Comprehensive understandings of energy confinement in LHD plasmas through extensive application of the integrated transport analysis suite

M. Yokoyama[1,2], R. Seki[1], C. Suzuki[1], K. Ida[1,2], M. Osakabe[1], S. Murakami[3], S. Satake[1,2], H. Yamada[1,2] and LHD Experiment Group

[1]National Institute for Fusion Science, 322-6, Oroshi-cho, Toki-city, 509-5292, Japan
[2]Department of Fusion Science, The Graduate University for Advanced Studies, 322-6, Oroshi-cho, Toki-city, 509-5292, Japan
[3]Department of Nuclear Engineering, Kyoto University, Kyoto 615-8540, Japan

E-mail contact of main author: yokoyama@LHD.nifs.ac.jp

Abstract. The integrated transport analysis suite, TASK3D-a [1], has enhanced energy transport analyses in LHD. It has clearly elucidated (i) the systematic dependence of ion and electron energy confinement on wide variation of plasma parameters, and (ii) statistically-derived fitting expressions for the ion and electron heat diffusivities (χ_i and χ_e), separately, taking also those radial-profile information into account. In particular, the latter approach can outstrip the conventional scaling laws for the global confinement time (τ_E) in terms of its considerations on profiles (temperature, density, heating depositions etc.). This has been made possible with the analysis database accumulated by the extensive application of the integrated transport analysis suite to experiment data. In this proceeding, TASK3D-a analysis-database for high-ion-temperature (high-T_i) plasmas [2] in LHD (Large Helical Device) [3] are exemplified. This approach should be applicable to any other combinations of integrated transport analysis suites and fusion experiments.

1. Introduction

Recent development of the integrated transport analysis suite, TASK3D-a (analysis version for LHD experiment), and its extensive application to a wide-ranging LHD plasmas have created the analysis-database including profile information such as of ion and electron temperatures (T_i and T_e,), electron density (n_e), NBI heating deposition, and ion and electron heat diffusivities (χ_i and χ_e), etc.

TASK3D-a, in brief, consists of modules for temperature/density profile fittings, VMEC [4] equilibrium specification, NBI deposition calculations [5] and steady-state/dynamic energy transport calculations, so that they are sequentially executed in an automated manner [1].

Conventionally, scaling laws for the global energy confinement time (τ_E) have been one of approaches to systematically grasp the energy confinement of fusion plasmas [6,7], and then also considered as one of guidelines to design/predict future devices, such as ITER [8].

On the other hand, the physics-based transport models have been employed to predict the plasma performance such as expected temperature profiles for certain plasma operation scenario. In such predictions, it has been always problematic whether employed transport model(s) are actually responsible for governing energy confinement in plasmas to be forecasted, in other words, how to validate them.

Here, in this proceeding, let us propose an innovative consideration based on a statistical approach, to overcome such difficulties.

2. Comprehensive Understandings Deduced from TASK3D-a Analysis Database

So far, NBI-heated high-T_i plasmas and medium-to-high density (3~5×10^{19} m^{-3}) plasmas have been mainly analyzed. Figure 1 shows the ion and electron heat diffusivity as a function of T_e/T_i, at r_{eff}/a_{99}~ (a) 0.4 and (b) 0.7, of multiple shots and timings (more than 250 data points). Here a_{99} is the plasma minor radius in which 99 % of the total stored energy is confined. At r_{eff}/a_{99}~0.4, T_i gradient becomes steeper in high-T_i plasmas (in principle, corresponding to data which extend towards low values of T_e/T_i<1; the improvement of the ion heat confinement). On the other hand, such extension is not observed in Fig. 1(b), which indicates that confinement mode there is similar among these shots and timings. The diffusivity is normalized by Gyro-Bohm temperature dependence, $T^{1.5}$. The general tendency is recognized that the normalized ion (electron) heat diffusivity increases (decreases) as T_e/T_i is increased at both radii. At r_{eff}/a_{99}~0.4, the normalized ion heat diffusivity continues to decrease at small T_e/T_i, which indicates that the ion energy confinement there keeps improving. It is also found that the dependence of the normalized electron heat diffusivity on T_e/T_i becomes weaker at r_{eff}/a_{99}~0.7. It indicates that the electron heat transport there is rather stiff than that in core region.

