $\omega_{E\times B}$ flow shear, magnetic shear (*s*), and the set of calibration coefficients (C_x) in every channel of transport coefficients: electron thermal diffusivity, ion thermal diffusivity, hydrogenic mass diffusivity and impurity mass diffusivity. As a result, the pedestal can be formed.

However, this core-edge model was validated and calibrated by DIII-D tokamak experimental data. Therefore, in this work, the method named the cross validation test is used to check the accuracy and the capability of this model by testing with the JET tokamak experimental data. This work is organized as follow. The next section describes briefly about the core-edge model, and then the third section shows the results and discussions. In the final section, the conclusion of this work is given.

2. The core and the core-edge modeling

A theory-based core-edge model for predicting a pedestal formation of electron and ion temperature, hydrogenic density, and impurity density is developed and tested in BALDUR integrated predictive modelling codes for self-consistently simulating the evolution of *H*-mode plasmas profiles. In the core plasma, an anomalous transport is computed using a semi-empirical Mixed Bohm/gyro-Bohm transport model[6], while a neoclassical transport is computed using the Chang-Hinton model[7]. For the pedestal, the anomalous core transport model is extended to be applicable for this region by a strong suppression using $\omega_{E\times B}$ flow shear and magnetic shear (*s*). It is shown in this equation[8].

$$f_s = \frac{1}{1+C_x\left(\dfrac{\omega_{E\times B}}{\gamma_{ITG}}\right)} \times \frac{1}{\max(1,(s-0.5)^2)} \tag{1}$$

where, C_x is the coefficient for each species which were calibrated with DIII-D experimental discharges, and γ_{ITG} is the liner growth rate of ion temperature gradient mode.

To quantify the comparison between simulations and experimental data, the root-mean-square (RMS) deviation and the offset are computed based on the difference between simulation results and experimental data. In this paper, the RMS and the offset, which are similar to Ref.[9], are defined as Equation 2 and 3, respectively.

$$\mathrm{RMS}(\%) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{X_{sim_i} - X_{\exp_i}}{X_{\exp_0}}\right)^2} \times 100 \quad (2)$$

$$\mathrm{offset}(\%) = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_{sim_i} - X_{\exp_i}}{X_{\exp_0}}\right) \times 100 \quad (3)$$

where, $X_{\exp_i}$ is the i^{th} data point of the experimental profile, X_{sim_i} is the corresponding data point of the simulation profile, and $X_{\exp_0}$ is the maximum data point of the experimental profile of *X* as a function of radius, which has *N* points in total. The RMS and the offset are evaluated for each of the four profiles: electron temperature, ion temperature, electron density, and deuterium density, for the discharges considered. Note that the offset is positive if the simulated profile is higher than the experimental profile, and negative if the simulated profile is lower than the experimental profile. If the offset is zero, then the RMS is a measure of how much the shapes of the profiles differ between simulation and experiment. Because of the significant reduction of transport in the outer region of the plasma, the pedestal can be formed.

3. Results and discussions

After the suppression function is completed with $\omega_{E\times B}$ flow shear, magnetic shear and the optimal coefficient that is calibrated by 10 DIII-D *H*-mode discharges[8], so in this section, the complete suppression function is used to evaluate and to validate the accuracy of the core-edge model by the cross validation test method. Thus, the BALDUR code is used to carry out core-edge simulation of 12 JET *H*-mode discharges get from the International Profile Database[10]. All plasma parameters in which are used 12 by JET *H*-mode discharges are listed in Table 1, and are used as the boundary conditions of the simulations. The example simulation profiles of electron temperature, ion temperature, electron density and deuterium density as a function of minor radius that compared to the JET experimental data discharge 35156 (low ρ^*) and 35157 (high ρ^*) are shown in Fig. 1.

Table 1 Details of plasma parameters for 12 JET *H*-mode discharges (L: Low and H: High).

