Quasilinear Turbulent Particle and Heat Transport Modeling with Development of Unique Saturation Rules for Insights into Profile Formation Mechanisms

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Abstract

• A novel quasilinear turbulent transport model DeKaNIS has been constructed, which is suitable to investigate formation mechanisms of density and temperature profiles.

• DeKaNIS predicts turbulent particle and heat fluxes quickly with machine-learning techniques.

• While the original model covered only particle transport and determined a turbulent saturation level based on experimental particle fluxes (Narita NF2019), the capability has been extended to cover both particle and heat transport, and a new saturation rule has been introduced, which offers potential for applying to different devices and improves the prediction accuracy.

Background

• Some transport models (e.g., TGFL and QualiKiz) have been used to predict the density and temperature profiles, but they require high computational costs.

→ A neural-network (NN) based approach has been undertaken, resulting in a ~$10^4$-fold acceleration of the calculations. (e.g. TGFL-NN (Honda Pop 2019, Meneghini NF 2017), QualiKiz-NN (van de Plassche Pop 2020))

• The existing models are hard to use to investigate relationships between profile formation and transport processes.

Key features of DeKaNIS

• The training dataset is based on a combination of the gyrokinetic code GKW calculations and JT-60U experimental data.

• DeKaNIS predicts particle and heat fluxes, considering the diagonal and off-diagonal terms individually.

Quasilinear transport modeling and saturation rules

• Electron particle and heat fluxes:

$$\Gamma_e = D_e \left( \frac{C_N}{\tau_{ce}} + \frac{C_p}{\tau_{pe}} \right)$$

- Predicting diagonal and off-diagonal terms individually can be helpful to understand profile formation mechanisms.

- $\Gamma_{eH}$ is given by linear calculations with the gyrokinetic code GKW [Peeters CPC2009].

- The off-diagonal terms satisfy the Onsager symmetry: $\Gamma_{eH} = D_{eH} + \frac{1}{2}$

- The 7 coefficients are estimated for the plasma parameters taken from JT-60U 23 H-mode plasmas [Takegaki NF2008], and the results are used as NN training data.

- NB injection without gas puffing

- Positive magnetic shear

A. Semi-empirical saturation rule [Narita NF2019, IAEA FEC 2018]

$D$ is estimated to match $\Gamma_{eH}$, that satisfies $\Gamma_{eH,\text{NB}} + \Gamma_{eH,\text{exp}} + \Gamma_{eH,\text{turb}} = 0$.

B. Mixing-length-like saturation rule: newly introduced

• Turbulence: linear instability

$$\sqrt{\frac{\nu_{\text{eff}}}{k_{\text{eff}}}}$$

• Zonal flows: linear zonal flow response

- The linear zonal flow response function $K_{\text{eff}} = 1/(1 + 1.646 kg^{0.73})$

- The residual zonal flow level $L_{ZF} = K_{\text{eff}} = \sqrt{\nu_{\text{eff}}/k_{\text{eff}}} + 0.5$

representing the zonal flow potential (M. Nunami Pop2013)

- $a$ and $\beta$ are optimized with Genetic algorithm against two different $D$.

(1) $D_{\text{exp}}$: estimated to match $\Gamma_{eH,\text{exp}}$

(2) $D_{\text{turb}}$: estimated to match $\Gamma_{eH,\text{turb}}$ that satisfies $\hat{Q}_{\text{source}} + \hat{Q}_{\text{EQU}} + \hat{Q}_{\text{rad}} + \hat{Q}_{\text{eddy}} + \hat{Q}_{\text{turb}} = 0$.

The two scaling formulas show similar effects of instabilities and zonal flows.

- The inclusion of $\Gamma_{eH,\text{turb}}$ increases $\sigma_{\text{pert}}$.

Potential for applying to other devices

• Saturation rule A may increase the accuracy within the known parameter range by learning the experimental value directly.

• However, it cannot guarantee the validity of the predictions outside the known parameter range.

→ It is easy to expand the applicable plasma parameter range.

Dependence of prediction trends on the saturation models

• Saturation rule A tends to overestimate the temperature of JT-60U plasmas because the saturation level is determined based on $\Gamma_{eH,\text{exp}}$.

Mean offsets of predicted density and temperature for 14-JT40 test cases

- Temperature overestimation has been reduced due to inclusion of $\Gamma_{eH,\text{turb}}$

Future work

- The validity of the mixing-length-like saturation rule will be checked.

- Inconsistency between $D_{\text{exp}}$ and $D_{\text{turb}}$ means that $\hat{Q}_{\text{source}} + \hat{Q}_{\text{EQU}} + \hat{Q}_{\text{rad}} + \hat{Q}_{\text{eddy}} + \hat{Q}_{\text{turb}}$ calculated by the quasilinear theory does not match the experimental value.

- Weak dependence of $\hat{D}$ on $\sqrt{\nu_{\text{eff}}/k_{\text{eff}}}$ contradicts the well-known mixing-length rule.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number 20K14450 and MEXT as “Program for Promoting Researches on the Supercomputer Fugaku” (Exploitation of burning plasma confinement physics, hp200127) and used computational resources of FX100 provided by Nagoya University. This work was also carried out using the IFPS-I supercomputer at the Computational Simulation Centre of International Fusion Energy Research Centre (IFERC-CSC) in Rokkosho Fusion Institute of QST (Aomori, Japan).

ID: 825, TH/P7-7