Benchmarking Tokamak edge modelling codes

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Abstract

Tokamak edge modelling codes are in widespread use to interpret and understand existing experiments, and to make predictions for future machines. Little direct benchmarking has been done between the codes, and the users of the codes have tended to concentrate on different experimental machines. An important validation step is to compare the codes for identical scenarios. In this paper, two of the major edge codes, SOLPS (B2.5-Eirene) and EDGE2D-NIMBUS are benchmarked against each other. A set of boundary conditions, transport coefficients, etc. for a JET plasma were chosen, and the two codes were run on the same grid. Initially, large differences were seen in the resulting plasmas. These differences were traced to differing physics assumptions with respect to the parallel heat flux limits. Once these were switched off in SOLPS, or implemented and switched on in EDGE2D-NIMBUS, the remaining differences were small.
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1. Introduction

Three codes are in widespread use for simulating the edge regions of present tokamaks, and for predicting the performance of future machines. To-date, no detailed benchmarking of the full codes on realistic cases has been performed. Since two of these codes (EDGE2D-NIMBUS and SOLPS, described in Section 2) are in widespread use at JET, it seemed an excellent opportunity to benchmark at least these two codes against each other.

In order to minimise the differences between the two codes, the same grid based on a JET high clearance discharge (# 50401) was used by both codes, generated by the JET GRID2D [1] modified to produce the differing grid information required by the two codes.

In order to facilitate the comparison between the two codes, a version of the EDGE2D-NIMBUS backend was produced for SOLPS, which saved the output from a subset of the variables in a format that could then be processed by the same tools that are used for EDGE2D-NIMBUS. This proved very useful in analysing the outputs from the codes.

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Section 2 discusses the two codes. Following that, the present status of the comparison for the pure deuterium case without drifts is presented. A section discussing some of the issues addressed follows (including a brief mention of the current status of the drift comparison), and the paper concludes with a summary, some conclusions and observations, and an indication of where the work will go next.

2. The two codes

EDGE2D-NIMBUS [1–4] consists of a fluid plasma code EDGE2D coupled to a Monte-Carlo neutrals code, NIMBUS.

SOLPS [5–8] consists of a fluid code B2 [9–14], coupled to a Monte-Carlo neutrals code Eirene [15,6,16].

B2 has gone through a number of development iterations, starting with a formulation without drifts and the assumption of zero parallel current [9,10] (sometimes referred to as B2-SOLPS4.0, and the basis of most of the present ITER calculations), and then extended to include drifts [11], and then with further improvements to the drift equations [12–14] (sometimes referred to as B2.5 or as B2-SOLPS5.0). The latest version solves implicitly for each equation in turn, where there are equations for the density of each charge state; the parallel momentum of each charge state and for the sum over all charge states; the electron and ion energy equations, and for their sum; and for the potential. It is usually used in a mode where the code cycles through all of these equations a number of times, before moving onto the next time-step. A 5-point discretisation of the equations is used (except that a 7-point solver has been implemented for treating fourth order effects in the radial viscosity). All the primary quantities (densities, parallel velocities, temperatures and the potential) are at cell centres, and a finite volume discretisation is used. (Earlier versions of the code used a staggered grid for the velocities.) The code includes a model for fluid neutrals, but is used here mostly in the form where it is coupled to the Monte-Carlo code (EIRENE) to provide the sources and sinks of particles, momentum and energy arising from the neutrals (in this event, B2 still solves for the fluid neutrals, but with sources scaled by a factor usually set equal to 1×10^{-10}). When run without drifts, the code can usually take time-steps of 1×10^{-4} s or larger, but when drifts are activated the time-step often has to be significantly smaller.

EDGE2D employs a 9-point stencil on which very similar equations as B2-SOLPS5.0 are solved, with the densities and temperatures at cell centres and the parallel velocity defined at cell faces. Each equation is solved in turn and the equations are cycled through until convergence is achieved. The sources arising from neutrals are reconstructed from the neutral density background provided by the Monte-Carlo code (NIMBUS), which, in contrast to the usual SOLPS procedure of being called on each time-step, is only called at pre-determined times or when the plasma has changed by more than a specified amount. EDGE2D uses an adaptive time-step.

SOLPS has the advantage of flexibility, being installed at a large number of sites on a variety of different types of computers. EDGE2D-NIMBUS is tied quite strongly to the JET computing infrastructure, and, perhaps as a consequence, is somewhat easier to use. The choice of using the background neutral profiles instead of the sources directly, also means that EDGE2D-NIMBUS is often 'faster'.

The two codes solve very similar sets of equations and should produce similar results when simulating a plasma on the same grid, with the same sources and sinks, and boundary conditions.

