

EXPERIMENTAL STUDY ON CONFIGURATION DEPENDENCE OF TURBULENT TRANSPORT ON LHD

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Abstract

An experimental study of the magnetic configuration dependence on turbulent transport was performed in Large Helical Device. To evaluate parameter dependence on ion thermal diffusivity, a transport database was developed by the LHD plasma experiment. In the previous study, the geodesic curvature was confirmed to contribute to the turbulent transport due to the zonal flow effect. In this paper, the helicity (helical Fourier components of the magnetic field) and the magnetic shear were included in the database because both of them are considered to affect the turbulent transport. Akaike Information Criterion with multivariate regression analysis was applied to the database, and it was found that the geodesic curvature is statistically a much more important parameter than the helicity, in which both of them should have an impact on zonal flow damping.

1. INTRODUCTION

Nuclear fusion energy development for electricity generation is a crucial and common issue in the world and is listed in the Sustainable Development Goals (SDGs). Control of particle and heat transport in high-temperature plasma is necessary to realize fusion reactors. Two transport processes are recognized in torus plasmas. One is neoclassical transport driven by the collision of particles and the particle orbit effect, and low neoclassical transport is considered to be crucially important for particle transport, including impurity ions and alpha particles. The other is anomalous transport induced by fluctuations and turbulence, and the reduction of anomalous transport is considered to realize the confinement improvement in the core plasmas. Therefore, one of the most critical issues in the core plasma is the reduction and control of turbulent transport in magnetically confined burning fusion plasmas, where microinstabilities become unstable, such as the ion temperature gradient mode, trapped electron mode, electron temperature gradient mode, etc. A considerable effort has been made to understand and characterize the nonlinear turbulent transport in theory, simulations, and experiments so far.

Zonal flow attracted much attention because turbulent transport may be suppressed and the resultant confinement improvement [1-3]. In the Compact Helica System (CHS), the zonal flow excitation in the turbulent plasma was identified for the first time in the torus plasma experiment [4]. The turbulent transport with zonal flow generation has been intensively studied in torus plasmas with a variety of configurations. In the Large Helical Device (LHD), it was observed that plasma confinement became better with inwardly shifted plasmas in which the stability is predicted to be worse [5]. A theoretical study and nonlinear simulations with gyrokinetic modelling using GKV code revealed that the zonal flow generation can contribute to reducing turbulent transport in the inwardly shifted LHD plasma and the helicity (helical Fourier component of the magnetic field) may affect zonal flow damping with helical magnetic field configurations[6-7].

Turbulent transport control with external magnetic field geometry is an important issue in optimizing the three-dimensional configuration design of next-generation stellarators. There are some studies on the turbulent transport optimization with linear growth rate calculations of the limited unstable modes [8-11]. The development of nonlinear transport modeling with zonal flow effects is an urgent issue in stellarator design studies. Recently, a simple model of turbulent thermal transport with zonal flow effect was proposed based on the geodesic curvature

dependence of zonal response. The enhancement of zonal flow amplitudes with the reduction of geodesic curvature was observed in the gyrokinetic simulations with LHD configurations, NCSX-like configuration and axisymmetric configuration[12].

An experimental investigation of the zonal flow effect on turbulent transport with different geodetic curvatures (radial scan of magnetic axis) in LHD. The significant reduction of thermal conductivity was observed with small geodesic curvature configurations, and it is consistent with the simulation result [13]. However, the comparison with helicity and geodesic curvature effects on turbulent transport has not been performed yet. In this study, we report the comparison of helicity, geodesic curvature and magnetic shear effects on turbulent transport using the transport database of LHD plasmas.

