# 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. TGLF 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 ~$10^5$-fold acceleration of the calculations. (e.g. TGLF-NN [Honda PoP 2019, Meneghini NF 2017], QuaLiKiz-NN [van de Plassche PoP 2020])
- The existing models are hard to use to investigate relationship 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:

$$\bar{\Gamma}_e = \bar{D}\left(\frac{R}{L_{n_e}} + C_T\frac{R}{L_{T_e}} + C_P\right)$$

$$\bar{Q}_e = \bar{\chi}_e\left(C_N\frac{R}{L_{n_e}} + \frac{R}{L_{T_e}} + C_{HP}\right)$$

$\propto (\tilde{\phi} - v_{\parallel}\tilde{A}_{\parallel})^2$ : The turbulent fluctuation amplitude

$C$: Off-diagonal term coefficients

- Ion heat flux: $\bar{Q}_i = \frac{\bar{\chi}_{\mathrm{eff,i}}}{\bar{\chi}_{\mathrm{eff,e}}}\bar{\chi}_{\mathrm{eff,e}}\frac{R}{L_{T_i}}\frac{n_i}{n_e}\frac{T_i}{T_e}$

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

- $C_{\mathrm{T,P,N,HP}}$ are given by linear calculations with the gyrokinetic code GKW [Peeters CPC2009].
- The off-diagonal terms satisfies the Onsager symmetry: $\bar{\chi}_e = \bar{D}\frac{C_T + 3/2}{C_N}$.

- The 7 coefficients are estimated for the plasma parameters taken from JT-60U 23 H-mode plasmas [Takenaga NF2008], and the results are used as NN training data.
  - NB injection without gas puffing
  - Positive magnetic shear
  - $I_P/B_\phi = 1\mathrm{MA}/2.0\text{-}2.2\mathrm{T}$
  - ITG or ITG/TEM modes ($0.3 \le \rho \le 0.65$)

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

➢ $\bar{D}$ is estimated to match $\bar{\Gamma}^{\mathrm{exp}}_{\mathrm{e,turb}}$ that satisfies $\bar{\Gamma}_{\mathrm{e,NB}} + \bar{\Gamma}_{\mathrm{e,neo}} + \bar{\Gamma}_{\mathrm{e,turb}} = 0$.

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

➢ Turbulence: linear instability
- $\bar{\gamma}/\bar{k}_\theta^2$ calculated at $\bar{k}_\theta$ with $\bar{\gamma}_{\max}$

➢ Zonal flows: linear zonal flow response

$$\bar{D}_{\mathrm{scaling}} = \mathrm{coef}\,(\bar{\gamma}/\bar{k}_\theta^2)^\alpha L_{ZF}^\beta$$

(Turbulence; Zonal flow) [Narita PPCF2018]

- The linear zonal flow response function [Rosenbluth PRL1998]:

$$K_{RH} = 1/(1 + 1.6q^2/\epsilon^{1/2})$$

- The residual zonal flow level: $L_{ZF} \equiv K_{RH}(\bar{\gamma}/\bar{k}_\theta^2)^{0.5}$

representing the zonal flow potential [M. Nunami PoP2013]

■ $\alpha$ and $\beta$ are optimized with Genetic algorithm against two different $\bar{D}$.

(1) $\bar{D}_{\Gamma_e}$: estimated to match $\bar{\Gamma}^{\mathrm{exp}}_{\mathrm{e,turb}}$

(2) $\bar{D}_{Q_e}$: estimated to match $\bar{Q}^{\mathrm{exp}}_{\mathrm{e,turb}}$ that satisfies $\bar{Q}_{\mathrm{e,source}} + \bar{Q}_{\mathrm{e,equi}} + \bar{Q}_{\mathrm{e,rad}} + \bar{Q}_{\mathrm{e,neo}} + \bar{Q}_{\mathrm{e,turb}} = 0$.

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

✓ The inclusion of $\bar{Q}^{\mathrm{exp}}_{\mathrm{e,turb}}$ increases coef.