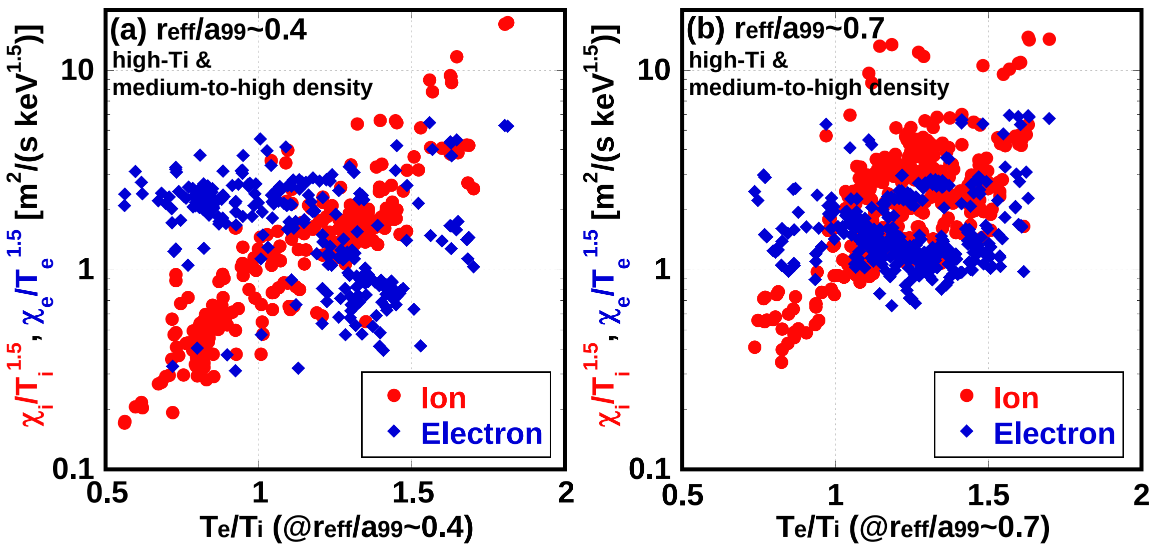

FIG. 1. Ion and electron heat diffusivity (normalized by Gyro-Bohm temperature dependence, $T^{1.5}$) as a function of T_e/T_i, at r_{eff}/a_{99}~(a) 0.4 and (b) 0.7. The general tendency is recognized that the normalized ion (electron) heat diffusivity increases (decreases) as T_e/T_i is increased.

Accumulation of TASK3D-a analyses results has led to the attempt at deducing functional fittings for χ_e and χ_i with local parameters. This approach has remarkable advantages such as fitting can be performed separately for ions and electrons, and gradients of profiles can be taken into account. Thus, it is much more relevant to interpret the physics mechanism of the energy confinement than the conventional scaling approach for τ_E. Moreover, such deduced fitting expressions for heat diffusivities, radius to radius, can be directly implemented into the predictive modelling, so that the transport model assumption (like a Gyro-Bohm) is no longer required. This approach may be considered to be the most relevant ("validated") to the existing experiment database, because it is based on experimental data. Below, only a tiny part of the analysis-database (high-T_i plasmas) is utilized to describe an approach which is meant to be proposed.

Figure 2 shows radial profiles of fitted values of (a) T_i (measured by charge exchange spectroscopy [9]), (b) T_e (Thomson scattering system [10]) and (c) the electron density, n_e (Thomson scattering calibrated with far-infrared laser interferometry [11]) for analysed cases. The number of discharges considered here is 31. Multiple timings are analyzed in each discharge (corresponding to the timing of T_i-profile measurement, leading to about 200 timings), so that the evolution of T_i at core region from low-T_i to high-T_i phase can be tracked, not only at the timing with the highest values of T_i. The T_e profile is rather stiff compared to that of T_i in this database. The n_e profiles are flat to hollow. Figure 3 shows (a) χ_i and (b) χ_e, obtained from the dynamic transport analysis [12] which takes into account the NBI slowing down and temporal change of plasma parameters. The total number of data points (either ion or electron) shown in Figure 3 is around 3000.