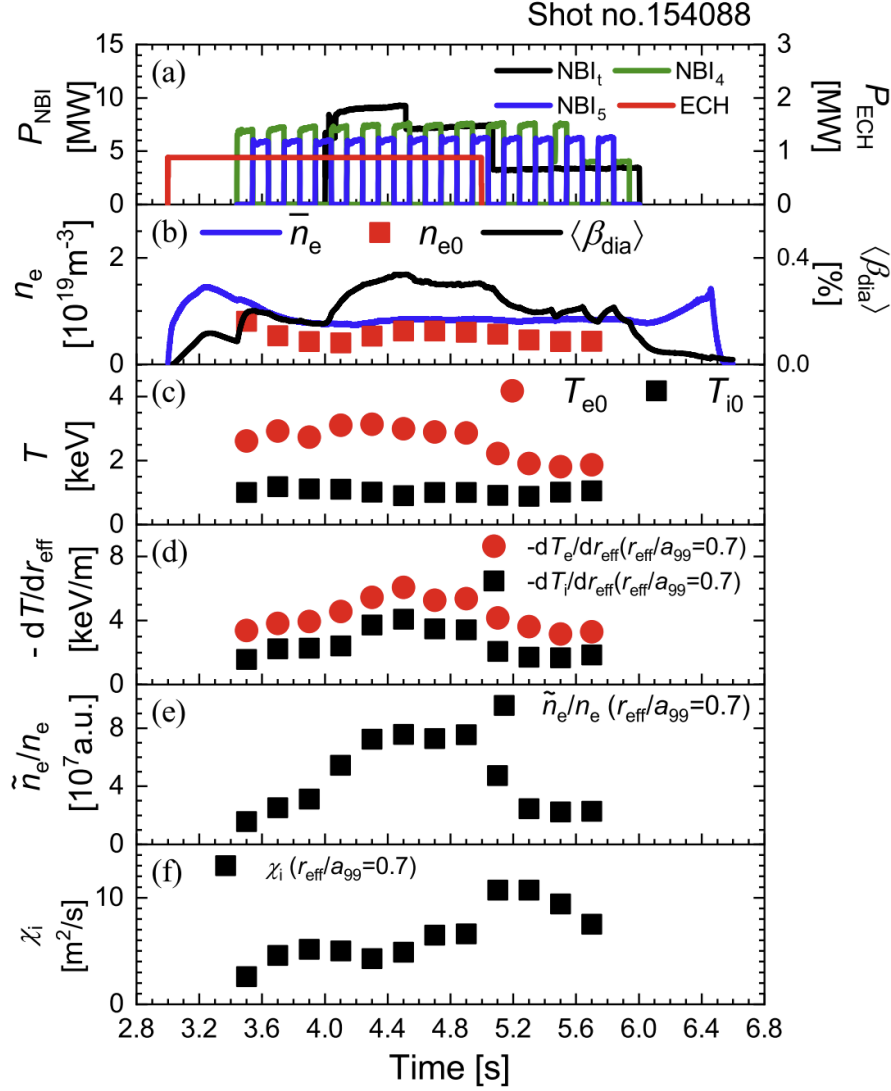


FIG. 1. Typical waveform of the plasma discharge used in the present study [13]. (a) Tangential NBI (NBI_t), perpendicular NBI (NBI_4 and NBI_5), and ECH port through power, (b) line-averaged electron density ($\bar{n}_e$), central density (n_{e0}) and volume-averaged diamagnetic beta (β_{dia}), (c) central electron and ion temperature (T_{e0} and T_{i0}), (d) temperature gradient of electron ($-dT_e/dr_{eff}$) and ion ($-dT_i/dr_{eff}$) at the minor radius of $r_{eff}/a_{99} = 0.7$, (e) ion-scale electron density fluctuation normalized by electron density ($\tilde{n}_e/n_e$) at $r_{eff}/a_{99} = 0.7$, (f) ion thermal diffusivity (χ_i) at $r_{eff}/a_{99} = 0.7$.