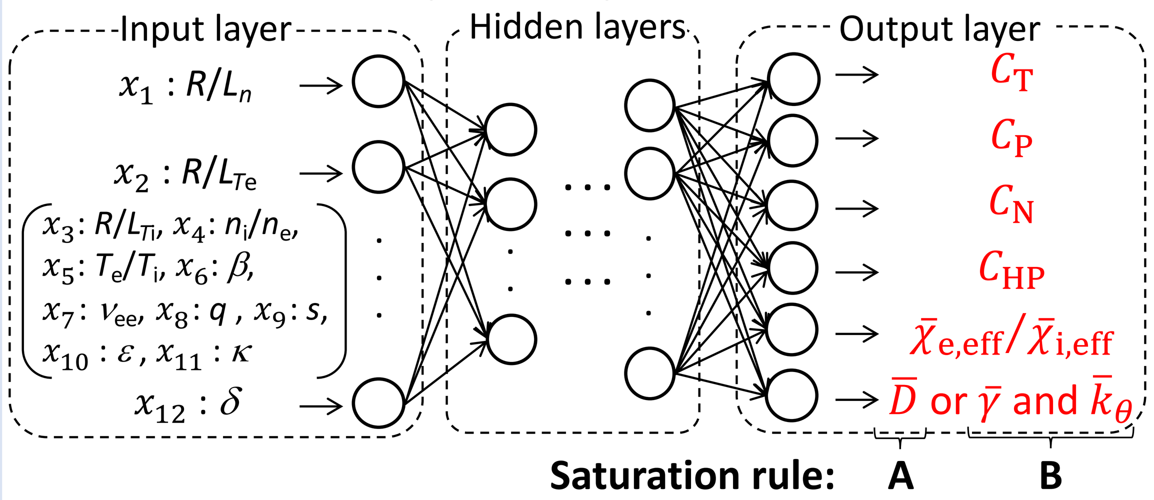
| Base | $\alpha$ | $\beta$ | coef $[10^{-4}]$ |
|---|---|---|---|
| (1) $\bar{\Gamma}^{\mathrm{exp}}_{\mathrm{e,turb}}$ | 1.1008 | −2.8024 | 1.6996 |
| (2) $\bar{Q}^{\mathrm{exp}}_{\mathrm{e,turb}}$ | 1.1990 | −2.4732 | 7.8584 |

◆ $\alpha > 0$: turbulence enhancement due to instabilities

◆ $\beta < 0$: turbulence suppression due to zonal flows

## Density and temperature profile predictions with NN models

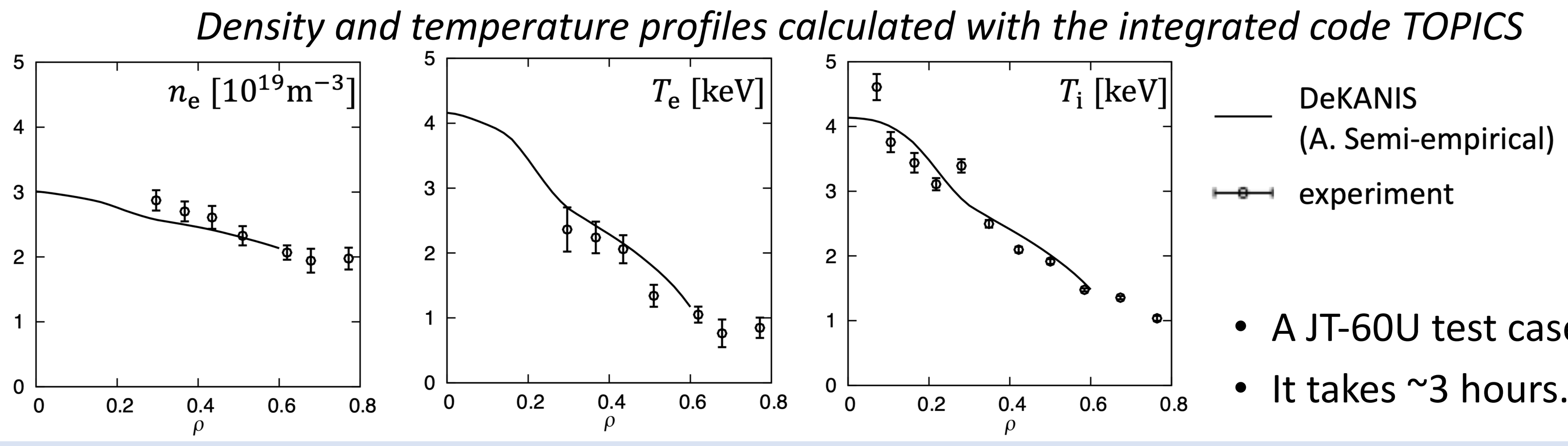
□ NN models to predict particle and heat fluxes




- Training and validation data: ~7,000 data points
- Experimental data with large errors has been eliminated.
- $\bar{\chi}_e$ is calculated not to break the Onsager symmetry.

✓ After optimizing hyperparameters and activations functions, density and temperature profile predictions have been realized.

