Validation of the isotope model in the PENN neural network code using European Transport Simulator

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Abstract

Predictions of heat and particle transport in present and future fusion devices play a crucial role in the modelling and analysis of the performance properties of plasma scenarios. It is observed that the transport properties in the core and in the edge regions are coupled in H-mode plasmas, where the core pressure and the pedestal pressure are connected in a loop via the Shafranov shift and profile stiffness effects [1]. Therefore it is important to have accurate predictions in both core and edge regions. The core transport properties are modelled routinely using integrated modelling tools [2]. On the other hand, the existing pedestal transport models based on the first principles do not cover all parameter spaces accurately, such as when resistive effects cannot be neglected, or when the pedestal density or separatrix density is not known. Therefore other approaches were developed to be able to model whole plasma domain in the integrated modelling workflows. The neural network prediction of the profiles in the edge region is one of the available approaches. The kinetic profiles are predicted in the edge region using available database of the limited set of (engineering) parameters and the values at the pedestal top (or slightly inwards into the plasma) are used as a boundary conditions for the core transport modelling. The PENN model [3] utilizes such an approach and is trained on JET data using the available database [4]. The PENN model is coupled to the European Transport Simulator (ETS) integrated modelling workflow [5]. Recently the PENN model was updated to include isotope effect into the predictions. This work concentrates on validation of the updated PENN model by modelling the core transport of the JET-ILW type I ELMy H-mode plasmas for different isotope mixtures with the ETS workflow using TGLF-SAT2 quasi-linear transport model [7] in the core and PENN predictions as a boundary conditions. The comparison with earlier obtained core modelling and experimental results [6] is performed.

1. Introduction

Prediction of the performance of the fusion reactor relevant plasmas is an important step in designing the operation scenarios for future reactor devices. The effect of different hydrogen isotopes on the performance of the fusion plasmas should be understood as the reactor plasmas of the first fusion reactors will be a mixture of Deuterium (D) and Tritium (T) ions. Both experimental and theoretical studies of isotope effect on heat and particle transport were performed for the presently operating fusion devices. For H-mode plasmas, where the mass dependence differs for the core and pedestal regions the effects connected to the core-edge coupling (pressure connection via Shafranov shift and profile stiffness [1]) are observed to affect the performance. An integrated modelling approach is required to take the coupling effect into account together with the accurate transport models in both core and edge regions. The core transport models were extensively developed during recent years, and overall understanding of the sore transport properties are gained [2]. On the other hand, the edge transport modelling based on the first principles is more challenging and the complete understanding of the transport properties in the pedestal regions is still to be achieved. Presently other approaches are used to model the edge region in the integrated modelling framework. Neural network prediction of the profiles in the edge region is one of the available approaches, where the kinetic profiles are predicted using available experimental database for the one or several fusion devices. In this work, the integrated modelling workflow European Transport Simulator is used to model the JET H-mode scenario with different hydrogen isotopes (Deuterium or Tritium) as a main ion species. The core turbulent transport is modeled using quasilinear TGLF-SAT2 model [7]. The edge profiles are calculated using the Pedestal Neural Network (PENN) code coupled to the ETS workflow. Comparison with the earlier obtained experimental results [6] is performed.

2. Experimental data and simulation setup

The integrated modelling workflow European Transport Simulator (ETS) [5] is used in this work to model kinetic profiles of the H-mode JET discharges from the experimental scenario where isotope effect on the plasma performance was studied with different hydrogen isotopes as a main ion species. Two pulses are considered for the present work: pulse #97036 with Deuterium ions are the main ion species and pulse #98795 where Tritium ions are the main species. Experimental profiles of

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[a] See the author list of "Overview of T and D-T results in JET with ITER-like wall" by C.F. Maggi *et al, Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16–21 October 2023).*

the electron density and temperature are obtained using HRTS diagnostics [15] and the ion temperature profile data is obtained using CXRS diagnostic [16]. The details of the kinetic profiles processing could be found in [6]. Input to ETS simulation is provided by the interpretive TRANSP runs where kinetic profiles of the electron and ion density and temperature fitted using experimental data are used [6]. The following ETS setup is used in this work:

- Plasma composition: electrons, main ion species, either Deuterium (D) or Tritium (T), hydrogen minority (H), impurities (Beryllium (Be), Tungsten (W)).
- Solver setup:
  - predictive – electron density, electron and ion temperatures;
  - static – minority density, impurity densities;
  - from quasineutrality – main ion density.
- Equilibrium: fixed boundary code CHEASE [14]
- Transport modules: TGLF-SAT2 [7] (anomalous), NCLASS [8] (neoclassical), additional background transport.
- Heating models: fast particle source code – BBNBI [9], NBI heating code- NBISIM, ohmic heating.