2. PLASMA EXPERIMENT ON THE LHD

We performed the experimental study with the LHD, a heliotron-type plasma confinement device [14] with a poroidal/toroidal period of $l = 2/m = 10$. The magnetic field strength is up to 3 T. The major and minor radii

are 3.5 – 4.0 m and 0.6 – 0.65 m, respectively. A pair of helical coils and three sets of poloidal coils produce the flexible magnetic field configurations. In this study, the magnetic field strength at the magnetic axis is fixed as $B_{\text{ax}} = 2.63$ T. The radial position of the magnetic axis was scanned as $R_{\text{ax}} = 3.60, 3.75, 3.90$ m. We discuss the three parameters related to the magnetic configuration that would be considered to affect the turbulent transport. The first one is the flux-surface-averaged geodesic curvature defined as

$$\langle \kappa_g \rangle = \left(\frac{\int_{-\pi}^{\pi} \kappa_g^2 \times f(z) dz}{\int_{-\pi}^{\pi} f(z) dz} \right)^{1/2} \quad (1)$$

where the geodesic curvature κ_g is defined as

$$\kappa_g = \kappa \cdot \left(\nabla \psi / |\nabla \psi| \right) \times \mathbf{b}, \quad (2)$$

where $\mathbf{b}$ is a unit vector along the magnetic field line, κ is the curvature, $\kappa = \mathbf{b} \cdot \nabla \mathbf{b}$, and the ψ is a flux coordinate, respectively. The wight function $f(z)$ is defined by a Gaussian profile with the e -holding length of 0.5, which is a typical scale of eigenfunction for ITG mode [12]. For simplicity, the averaged geodesic curvatures of $\kappa_g = 0.45$ for $R_{\text{ax}} = 3.60$ m, 1.10 for $R_{\text{ax}} = 3.75$ m and 2.09 for $R_{\text{ax}} = 3.90$ m. The second is the so-called helicity, ϵ_h , which is a Fourier component of the magnetic field with the mode number of $l = 2$ and $m = 10$. The helicity decreases with the magnetic axis position from 0.13 to 0.09 in this experiment. The third is the magnetic shear

$$s = \frac{\rho}{\iota} \frac{d\iota}{d\rho} \quad (3)$$

where $\rho = r_{\text{eff}}/a_{99}$ is a normalized minor radius, where r_{eff} and a_{99} are the effective minor radius and the effective minor radius which encloses 99% of the total electron pressure, respectively, and ι is rotational transform.

The plasma was broken down and heated using electron cyclotron resonance heating (ECH) and neutral beam injection (NBI). Three gyrotrons with a frequency of 77 GHz and two gyrotrons with a frequency of 154 GHz were operational with a maximum power of up to 5 MW. Three negative-ion-based NBIs with the maximum beam energy of 190 keV and two positive-ion-based NBIs with the beam energy of 40 keV for NBI-4 and 60 keV for NBI-5 in hydrogen plasma experiments on the LHD. Typical waveforms of the LHD plasma discharge are shown in Fig. ???. The beam modulations in the NBI-4 and NBI-5 were performed for the background signal extraction in charge-exchange spectroscopy (CXS) diagnostics, which provided the ion temperature profiles. The line-averaged electron density measured by an interferometer and the stored energy measured by magnetic probes are shown in the second panel. A Thomson scattering (TS) diagnostic provided the electron temperature and electron density profiles. The absolute values of electron density are calibrated with the interferometer diagnostics [15]. The electron density at the magnetic axis is also shown in the second panel. The electron and ion temperatures at the magnetic axis are shown in the third panel. The electron and ion temperature gradients at the minor radius of $r_{\text{eff}}/a_{99} = 0.7$ are shown in the fourth panel. The radial profile of the electron density fluctuation with the scale of ion Larmor radius was routinely measured by a phase contrast imaging (PCI) diagnostic [16]. The normalized electron density fluctuation amplitude at the minor radius of $r_{\text{eff}}/a_{99} = 0.7$ is shown in the fifth panel. The density fluctuation amplitude became large when the plasma heating power was large ($t = 4.0 - 5.0$ sec).

The ion thermal diffusivity χ_i was evaluated with dynamic transport analysis with TASK3D-a, which routinely calculates the ion and electron heat transports with the dynamic effects in the plasma profiles and the plasma heating [17]. The ion thermal diffusivity at the minor radius of $r_{\text{eff}}/a_{99} = 0.7$ is shown in the bottom panel in the Fig.??.