Discharges	33131	33140	33465	34340	35156	35171	35174	37379	37718	37728	38407	38415
Type	L ρ^*	H ρ^*	Identity	-	L ρ^*	H ρ^*	-	-	L υ^*	H υ^*	L β	H β
R(m)	2.94	2.93	2.87	2.88	2.87	2.88	2.87	2.91	2.94	2.92	2.91	2.88
a(m)	0.94	0.92	0.95	0.88	0.93	0.94	0.84	0.83	0.93	0.96	0.94	0.97
κ	1.70	1.56	1.55	1.66	1.56	1.58	1.56	1.62	1.58	1.64	1.60	1.55
δ	0.28	0.26	0.19	0.15	0.11	0.24	0.22	0.18	0.13	0.20	0.16	0.11
B_T(T)	3.13	1.77	1.10	2.16	2.17	1.09	1.08	1.05	2.11	2.71	1.59	1.84
I_p (MA)	2.83	1.61	1.04	2.03	2.05	1.01	1.02	1.00	1.97	2.57	1.47	1.67
$\bar{n}_e(10^{19} m^{-3})$	7.10	3.65	3.26	6.27	5.44	2.44	2.50	2.00	4.54	4.90	3.05	4.02
Z_{eff}	1.92	1.66	1.52	1.99	1.25	1.10	1.44	2.27	1.93	1.76	2.09	2.06
P_{NB} (MW)	18.0	5.80	2.77	2.00	8.60	2.91	3.00	4.70	9.70	13.3	5.60	15.7
Diagnostic time(sec)	55.69	56.50	63.76	56.37	55.85	65.00	64.38	63.38	55.38	58.12	57.40	56.61

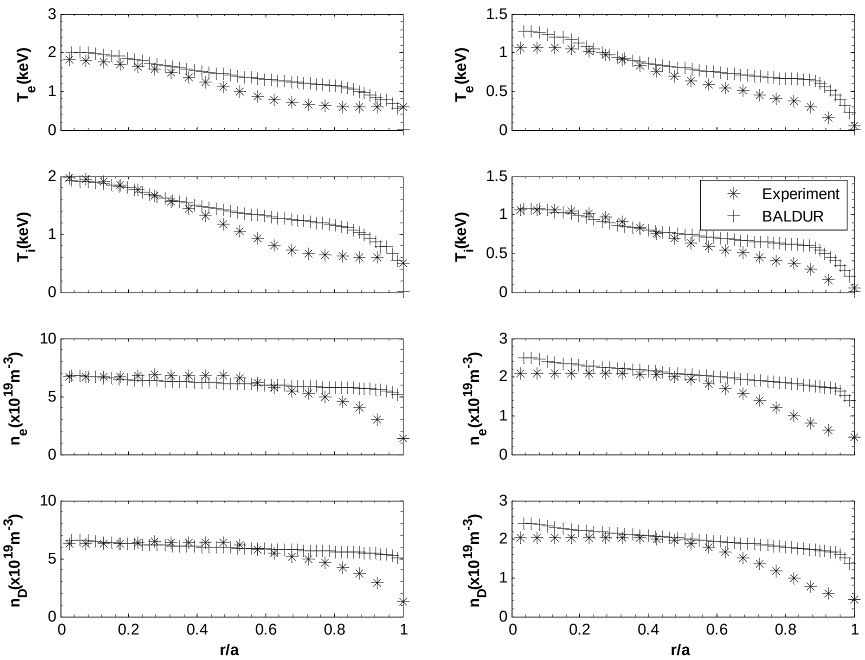

Fig. 1 The profiles of electron temperature, ion temperature, electron density and deuterium density as a function of minor radius. The simulation results are carried out by BALDUR with the core-edge transport model, compared to the JET experimental data discharge 35156 (Low ρ^*; Left panel) and 35171 (High ρ^*; Right panel) at diagnostic time.

In this figure, all temperature and density profiles fit well in the core region, but quite overpredict at the edge region, because the JET experimental data are not obviously depict the pedestal formation. Therefore, to measure the accuracy of the model by cross validation method, the summary of RMS and offset which are carried out by the integrated predictive modeling code of 12 JET *H*-mode discharges, the average of RMS and the average of offset are shown in Fig. 2. In this figure, the RMS average and the offset average of electron temperature, ion temperature, electron density and deuterium density of 12 JET *H*-mode discharges deviate from the RMS average of 10 DIII-D *H*-mode discharges[8] 6.90%, -0.25%, 7.74%, and 6.91%, respectively.

