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Comparative analysis of the SOL plasma in DEMO using EDGE2D/EIRENE and TECXY codes

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Abstract

In this contribution a benchmark of the 2D edge codes TECXY and EDGE2D-EIRENE is presented. A conventional DEMO scenario is considered by assuming a simplified geometry, with the target plates perpendicular to the separatrix, and a pure Deuterium plasma. Despite the different models adopted in the two codes, mainly related to the description of the neutral dynamics and to the different boundary conditions, the results show a good match both in terms of power load profiles on the outer target and predicted trends for global quantities. A scan in density and in diffusion coefficients is performed in order to identify the characteristic conditions and the different regimes of the SOL. Comparable values and simlar dependency of the global quantities as a function of the power decay length is also observed.

1 Introduction

The development of a Demonstration Fusion Power Reactor (DEMO) is a crucial step to reach the goal of exploiting fusion power in a future commercial reactor. A large range of design parameters is currently explored and the reactor design is still far from a precise definition. In particular, the power exhaust issue is one of the most limiting factor. A large amount of the power conducted and convected from the main plasma towards the divertor concentrates on a relative small surface area very close to the separatrix and could result in the melting of the target materials. In addition, the high heat fluxes could also lead to unacceptable thermal stesses on the divertor. In order to mitigate the problem, several possibilities are considered including the adoption of new equilibrium magnetic configurations, e.g. the SnowFlake (SF), X-divertor and super-X divertor. However, in order to evaluate the benefits of the various solutions we should clearly understand what are the physical processes that could lead to a reduction of power loads on the divertor plates, e.g. as seen in numerical simulations of snowflake divertor configurations in EAST at high densities due to the increase in the connection length[1]. In this framework, the numerical modeling plays a key role in the analysis; therefore, it is very important to assess the reliability of the different numerical tools that can be used to study the Scrape-Off Layer (SOL) plasma.

Several 2D edge codes are currently available to simulate the SOL plasma. In this paper we present a comparison of the results of a preliminary study obtained by using two different numerical tools, TECXY and EDGE2D-EIRENE, on a conventional DEMO scenario. TECXY is a simple and "fast" 2D code [2] where the plasma description, based on the Braginskii equations[3], is coupled with an analytical treatment of the neutral particles. The target plates are imposed perpendicular to the poloidal field lines and the private region is not taken into account, while the real SOL geometry of the flux surfaces and field lines is considered. For every ion species the continuity, momentum and energy equations are solved and appropriate coefficients for the recombination, ionization and line emission rates are assigned to each charge state. The transport of particle and energy is anomalous radially, whereas it is classical along the field lines. Other external parameters are the coefficients for recycling (R_c), for particle ($D_\perp$) and energy (χ) diffusion as well as the power (P_{SOL}) and particle flux ($\Gamma_\perp$) entering the SOL.

The results of the analysis are then compared to the prediction of the more sophisticated code EDGE2D-EIRENE. As for TECXY, EDGE2D is based on the Braginskii transport equations, where electrons and ions are considered as separate fluids. Transport is classical along the field lines and anomalous radially. Radial transport coefficients are given as inputs, while the parallel ones follow from the 21-moment Grad approximation. All ions have the same temperature T_i, while electrons have temperature T_e[4]. Contrarily from TECXY, the neutral particle description is performed by the Monte Carlo code EIRENE that, in addition to the real target geometry considered, allows a more realistic evaluation of the neutral dynamics. The particle sink is given externally by defining the pump with an albedo coefficient physically linked to the recycling.

The paper is organized as follow: in section 2 the DEMO baseline scenario and the inputs for the numerical simulations are described. In section 3 the results are presented, considering both the density and diffusion coefficients parameters scans. In particular, the prediction of the two numerical codes are compared in order to assess the differences in the predicted trends given by the two numerical model adopted. Finally, in section 4 the conclusion will be drawn.