3. Pure deuterium simulations

Three cases were initially foreseen, with separatrix densities of 5×10^{18}, 1×10^{19} and 1.5×10^{19} m^{-3} to be achieved by feedback control of a gas puff, and a constant heating power of 2.5 MW equally split between the electrons and the ions. The anomalous radial transport diffusivity was chosen to be 0.5 m^2 s^{-1}, and the anomalous radial electron and ion heat diffusivities to both be 0.7 m^2 s^{-1}.

The final result for the 5×10^{18} m^{-3} and 1×10^{19} m^{-3} cases are shown in Fig. 1, where the electron density, and electron and ion temperatures are shown at the outer midplane as well as at the outer target. Despite the differences in the formulations of the equations, and of their method of solution, the results are very similar – particularly at the outer divertor which depends in a highly non-linear way on the upstream parameters.

4. The path to the match

The initial comparison between the two codes was not nearly as encouraging, with strong differences seen in, for example, the target densities and poloidal ion temperature close to the separatrix, Fig. 2.

These preliminary comparisons were also done with the SOLPS fluid model, but this option was dropped for most of the rest of the comparisons. The comparison of a kinetic model and a fluid model has been addressed recently elsewhere [17].

The strong difference in the poloidal ion temperature profile was traced to a difference in the choice of parallel heat flux limiters (EDGE2D-NIMBUS was being run without, and SOLPS with flux-limiters), in combination
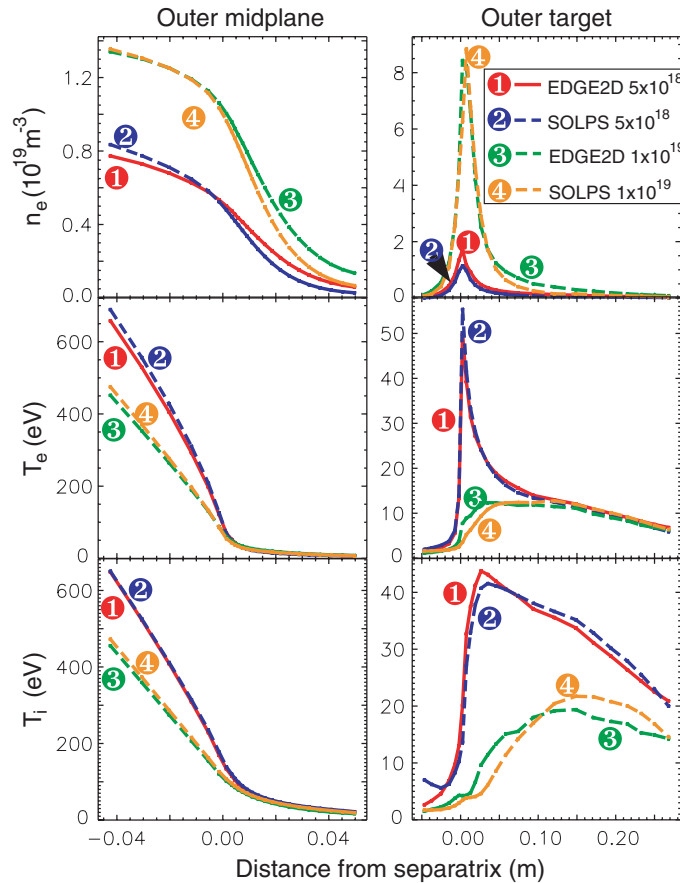
Fig. 1. Outer midplane (left) and outer target (right) profiles of the electron density, electron temperature and ion temperature (top to bottom), each for EDGE2D-NIMBUS and SOLPS with kinetic neutrals (B2-Eirene), for the 5×10^{18} and $1 \times 10^{19} \mathrm{m}^{-3}$ separatrix density cases. Parallel ion and electron heat flux limiters were disabled, and a Mach equals one sheath boundary condition was used.

with a localised gas-puff for the SOLPS case in contrast to a distributed gas puff in EDGE2D-NIMBUS. Another difference that was quickly identified was that SOLPS implemented a Mach greater than one target boundary condition, whereas EDGE2D-NIMBUS had forced Mach equals one.

Other differences were identified, and found to have only a small effect – examples include differing pumping models (investigated by scanning the pump 'strength' in SOLPS), and the effect of the 9-point stencil in EDGE2D-NIMBUS (investigated by comparing EDGE2D-NIMBUS results with a 5- and 9-point stencil) – or were corrected. (Examples of the latter include the implementation in SOLPS of the 'recycling' of neutrals at the core boundary into ions, and the removal of an additional particle source at the core boundary in EDGE2D-NIMBUS.)

The runs shown earlier, Fig. 1 were done with the flux limiters switched off and the Mach number forced to one at the target.