3. TRANSPORT DATABASE ON LHD

A transport database was developed to investigate the thermal transport, in particular, the turbulent transport characteristics. The database covered a large parameter regime as far as possible, such as the plasma density, plasma heating power, the ratio of electron and ion heating power, and the magnetic configuration, which are summarized in Fig.??.

In this study, we focus on the parameter dependence of the ion thermal diffusivity at the minor radius of $r_{\text{eff}}/a_{99} = 0.7$. In the previous study, seven normalized parameters were discussed that are important for characterizing the ITG mode; ion thermal diffusivity: $\chi_i/\chi_i^{\text{GB}} = \chi_i/(v_{T_i}\rho_i^2/R)$ (where v_{T_i} and ρ_i are the ion thermal velocity and ion gyroradius, respectively), normalized geodesic curvature: $\langle \kappa_g \rangle / \langle \kappa_g^{\text{ref}} \rangle$ (where $\kappa_g^{\text{ref}} = 1.10$), temperature ratio: T_e/T_i , the normalized electron temperature gradient: $R/L_{T_e} = -(R/T_e)\partial T_e/\partial r_{\text{eff}}$, normalized ion pressure gradient: $R/L_n + R/L_{T_i} = -(R/n_e)\partial n_e/\partial r_{\text{eff}} - (R/T_i)\partial T_i/\partial r_{\text{eff}}$, normalized density fluctuation: $\tilde{n}_e/n_e$, normalized collisionality $\nu_{ii}^* = 4L\nu_{ii}/(3\sqrt{2}\pi v_{T_i})$ (where $L = qR/\epsilon^{3/2}$ with $q = 1.3$, $\epsilon = r_{\text{eff}}/R_{\text{ax}}$,