2 DEMO baseline scenario and setup of the simulations

DEMO is thought as the nearest-term reactor, which must be able to produce several hundreds of MW of electric power and to operate with a closed fuel cycle, achieving the condition of Tritium self-sufficiency. A set of relevant parameters for the design, which are not expected to change drastically, can be defined by considering a reference scenario, which is based on a "conservative baseline design". This baseline concept foresees the production of P_{net}=500 MW of electric power with a conventional plasma scenario in Single Null divertor configuration (SN) with tungsten (W) divertor plates. The plasma performance is based on H-mode confinement, which results in a lower limit for the the power crossing the separatrix $P_{SOL}>P_{L\text{-}H}$, where $P_{L\text{-}H}$ is the threshold to operate in H-mode. Here, the power across the separatrix is fixed to P_{SOL} = 150 MW. The aspect ratio and the major radius are given by A=3 and R_0=9 m, respectively[5]. Strong requirements are imposed by the tolerable heat loads on the divertor targets, due to the materials technological limits and by the high particle and neutron fluence. In addition, the maximum allowable energy of the particles hitting the targets is constrained by the erosion limit which must be compatible with at least 2 years lifetime of the components. These limitations yield a maximum divertor plasma temperature of 5 eV. As a results, DEMO should work in detached conditions, that is a regime where a cushion of neutral particles forms in front of the target, thus enhancing the interaction between the plasma and the neutrals. In order to reach these conditions and considering the main parameters, the injection of external impurities is necessary.

The main goal of this work is the benchmark of TECXY with the more sophisticated code EDGE2D-EIRENE. Therefore, in this preliminary study we have considered a simplified case in order to speed up the simulations: a pure Deuterium plasma has been taken into account without the presence of external impurities. This is only the starting point for a complete characterization of the plasma conditions envisaged in the considered scenario. As said above, differently from the detailed Monte Carlo computation performed by EIRENE, TECXY describes the dynamics of recycled neutrals on the target plates by means of an analytical model; in particular, an outwardly decay exponential function defines the neutral density, with a top value and a decay length computed self-consistently by the code[2]. This feature allows to perform a much faster parameters scan, even though the neutrals particles are not well represented.

An important difference between the two numerical tools lies in the definition of the computation domain. Both codes take into account the full topology of the SOL, while EDGE2D also considers the private region and the external corona of the plasma core, highlighted in figure 1(a) with the green and blue area, respectively. Most importantly, TECXY does not reflect the actual geometry of the target, which is imposed to be perpendicular to the poloidal flux lines, as can be seen by observing the magenta dashed line and the red ones in figure 1(b). Although EDGE2D considers the real geometry of the target, perpendicular plates are also imposed in these simulations due to numerical noise arising in the calculations, which yields unphysical density profiles of the neutral particles on the outer target. Therefore, the similar geometries imposed in the two different codes allow to make a better comparison of the results, since we are able to rule out the effect of the divertor closure. It is important to point out that in both meshes we have chosen a grid resolution compatible with the predicted power decay length at outer midplane (OMP), $\lambda_{q,OPM} \approx 3$ mm, as can be seen from the zooms where at least 4 points are defined within a $\lambda_{q,OMP}$. The particle sink has been assigned in EDGE2D through the definition of the pump with an albedo equal to 0.94, while in TECXY through the recycling coefficient R_c = 0.9985. Since the analysis is focused on the low field side (LFS) divertor region and in order to speed up the simulations, the drifts are neglected in both cases.