The benchmarking of the pure deuterium drift cases has started. Both codes are somewhat more 'fragile' with drifts switched on, but the comparison is encouraging. The target profiles do not show quite the same agreement as the no-drift case. Fig. 3 shows the poloidal profile of the parallel velocity for the 5×10^{18} and $1 \times 10^{19} \mathrm{m}^{-3}$ separatrix density cases, respectively. Both codes show the expected Pfirsch-Schlüter effects on the velocity.

This work is being actively pursued, as is the comparison of the actual drift equations being solved in the two codes.

5. Summary, conclusions, and future plans

The initial large differences in the simulations from EDGE2D-NIMBUS and SOLPS (B2-EIRENE) were tracked down to differing choices in the parallel flux limiters, target Mach boundary condition and the distribu-
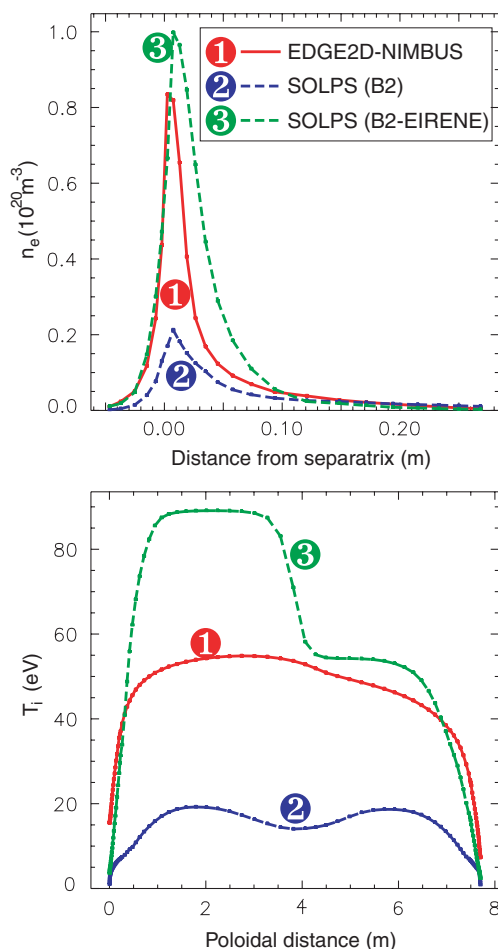
Fig. 2. Outer target profiles of the electron density (top) and poloidal profile of the ion temperature (bottom) for EDGE2D-NIMBUS, SOLPS with fluid neutrals (B2), and SOLPS with kinetic neutrals (B2-Eirene), for the initial comparison between the codes.

Fig. 3. Poloidal profile of the parallel velocity, for the 5×10^{18} (top) and $1 \times 10^{19} \, \mathrm{m}^{-3}$ (bottom) separatrix density cases, each for EDGE2D-NIMBUS and SOLPS with kinetic neutrals (B2-Eirene), for forward and reversed field cases.

tion of the gas puff used to control the separatrix density. Once these effects were corrected for, the agreement for the pure deuterium, no drifts cases were very satisfactory.

The agreement for the cases with drifts is not quite so good, and this will be pursued. Once this is completed, this benchmarking activity will be extended to the cases with impurities (with and without drifts), and perhaps to include a third code, UEDGE [18].

The strong effect of the ion parallel heat flux limiter points to the importance of doing more kinetic work in this area, as well as trying to verify the choice of flux limiter by careful analysis of experiments where both good upstream and downstream data are available. In the meantime, a sensitivity analysis should be performed for predictive runs to test the role the flux limiters might play in the particular scenario.
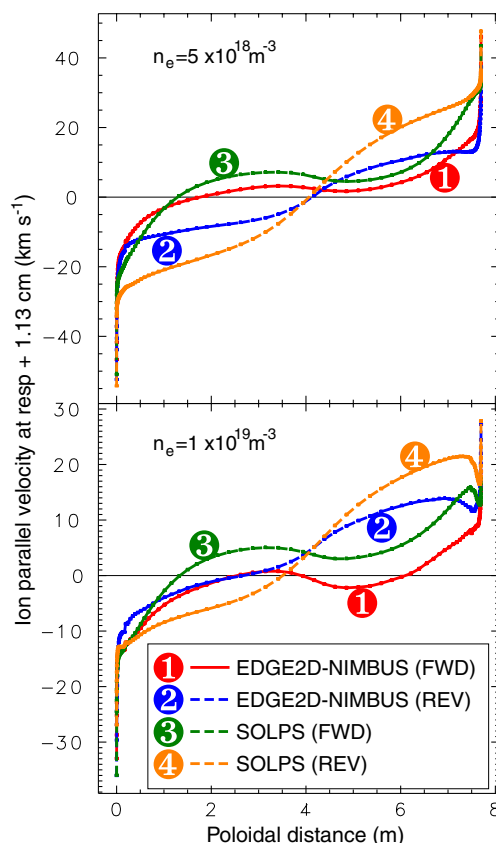
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