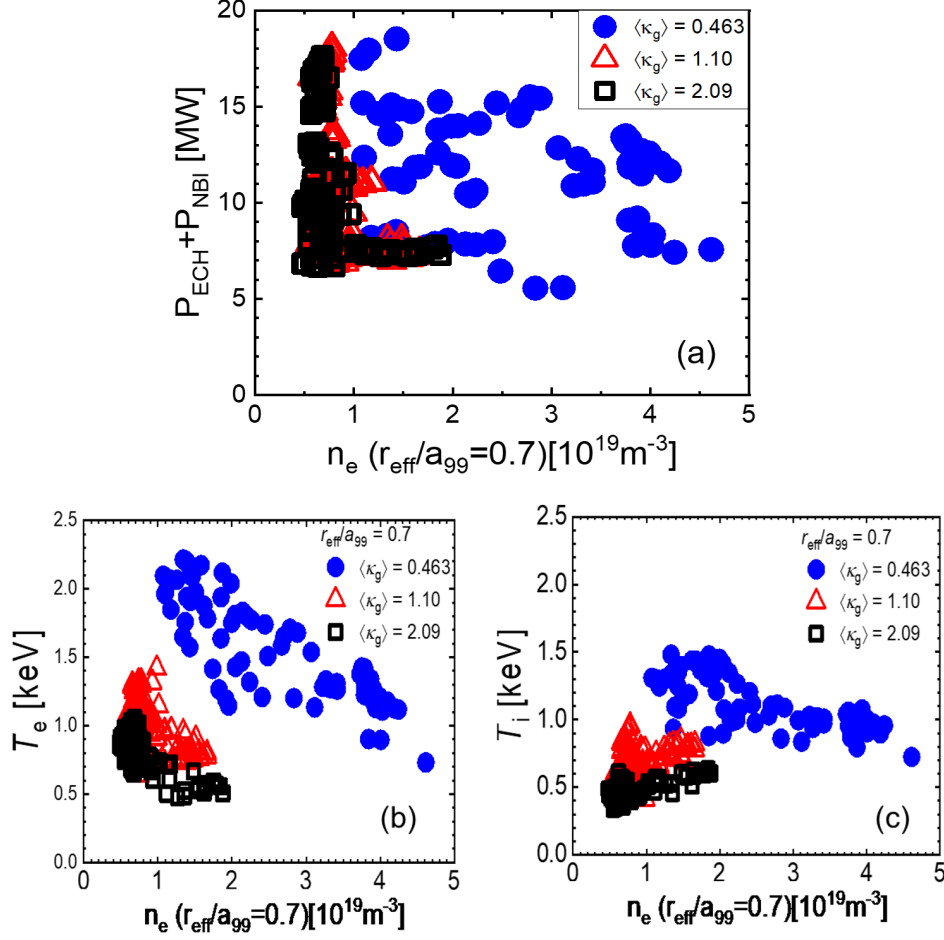


FIG. 2. (a) Operation regime of the plasma discharges; heating power and electron density, (b) electron and (c) ion temperature as a function of electron density at the minor radius of $r_{\text{eff}}/a_{99} = 0.7$.

$\nu_{ii} = n_e e^4 \ln \Lambda_{ii} / (8\sqrt{2}\pi\epsilon_0^2 m_i^2 v_{Ti}^3)$ and $\ln \Lambda_{ii} = 17$. The electron density sometimes became a hollow profile, and the density gradient was positive. Therefore, the ion pressure gradient was selected instead of the ion temperature gradient. In this study, we added two normalized parameters related to the magnetic configuration, the helicity: ϵ_h and magnetic shear: s shown in eq.??.

Figure ?? summarizes the parameter distribution of the transport database discussed here. A total of 330 samples of the plasma transport data obtained by the LHD plasma experiments are included. One can see clear positive correlations between ion thermal diffusivity and the density fluctuation, the temperature ratio, the electron temperature gradient, and the ion pressure gradient. When we examine the dependence of geodesic curvature on ion thermal diffusivity, a negative correlation is also observed. These characteristics appear to be consistent with the ITG-driven turbulent property and the zonal flow effect on turbulent transport. The thermal ion diffusivity depends on the helicity and the magnetic shear in much more complex ways.

The neoclassical thermal diffusivity also contributes to the thermal diffusivity. In the previous study [13], the thermal diffusivity obtained by the power balance analysis was compared with the turbulent thermal diffusivity which is evaluated by the subtraction of the neoclassical thermal diffusivity calculated by the GSRAKE code [18] from that obtained by the power balance analysis. The results agree well with each other, and the statistical significance is better in the case of the power balance thermal diffusivity because a large uncertainty or overestimation exist in the neoclassical transport calculation when the radial electric field is close to zero. More accurate calculation of the neoclassical transport, for example, with the global effect taken into account, is necessary. However, creating an extensive database is not easy due to the high calculation cost. Therefore, we discuss the thermal diffusivity evaluated by the power balance analysis in this study.