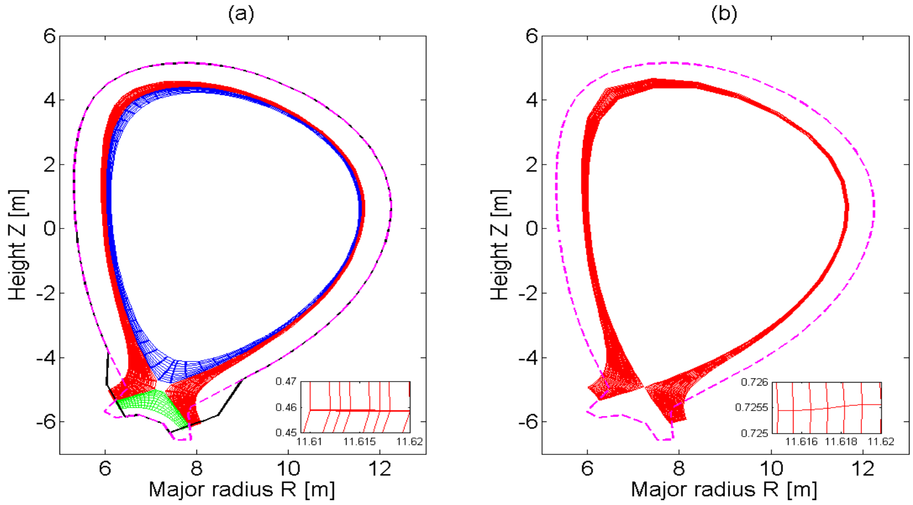

Figure 1. *(a) Mesh used in EDGE2D-EIRENE for the simulation of the SOL plasma. The main SOL is depicted in red, the Private region in green and the external core corona in blue. The black line denotes the vessel geometry used in the simulations. (b) Mesh used in the TECXY simulations. The magenta dashed lines indicate the actual geometry of the vessel. In both the figures the zoom of the grids at the OMP is shown in the lower right corners.*

3 Results

The results of the analysis are here presented both in terms of global quantities and profiles of the electron density, electron temperature and power density. In particular, the temperature and power profiles along the target represent a key point in the divertor design, since the former is linked to the sputtering and the latter to the allowable heat loads. The analysis has been carried out by considering two different parameters scans. The first one involves a variation of $n_{e,LCMS}$, while all other parameters are kept constant and equal in both numerical tools. The diffusion coefficients are kept constant in the radial direction and equal to $D_\perp = 0.32$ m^2/s, for the particle, and $\chi=0.12$ m^2/s, both for the ion and electron energy diffusion. The second scan has been performed by changing the diffusion coefficients and imposing $n_{e,LCMS}=3.0 \times 10^{19}$ m^{-3}, in order to match the $\lambda_{q,OMP}$ foreseen by the scaling with the poloidal gyro radius[6].

3.1 Density scan

The values of $n_{e,LCMS}$ in the density scan are constrained to 2.7, 3.0, 3.2, 3.4 and 3.5 x 10^{19} m^{-3}, which are compatible with a volume average density $\langle n \rangle = 7.7 \times 10^{19}$ m^{-3} predicted in the considered scenario[5].

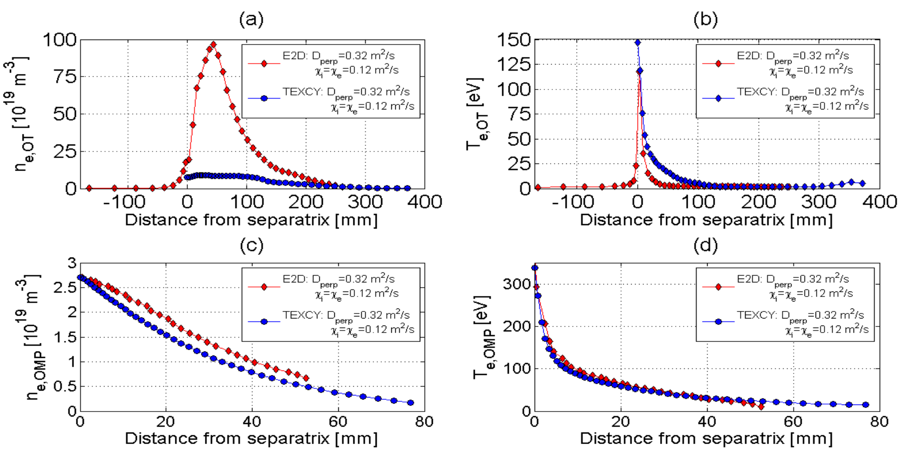

Figure 2. *Profiles of (a) the electron density and of (b) the electron temperature at the outer target as a function of the distance from the separatrix obtained with EDGE2D-EIRENE and TECXY (red diamonds and blue circles, respectively). The input parameters in the simulation are $n_{e,LCMS}$ = 2,7 x 10^{19} m^{-3}, P_{SOL} = 150 MW and diffusion coefficients $D_\perp$= 0.32 m^2/s and χ=0,12 m^2/s. The profiles of (c) n_e and (d) T_e at the OMP are also shown.*