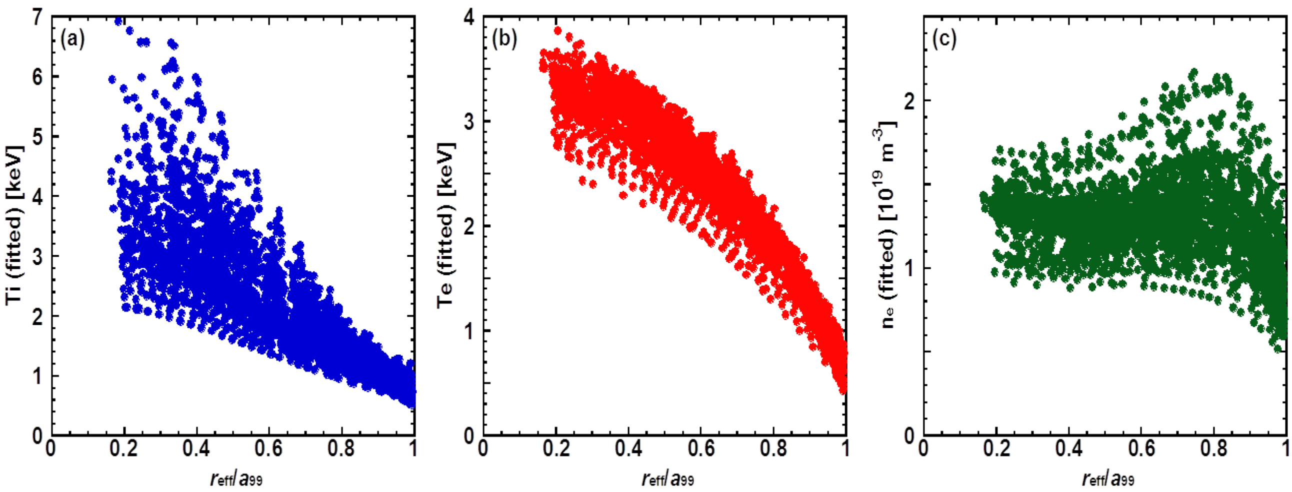

FIG. 2. Radial profiles (fitted) of (a) T_i ,(b) T_e , and (c) n_e for analyzed cases.

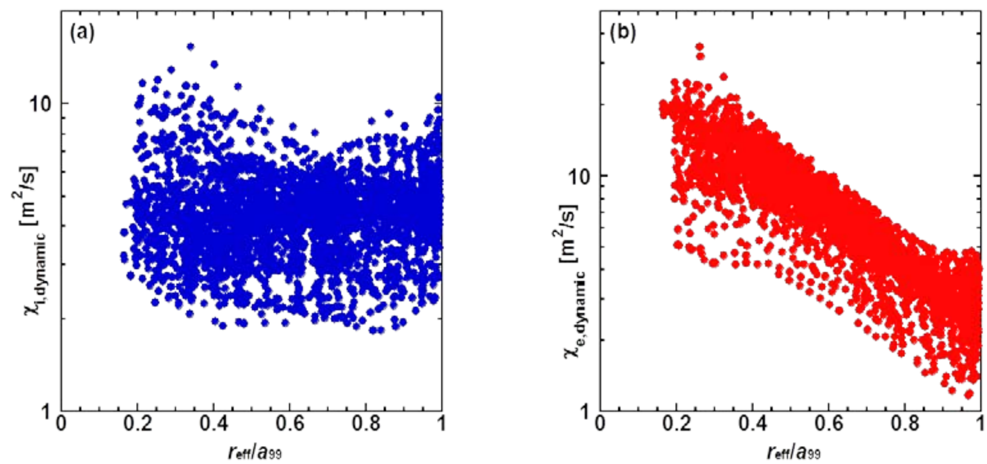

FIG. 3. Radial profiles of (a) χ_i and (b) χ_e for analysed cases.
The total number of data points of χ_i and χ_e is around 3,000, respectively.

Since χ_i and χ_e have radial dependence, the variables which are appropriate for describing radial position should also be implemented into the database. Although there are several candidates for such variables, the effective helicity, ε_{eff} [13, 14], has been implemented. Here, it should be noted that the employed VMEC equilibria in automated TASK3D-a analyses are sequentially defined by only ensuring that the T_e peak is at the magnetic axis and satisfies in-out symmetry [15], so that they do not necessarily reproduce all the equilibrium properties well. Thus, it should be considered that the above-mentioned configuration-related variables are based on one of practical approaches for providing equilibrium for experimental analyses [16].