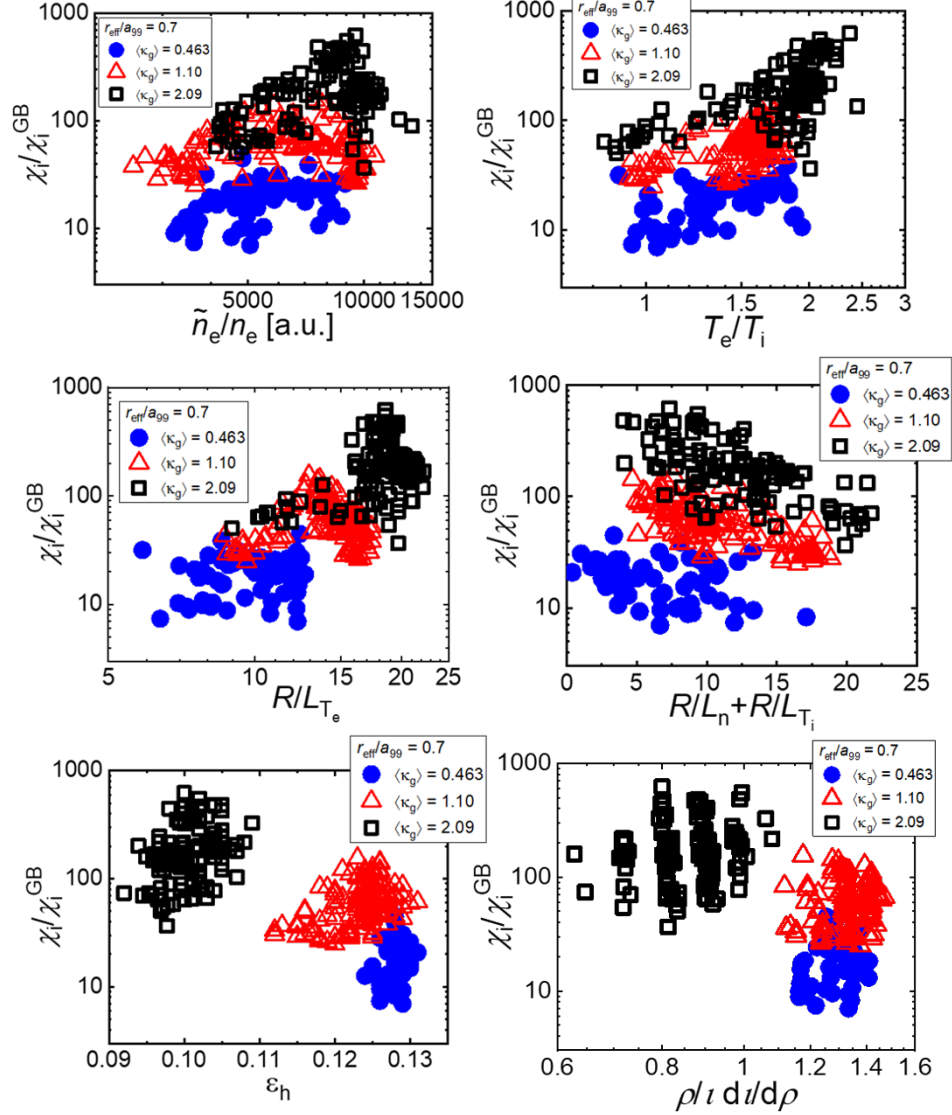


FIG. 3. Parameter dependence of ion thermal diffusivity as a function of (a) density fluctuation, (b) temperature ratio, (c) electron temperature gradient, (d) ion pressure gradient, (e) helicity, and (f) magnetic shear.

4. STATISTICAL ANALYSIS FOR ELUCIDATING PARAMETER DEPENDENCE

To analyze parameter dependence of the ion thermal diffusivity in detail, the corrected Akaike Information Criterion (AICc) was applied to the transport database shown in Fig. ???. The Akaike Information Criterion (AIC) evaluates statistical models by balancing goodness of fit with model complexity, penalizing excessive parameters to avoid overfitting [19]. The AICc refines this measure by adding a correction term that accounts for small sample sizes.

The lowest AIC, which indicates the best parameter combination for each number of parameters to characterize the ion thermal diffusivity, is shown in Fig. ???. The multivariate regression analysis for the selected parameter was also carried out, and the exponent for each parameter are also listed in Fig. ???. An order of significance to characterize the ion thermal diffusivity is obtained: the geodesic curvature $\langle \kappa_g \rangle / \langle \kappa_g^{\text{ref}} \rangle$, the temperature ratio T_e/T_i , the ion pressure gradient $R/L_n + R/L_{T_i}$, the electron temperature gradient R/L_{T_e} , the helicity ϵ_h , the turbulence $T = (\zeta/2)(R_{ax}/\rho_i)^2(\tilde{n}_e/n_e)^2$ (where ζ is a calibration factor and $\zeta = 4.5 \times 10^{-11}$ obtained by a comparison with nonlinear calculation results with GKV code), the collisionality ν_i , the magnetic shear s . The best result is obtained with seven parameters and the best characterization with the multivariate regression analysis