Figures 2 shows the obtained profiles for the electron density (panel (a)) and temperature (panel (b)) at the outer target by using EDGE2D-EIRENE (red diamonds) and TECXY (blue circles). These profiles refer to the lowest $n_{e,LCMS}$=2,7 x 10^{19} m^{-3}. Both the codes provide a plasma in "well attached conditions" and temperature peaks above 100 eV, much higher than the values imposed by the sputtering limits. By varing the OMP density, the temperature peaks decrease by 42% in EDGE2D-EIRENE and by 48% in TECXY, reaching $T_{e,peak}$= 68 eV and $T_{e,peak}$= 83 eV, respectively. These values are clearly too high for the detached conditions, which must be reached in DEMO and totally unacceptable from an operational point of view.

However, it is interesting to compare the profiles obtained in the two calculations. While the OMP electron density (panel (c)) and temperature (panel (d)) are quite close, the target ones show large mismatches. In particular, the density peak at the outer target is one order of magnitude smaller in TECXY than in EDGE2D -EIRENE; as a consequence, considering the simlar upstream (at the OMP) plasma conditions and that in the predicted plasma regime the plasma pressure should preserve, a higher temperature peak is observed in TECXY. This behaviour is mainly related to the different descriptions of the neutral particles, which represent the sources in the balance equations[3][4]. In particular, the neutral density provided by EIRENE is two order of magnitude higher than that of the analytical model of TECXY; in addition, also the ionization is different in the two codes, being more spread in TECXY than in EDGE2D-EIRENE. These features can explain the differences in both the order of magnitude and the shape of the electron density along the target. It is important to remark that the difference in temperature should affect the parallel heat flux at the target. However, the obtained target pressure profiles also differ in the two codes and in particular in the proximity of the strike point; while in TECXY the pressure maintains approximately constant along the flux tube, in EDGE2D-EIRENE a slight decrease in the pressure is observed near the target due to the interaction with the neutral particles. As a consequence, a small difference in the target power density profile profiles is observed.

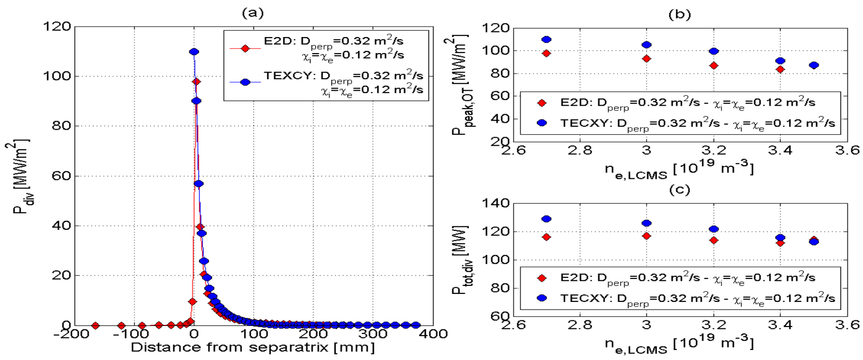

Figure 3:*(a)Profiles of power onto the outer divertor as a function of the distance from the separatrix obtained with EDGE2D-EIRENE and TECXY (red diamonds and blue circles respectively) by imposing* $n_{e,LCMS}$*=2.7 x* 10^{19} m^{-3}*. (b) Power peaks on the outer target and (c) total power reaching the inner and outer divertor plates as a function of the OMP electron density. The input parameters are* P_{SOL} *= 150 MW, diffusion coefficients* $D\perp$*= 0.32* m^2/s *and* χ*=0.12* m^2/s*.*