*Density and temperature profiles calculated with the integrated code TOPICS*

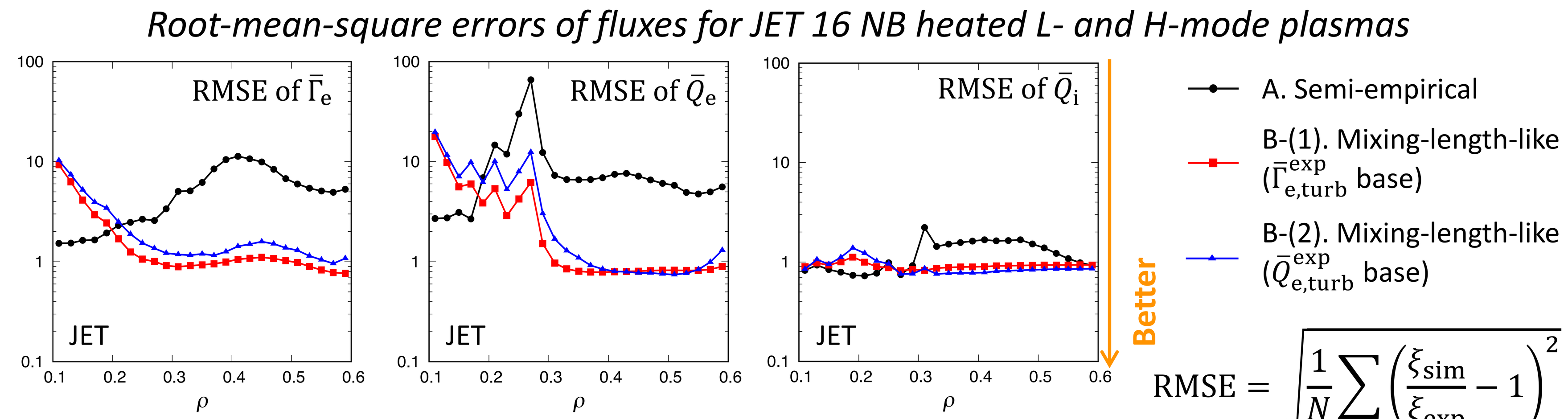



- A JT-60U test case is used.
- It takes ~3 hours.

## 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.

*Root-mean-square errors of fluxes for JET 16 NB heated L- and H-mode plasmas*




$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum\left(\frac{\xi_{\mathrm{sim}}}{\xi_{\mathrm{exp}}} - 1\right)^2}$$

$N$ : the number of plasmas

- The JET data have been taken from the ITPA International Multi-Tokamak Profile Database.
- $I_P/B_\phi = 0.96\text{-}3.2\mathrm{MA}/1.1\text{-}3.1\mathrm{T}$

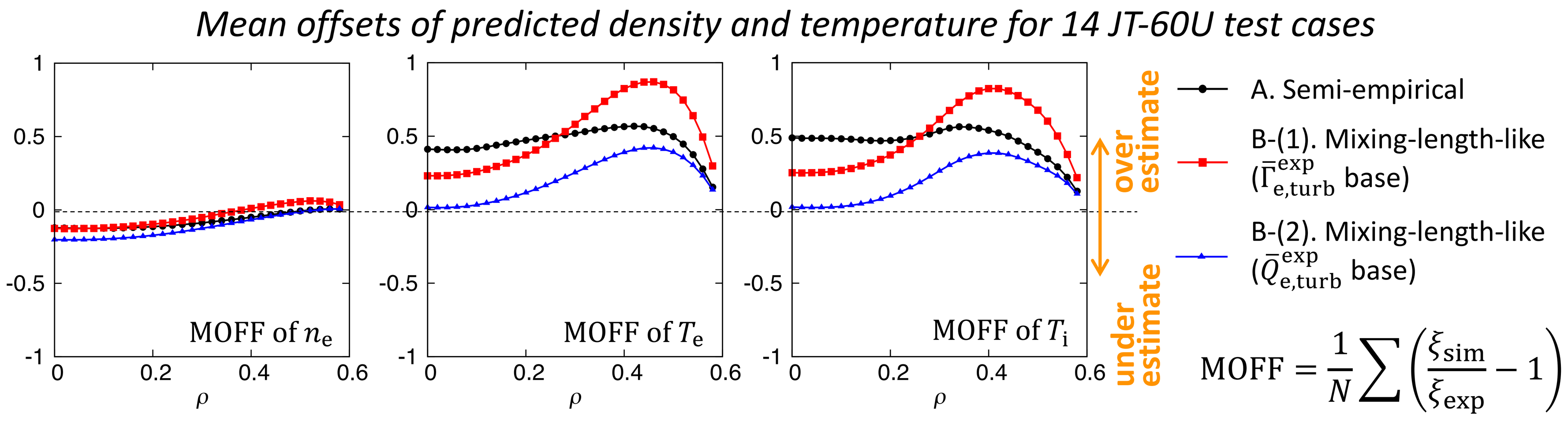
✓ Saturation rule B has a better accuracy for the JET plasmas.

- The NN model of Saturation model B is separated from the experimental values, and has learned only the GKW results.
  - ➔ 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 $\bar{\Gamma}^{\mathrm{exp}}_{\mathrm{e,turb}}$.

*Mean offsets of predicted density and temperature for 14 JT-60U test cases*




$$\mathrm{MOFF} = \frac{1}{N}\sum\left(\frac{\xi_{\mathrm{sim}}}{\xi_{\mathrm{exp}}} - 1\right)$$

✓ Temperature overestimation has been reduced due to inclusion of $\bar{Q}^{\mathrm{exp}}_{\mathrm{e,turb}}$.

## Future work

➢ The validity of the mixing-length-like saturation rule will be checked.
- Inconsistency between $\bar{D}_{\Gamma_e}$ and $\bar{D}_{Q_e}$ means that $\bar{Q}_e/\bar{\Gamma}_e$ calculated by the quasilinear theory does not match the experimental value.
- Weak dependence of $\bar{D}$ on $\bar{\gamma}/\bar{k}_\theta^2$ contradicts the well-known mixing-length rule.

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