On performing statistical analysis for TASK3D-a analysis-database, χ_i and χ_e are dimensionally normalized by Bohm diffusion coefficients, $T_{i,e}/(eB)$. Candidate predictive variables are also made into dimensionless, such as, for ions, the collision frequency normalized by that of plateau_Pfirsch-Schlüter boundary (ν_i*), normalized Larmor radius (ρ_i*) and the temperature ratio (T_e/T_i).

There are wide freedoms for the fitting model selection including choices and combinations of predictor variables. In addition to the above mentioned 4 variables (ν_i*, ρ_i*, T_e/T_i, and ε_{eff}), physically important variables such as E_r (radial electric field) shearing rate etc. do exist. However, the complete implementation of such variables into the analysis-database has not yet been done. Thus, let us limit ourselves here to propose an approach by employing available 4 variables.

It should be also noted that the very recent publication on this approach [17] employs only three variables (ν_i*, ρ_i*, T_e/T_i) to reach fitting formula different from Eq. (1) shown below, but with a comparable statistical confidence level. It also clearly shows the freedom on choices of predictor variables.

Here, as a standard exercise in scaling studies, the assumed simple power-law scaling model has been transformed to the log-linear form. Multiple ordinary least squares (OLS) regression analysis has resulted in the fitting expression for $\chi_i/[T_i/(eB)]$, by employing data shown in Figure 2.

$$\chi_{i,\mathrm{fit}}/(T_i/eB) = 2.9\times10^{-10}\,\nu_i^{*-0.182}\,\rho_i^{*-2.72}\,(T_e/T_i)^{0.77}\,\varepsilon_{\mathrm{eff}}^{-0.136}\,. \quad (1)$$

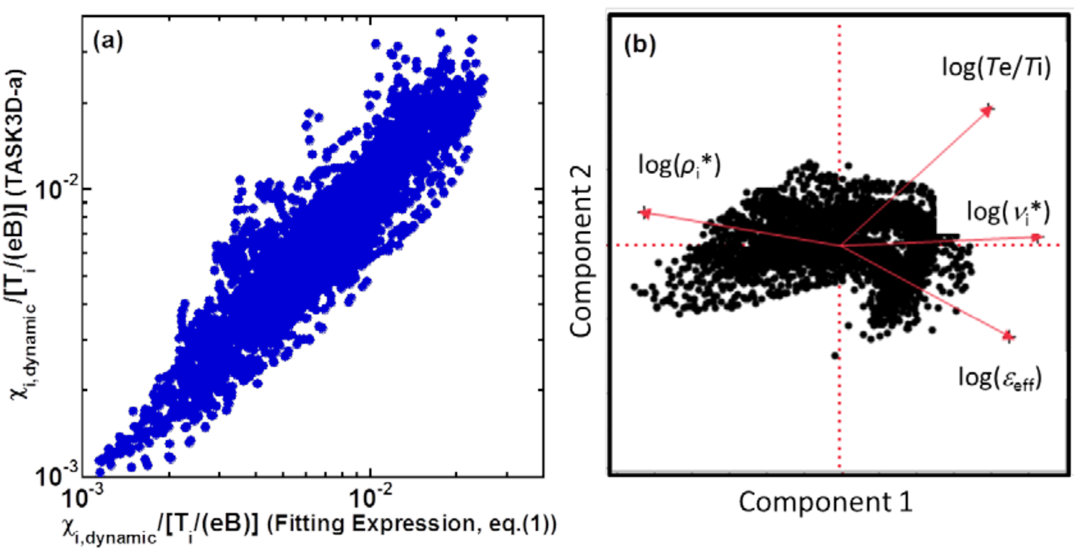

FIG. 4. (a) The comparison of $\chi_i/[T_i/(eB)]$ values between TASK3D-a analysis-database and the regression results, (b) Biplot for predictor variables employed in eq.(1).