Therefore, in order to perform a benchmark of TECXY, a further test should involve the global quantities in terms of total power reaching the divertor plates. In addition, we also compare the power profiles and the power peaks onto the outer target. In attached conditions the power reaching the divertor plates is proportional to the product $nT^{3/2}$ and the radiation losses plays a minor role due to the high temperature in the SOL and in the divertor region. While the density and the temperature profiles on target obtained with the two codes are different, we have verified that the product $nT^{3/2}$ is similar yielding similar results in terms of power density onto the outer target, exept in the region close to the strike point. As can be seen in figure 3(a), the power profiles obtained by considering the lowest electron OMP density $n_{e,LCMS}$=2.7 x 10^{19} m^{-3} match very well. However, a higher peak value envisaged in TECXY. This feature is related to the different target profiles of the pressure and of the temperature due to the different neutral descriptions. In additon, one should also consider the differences in the geometry, i.e. the absence of the private region in TECXY that also leads to an increase in the power peak. The same trends are observed in whole density scan and the power peaks obtained in the two different calculations are depicted in figure 3(b). The peak values are quite close and slightly high in case of TECXY and shows the same decreasing trends as a function of the OMP density ($\propto$ 1/n). This result is also a proof of the negligible effect of the physical processes which causes the radiation losses to raise by increasing the OMP density. The similar predictions of the two codes can be also observed by considering the total power reaching the inner and outer divertor plates (figure 3(c)): the two codes predict a reduction of the power inversely proportional to the LFS equatorial plane density. In both codes, this reduction is mainly related to a slight increase of the hydrogen radiation, equal to 4 MW in EDGE2D-EIRENE (27%) and 10 MW(45%) in TECXY, which have comparable value although the difference in the neutral density at the target plate. Indeed, considering the temperature field, we observe that most of the hydrogen radiation occurs in the far SOL, where the temparature is low and where neutral densities obtained in the two calculations are similar. We should point out that a large part of the power loss mechanism are the atomic ionization and the charge exchange that remains approximately constant in the density scan. In addition, due to the simpler description of the neutral dynamics, TECXY provides a higher power onto the targets compared to EDGE2D-EIRENE, but less than the 10% in the lowest density scenario. By observing the value of the power loads in the highest density simulations and the high temperature field, it can be seen that less than 25% of the power entering the SOL is radiated, highlighting the minor role of radiation processes.

3.2 Diffusion coefficient scan

The effect of a variation of the diffusion coefficients has been studied in order to match the predicted $\lambda_{q,OMP}$= 3 mm obtained by means of the scaling with the poloidal gyro radius [6] and considering the reference parameters of the baseline scenario. Bearing in mind that both codes predict well attached plasma conditions, the OMP power decay lengths can be derived by considering that $P \propto n_e T_e^{3/2}$[7]. However, as previously noticed, the temperature and density profiles on the outer target differ in the two calculations mainly due to the two different neutral models; therefore, in order to have a more reliable tools for the TECXY benchmark in terms of power loads on the divertor plates able to well represent the effect of the transport properites of the plasma in both the numerical codes we decide to compare the results by considering $\lambda_{q,OMP}$ as scanning parameter. It is important to point out that the aim of this parameter study is to assess how the results in terms of target power loads are affected by the change in the diffusion coefficient rather than have a match of OMP power e-folding length in two calculations, since the two codes strongly differ in the physics model. The values of the diffusion coefficients have been set to $D_{\perp,1}$ = 0.22 m^2/s and χ_1 = 0,08 m^2/s, $D_{\perp,2}$ = 0.32 m^2/s and χ_2 = 0,12 m^2/s and $D_{\perp,3}$ = 0.42 m^2/s and χ_3 = 0,215 m^2/s in EDGE2D-EIRENE and to $D_{\perp,1}$ = 0.32 m^2/s and χ_1 = 0,12 m^2/s, $D_{\perp,2}$ = 0.42 m^2/s and χ_2 = 0,215 m^2/s, $D_{\perp,3}$ = 1 m^2/s and χ=0,5 m^2/s in TECXY. The corresponding power decay length are given by $\lambda_{q,OMP,1}$ = 4.5 mm, $\lambda_{q,OMP,2}$= 4.85 mm and $\lambda_{q,OMP,3}$ = 6 mm for EDGE2D-EIRENE and $\lambda_{q,OMP,1}$ = 3.3 mm, $\lambda_{q,OMP,2}$ = 5.1 mm, $\lambda_{q,OMP,3}$= 12.4 mm for TECXY. The results refer to a OMP density $n_{e,LCMS}$= 3 x 10^{19} m^{-3}. Figure 4 shows the total power (panel (a)) reaching both the inner and outer targets and the power peaks (panel (b)) onto the outer plate evaluated by means of EDGE2D-EIRENE (red diamonds) and TECXY (blue circles). The obtained values are comparable both in terms of power peaks and total power for similar value of the decay length. As expected, the power peaks increase by reducing the power decay length since most of the heat loads concentrate on a smaller and smaller area. In addition, the total power tends to get lower by increasing the heat diffusion, i.e. by increasing the $\lambda_{q,OMP}$, since there is an enhancing of the radiation losses processes. Finally, the predicted power reduction trends are similar in the two calculations, since a reduction proportional to $1/\lambda_{q,OMP}$ is observed.