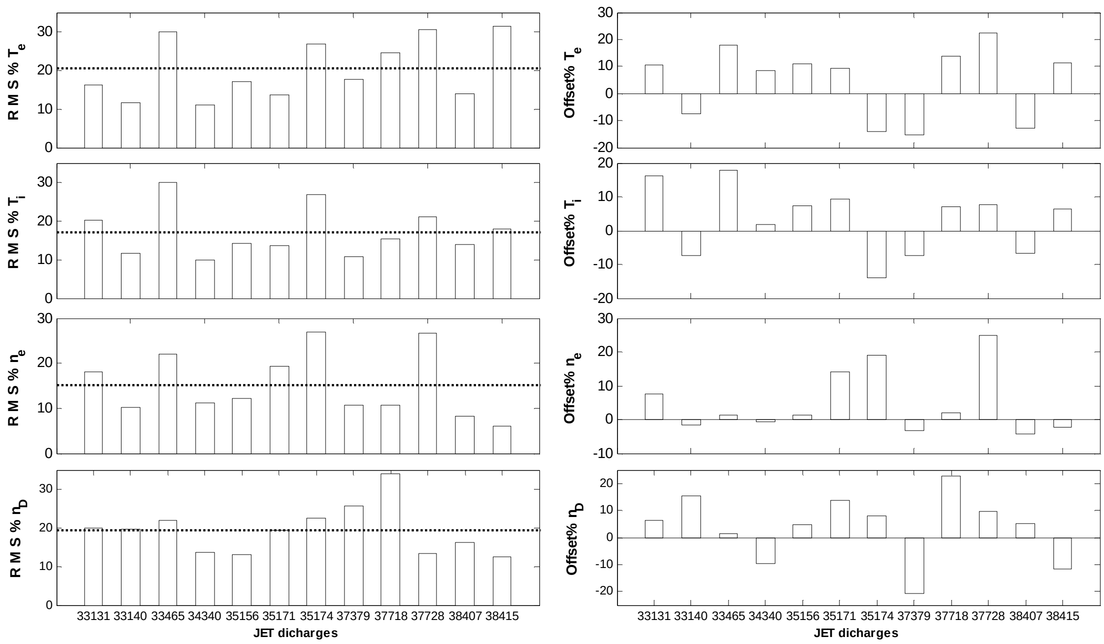

Fig. 2 The root mean square (RMS%) on left panel and the offset (offset%) on right panel for the electron temperature, ion temperature, electron density, and deuterium density profiles produced by simulation using the core-edge model from BALDUR code, compared with experimental data for 12 *H*-mode discharges (pedestal occurred), listed by JET device and the average of RMS% in each profile is shown by dash line in each graph on left panel.

4. Conclusions

A theory-based model for predicting the pedestal transports in *H*-mode plasma is developed and implemented in the integrated predictive modeling code BALDUR. It is found that the simulations using BALDUR code with both core and pedestal transport models can reproduce experimental data. It yields the average RMS of electron temperature, ion temperature, electron density, and deuterium density. To confirm the accuracy of this model, the results are cross validated with 12 JET *H*-mode discharges. The results of the RMS average of electron temperature, ion temperature, electron density and deuterium density of 12 JET *H*-mode discharges deviate from the RMS average of 10 DIII-D *H*-mode discharges 6.90%, -0.25%, 7.74%, and 6.91%, respectively.

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6. References

1. Wagner F. (s), *Physical Review Letters*, 1982, **49(19)** page-1408.
2. Connor J. W. and Wilson H. R., *Plasma Physics and Controlled Fusion*, 2000, **42** page-R1-R74.
3. Singer C. E. (s), *Computer Physics Communications*, 1988, **49** (2), page-275-398.
4. Honda M. and Fukuyama A., *Nuclear Fusion*, 2006, **46** page-580-593.
5. Cenacchi G. and Taroni A., *JET-IR*, 1988, **88**
6. Onjun T. and Pianroj Y., *Nuclear Fusion*, 2009, **49** page-075003.
7. Chang C. S. and Hinton F. L., *Physics of Fluids*, 1986, **29** (10), page-3314-3316.
8. Pianroj Y. and Onjun T., *submitted to Plasma Science and Technology*,
9. Hannum D. (s), *Physics of Plasmas*, 2001, **8** page-964.
10. Boucher D. (s), *Nuclear Fusion*, 2000, **40** (12), page-1955.