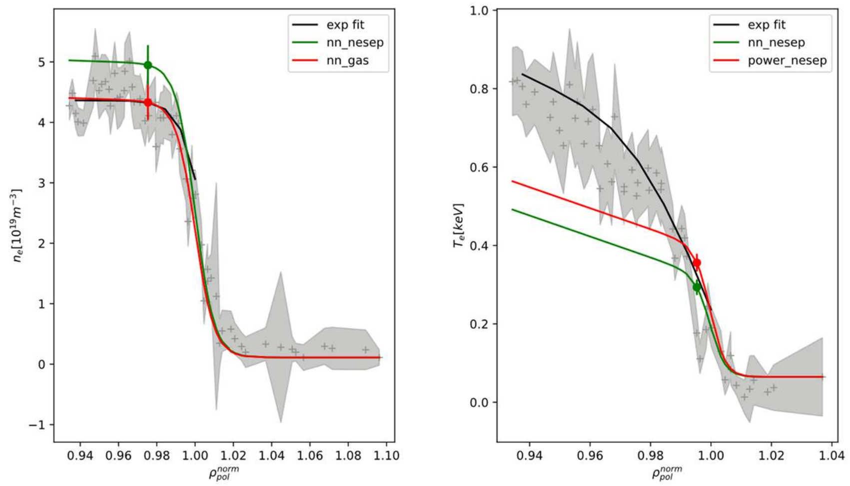
Hydrogen (H) minority is set as a fraction of the electron density (1%) to mimic the experimental conditions. Profiles of the Be and W density are set to match Z_{eff} and total radiation values respectively. Electrostatic version of TGLF-SAT2 transport model is used. The core and edge regions are separated at normalized toroidal flux value ρ_{tor}^{norm}=0.85, where $\rho_{tor}^{norm} = \sqrt{(\phi - \phi_0)/(\phi_a - \phi_0)}$, ϕ is the toroidal flux, ϕ_0, ϕ_a are the values of the toroidal flux at the magnetic axis and at the edge respectively. Transport equations using models mentioned above are solved inside this point, while the kinetic profiles outside are calculated by the PENN code. PENN [10,3] is the neural network model where pedestal top values of the electron density and temperature are predicted using the set of scalar parameters (mostly engineering) as input. The model is based on the pedestal database for the type I ELM H-modes JET plasmas [4]. The electron and ion kinetic edge profiles are calculated based on the pedestal top predictions and the assumptions made for the pedestal parameters (position and width). The values of the kinetic profiles at ρ_{tor}^{norm}=0.85 calculated by PENN are used as a boundary condition for the core simulations. Recently, the PENN model was extended to be able to model different hydrogen isotopes [11]. The main goal of this work is to validate this extension against the experimental data.

3. Results and Discussion.

The presented work is divided into two main parts: a) standalone predictions with the PENN code using the experimental data as input; b) simulation of the kinetic profiles with the ETS and comparison with the experimental data.

3.1 Standalone predictions with the PENN code.

The edge profiles of the electron density and temperature are predicted by PENN using the small set of (mostly) engineering parameters as input, together with the assumptions on the position of the pedestal center and the pedestal width. The values of the total plasma current (I_p), the total auxiliary power (P_{tot}), the normalized beta (β_N) and the average triangularity (δ) are taken from the interpretive ETS simulation. The value of the separatrix density (n_e^{sep}) and gas fueling rate (Γ) are taken from experiment. Different neural network models are used for predictions featuring different sets of input parameters. The models are abbreviated in the following as: *nn_nesep* – the model using n_e^{sep}, I_p and δ; *nn_gas* – the model using P_{tot}, I_p, Γ and δ ; *power_nesep* – power scaling model using n_e^{sep}, β_N and I_p. The edge profiles of the electron density and electron temperature calculated by the different models are shown on Fig. 1 for the T case (T ions are the main ion species) together with the experimental data and the fit of the experimental data reported in [6]. Profiles are plotted as a functions of $\rho_{pol}^{norm} = \sqrt{(\psi - \psi_0)/(\psi_a - \psi_0)}$, where ψ is the poloidal flux, ψ_0, ψ_a – values of the poloidal flux at the magnetic axis and at the edge correspondently. Note that different sets of neural networks are used to model density and temperature profiles (one set uses nn_nesep for both electron density and temperature, the other set uses nn_gas for the electron density and power_nesep for the electron temperature predictions, see [11] for details). It is seen that the electron density predictions are closer to the experimental data than the temperature predictions especially noticeable in the region inside the pedestal top (ρ_{tor}^{norm}<0.97). This is attributed to the nature of the PENN model using modified hyperbolic tangent for profile calculations where the slope of the quantity in the inside region is determined by the slope of the profile inside core computational boundary (ρ_{tor}^{norm}=0.85 in this case). It will be seen below (see Fig. 2) that the temperature gradient inside ρ_{tor}^{norm}=0.85 is lower than the one outside.