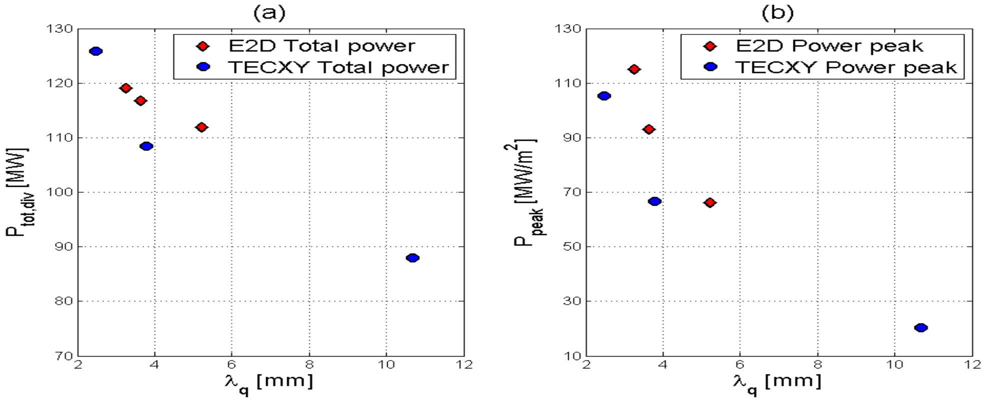

Figure 4. *(a)Total power onto the divertor plates and (b)power peaks as a function of the power e-folding length at the OMP obtained with EDGE2D-EIRENE (red diamonds)and TECXY (blue circles) by imposing $n_{e,LCMS}$= 3 x 10^{19} m^{-3} and P_{SOL} = 150 MW.*

4 Conclusions

In this paper we have presented a benchmark of the 2D edge code TECXY by comparing the results with the ones obtained with the more sophisticated code EDGE2D-EIRENE. A DEMO baseline scenario has been taken into account and we tackled the problem by assuming a simplified geometry and a pure Deuterium plasma. These hypotheses allow on one hand to speed up the simulations and on the other hand to get rid of numerical noises which yield to physically unacceptable results. The numerical models adopted in the two codes give rise to mismatches in terms of density, temperature and pressure target profiles, mainly raleted to the different description of the neutral dynamics. However, the obtained values in terms of total power reaching the divertor and power profiles onto the outer target are quite close since in the assumed plasma conditions both neutrals and radiation processes play a minor role. The results of two calculations are comparable in terms of absolute values both in case of a variation of the outboard equatorial separatrix density and of a variation of the diffusion coefficients. Furthermore, the foreseen power loads on the divertor targets and the power peaks on the outer one show the same dependence in both the parameters scans. Therefore, the coherence of the predictions of the two numerical codes confirm the reliability to use TECXY as a fast tool for a preliminary parameters scan, in well attached plasma, to explore the several potential solutions to take into account in order to mitigate the exhaust issue in DEMO.

Acknowledgments

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References

[1] G. Calabrò, et al., Nucl. Fusion 55 (2015) 083005

[2] R. Zagórski, H. Gerhauser, Phys. Scr. 70(Part 2/3) (2004) 173.

[3] S.I. Braginskii, Rev. Plasma Phys. V1, 205 (1965).

[4] R. Simonini, et al., Contrib. Plasma Phys. 34 (2/3) (1994) 368-373.

[5] G.Federici, et al., Fusion Eng. Des. 89(2014) 882.

[6] R. Goldston, Nucl. Fusion 52(2012) 013009.

[7] Stangeby, P. C., ‘‘The Plasma Boundary of Magnetic Fusion Devices’’, Plasma Physics Series, (IoP Publishing Bristol 2000)