$\chi_i/\chi_i^{\text{GB}}$	Parameter	$\langle\kappa_g\rangle/\langle\kappa_g\rangle^{\text{ref}}$	T_e/T_i	$R/L_n+R/L_{Ti}$	R/L_{Te}	ϵ_h	T	ν_i^*	s
Number of parameters	Minimum AICc	exponents for each parameter selected by AIC							
		a^1	a^2	a^2	a^3	a^4	a^5	a^6	a^7
1	521.3	1.44							
2	354.4	1.25	1.39						
3	266.3	1.52	1.12	-0.422					
4	231.0	1.80	1.61	-0.460	-0.837				
5	224.1	1.97	1.65	-0.457	-0.900	0.915			
6	221.6	1.95	1.46	-0.477	-0.997	0.997	0.0920		
7	218.5	1.83	1.56	-0.377	-1.01	1.32	0.105	0.121	
8	219.9	1.85	1.54	-0.370	-0.987	2.00	0.103	0.134	-0.276

FIG. 4. Summary of Akaike Information Criterion (AIC) and multivariate regression analysis.

is follows;

$$\frac{\chi_i}{\chi_i^{\text{GB}}} = \left(\frac{\kappa_g}{\kappa_g^{\text{GB}}}\right)^{1.83} \left(\frac{T_e}{T_i}\right)^{1.56} \left(\frac{R}{L_n} + \frac{R}{L_{Ti}}\right)^{-0.377} \left(\frac{R}{L_{Te}}\right)^{-1.01} \epsilon_h^{1.32} T^{0.105} \nu_i^{*0.121}. \quad (4)$$

The geodesic curvature dependence is the most significant and positively large (the power of 1.83). The second and third parameters are strongly related to the ITG mode stability. The helicity also shows a substantial contribution to the ion thermal diffusivity; however, it is weaker than the geodesic curvature. The magnetic shear does not show a clear contribution in this analysis.

5. CONCLUDING REMARKS

A transport database based on the LHD plasma experiment was developed with an integrated transport analysis suite. To investigate the magnetic configuration dependence, the radial position of the magnetic axis was scanned. The transport database was developed and analyzed with AICc scheme, and the multivariate regression analysis was also carried out. It was found that the geodesic curvature is the most important parameter to characterize the ion thermal diffusivity, suggesting the validity of the nonlinear proxy model of turbulent transport with the geodesic curvature dependence on zonal flow [12]. We should be careful to conclude this study because there are still some issues to be discussed. One is the evaluation of the geodesic curvature. In the database used in this study, the geodesic curvature is fixed when the vacuum configuration is the same. In the near future, we will evaluate the geodesic curvature for the equilibrium configurations of the entire dataset, and the results with more precise analysis will be reported. Second is the correlation among parameters. The negative dependence of the electron temperature gradient was found in the regression analysis, which could not be seen in Fig. ???. There are certain correlations among the electron temperature gradient, the temperature ratio and the ion pressure gradient, which are not strictly consistent with the requirement for the AIC application. There is the same discussion for parameters related to the magnetic field geometry, such as the geodesic curvature, the helicity and the magnetic shear. It is not realistic to change one of three parameters while keeping the others constant due to the limitations of the coil system. Therefore, further analysis to correct the correlation between parameters is required to conclude this study.

Finally, we would like to emphasize that the development and extension of the transport database with fluctuations are significantly important for understanding and characterizing turbulent transport in magnetically confined fusion plasmas. Although the previous study and this study analyzed only ion thermal diffusivity, the electron thermal diffusivity, it is crucial to analyze the particle transport study, including impurity ions such as helium and high-Z ions, which are also available with some extension of the database. In particular, the turbulent transport and particle transport models are missing parts in optimization studies of three-dimensional plasma configurations. The transport model based on experimental data in the present devices is inevitable for the reliable prediction of the performance of future plasma devices.

Recent progress in data-driven science also presents various opportunities to elucidate the complex properties of plasma transport. Applications of data-science techniques and further extension of the database to plasma confinement devices with different concepts and scales may enable the development of transport models for reliable prediction and/or extrapolation of future burning plasmas.

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DATA ABAILABILITY

The data supporting the findings of this study are available in the LHD experiment data repository at the webpage of <https://doi.org/10.57451/lhd.analyzed-data>.

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