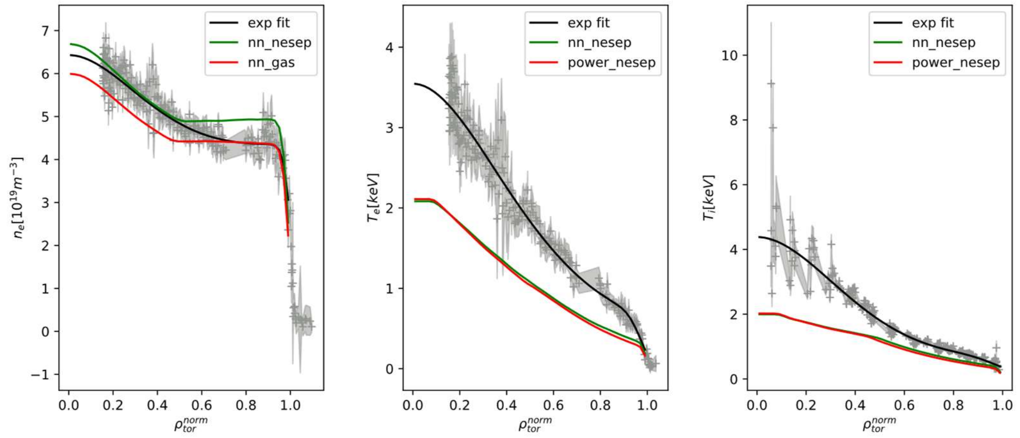


a) b)

Figure 1. Edge pedestal profiles for the T case (JET pulse #98795) obtained from the experiment (gray shaded area with '+' signs), fit of the experimental data (black) and modelled by the PENN using different neural network (NN) models: nn_nesep (green); nn_gas and power nesep (red). a) electron density, b) electron temperature. Circles show the position and the height of the pedestal top calculated by PENN. Error bars are calculated from the model uncertainty [see [11] for details].

3.2 Simulations of the kinetic profiles with ETS

The predictions of the PENN code are used together with the core transport codes and the heating models to simulate the full radius profiles of the electron density and the electron and the ion temperatures. The results are shown on Fig. 2 for the T case. The experimental data and the profiles fitted to the experimental data are included in the plots similarly as it is done on Fig. 1. The profiles are plotted as a function of ρ_{tor}^{norm}. Reasonably good agreement is seen in the electron density profile between the fitted data and the simulations results. It can be noted that the electron density profiles obtained using different models have the same shape in the center and are just 'shifted' based on the pedestal value. This points to the stiffness effect on the electron density profile. The profiles of both electron and ion temperatures are underpredicted over the whole profile. The edge part discrepancy can be explained by the nature of the PENN model for the electron temperature (see discussion above) and suggests adding another method to model the edge profile in PENN (for example bi-linear model used in [13]). The ion edge temperature profile is modeled using the same method as for the electron temperature but considering T_i/T_e ratio. For these simulations this ratio is set to 1.0 that seems to be slightly lower than the experimentally obtained results. It should be also noted that weak dependence of the temperature on the isotope mass is seen in experiment [6], while the PENN model predicts negative dependence (see [11]). This suggests the need to extend the training data set for the PENN model. The core part underprediction can be because electrostatic version of TGLF model is used while the β_N value for this case is 2.4 that could be high enough to justify the usage of electro-magnetic version of TGLF. Another possible reason for underprediction of the temperature in the core is the absence of the rotational stabilization in the TGLF version used in ETS. This effect can play an important role as can be seen in [12] for example. Both effects will be considered in future work.



a) b) c)

Fig. 2. Kinetic profiles for the T case (pulse #98795) obtained from the experiment, profiles fitted to the experimental data and profiles obtained from the ETS simulations. The same color code is adopted on this figure as on Fig. 1. a) electron density; b) electron temperature; c) ion temperature.

Summary

Simulations of the kinetic profiles for the JET H-mode scenario is performed using ETS integrated modelling workflow where the neural network model PENN is used to predict the edge profiles of the electron density, the electron and the ion temperatures. For the plasma with Tritium as a main ion species reasonable agreement is found between experimental data and the simulation results for the electron density, but both the electron and the ion temperatures are underpredicted. The possible reasons are the model used in PENN to calculate slope of the temperature profiles inside the pedestal and absence of the stabilizing effects for the turbulence transport (rotational and em stabilization) in the core. Both reasons will be considered in the future work.

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