Figure 4(a) shows comparison of $\chi_i/[T_i/(eB)]$ values between TASK3D-a analysis-database and the predicted values, eq.(1). Around 3000 data points, corresponding in a wide range of T_i and radial positions, are reasonably aligned on the diagonal line in Figure 4(a). Since the multi-collinearities between regression variables (dependencies in the multi-dimensional space) may have very destructive impact on the OLS regression analysis, an exact check of this problem must be done before using the model. The best way to assess the multi-collinearity is applying principal component (PCA) analysis [18]. Figure 3(b) shows a biplot [19] (data and regression variables) in the plane defined by the first two (the largest) principal components. It indicates there are dependencies between 4 variables, but still within acceptable limits. An important statistical measure of the goodness of the model is the ratio R^2 of the variation explained by the model to the total variation. The obtained value is R^2=0.84, which is a relatively high value, indicating that the eq.(1) reasonably reproduces the response variable, that is, $\chi_i/[T_i/(eB)]$. The value of the root-mean-square-error (RMSE) is 0.27.

There seems, at the most, ±50% difference between TASK3D-a and predicted values, seen from the horizontal width of the data cluster. This difference must be reduced, of course. However, the conventional transport model application for performance prediction is usually meant to predict for a case with a particular condition (*eg*., at a steady-state for certain operation scenario). On the other hand, the eq.(1) covers the evolution of plasma parameters (from low-T_i to high-T_i as seen in Figure 2(a)) in high-T_i plasmas in LHD. Thus, such a deduced fitting expression can be directly implemented into the predictive simulation, so that the transport model assumption/selection (like gyro-Bohm, ion-temperature-gradient mode etc.) is no longer required. This approach may be considered to be the most relevant (“validated”) to the existing experiment database.

As for electrons, $\chi_e/[T_e/(eB)]$, the same set of predictor variables as ions, (ν_e^*, ρ_e^*, T_e/T_i and ε_{eff}), gives a fitting expression with only R^2=0.29. This poor confidence level of statistics may be attributed to the small range of T_e (cf., Figure 2(b)) in the database causing smaller range of predictor variables compared to that for ions. Increasing the number of predictor variables, from 5 to 9 (addition of available variables such as the normalized temperature and density scale lengths, R/L_{Te}, R/L_{ne}, the rotational transform, the dominant helicity and the toroidicity), can increase R^2 to 0.54. However, it is still small value, and moreover, configuration-related variables have high multi-collinearity each other. Recently, trials have been made in LHD for increasing T_e in high-T_i plasmas (from $T_i > T_e$ towards $T_i \sim T_e$) by means of the increased available ECH power [20]. Corresponding increase of TASK3D-a analysis-database (inclusion of higher T_e cases in high-T_e plasmas) is foreseen, when it is anticipated to increase the confidence level of statistics for electrons as well.

The product that can be deduced from this proposed approach may not be only the fitting expression for heat diffusivities. Deviations of data points from the prediction of the given fitting expression may be considered as the “*measure of the freedom of confinement status*”. For example, RMSE varies as 0.27, 0.23 and 0.22, and the maximum residuals also varies as 0.8, 0.6 and 0.4 at r_{eff}/a_{99} (normalized minor radius)=0.25, 0.6 and 0.8, respectively, based on the OLS regression analysis for the subsets (radius to radius) of analysis-database by employing the same 4 predictor variables as in eq.(1). It may suggest that the confinement status has larger freedom (deviation from the mean: the fitting expression) at core region (ion internal transport barrier for high-T_i phase, in this case). In this way, the investigation on the confinement status, such as the probability density function suggested in Ref.[21], may be pursued based on the statistics on “big data”. This will also be the direction that this approach should evolve.

3. Summary

In this proceeding, comprehensive understandings of energy transport in LHD plasmas which deduced from the analysis database being accumulated by the extensive application of the integrated transport analysis suite, TASK3D-a. In addition to the elucidation of general tendency (that is the normalized ion (electron) heat diffusivity increases (decreases) as T_e/T_i is increased), a statistical approach is proposed as an energy transport “modelling”. Statistically-confident fitting expression for the ion heat diffusivity (covering wide range of T_i, also from core to edge) for LHD high-T_i plasmas has been provided, which can be directly implemented into the predictive simulation as a transport “model”. Here, in this letter, only a tiny part of TASK3D-a analysis-database (high-T_i plasmas) has been employed to demonstrate the possibility of the approach.

It may be ultimately anticipated to elucidate fitting formulae for ion and electron heat diffusivities, separately, regardless the confinement mode. Further application of TASK3D-a in wider range of LHD plasmas and resulting increase of TASK3D-a analysis-database will be performed towards this direction.

Lastly, it should be emphasized that this approach is comprehensive to any other combinations of integrated transport analysis suits and fusion experiments.

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