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Benchmarking the PROCESS systems code with the SONIC divertor code

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In a demonstration (DEMO) reactor, reduction of the large heat load on the divertor target is a key criterion for operation. Systems modelling is used to design entire fusion power plants and therefore has to be able to appropriately capture the divertor challenge. Therefore, it is important to validate these models against comprehensive SOL-divertor simulation codes and experiments. A one dimensional divertor model in PROCESS was investigated, compared to results of 2-D SONIC simulation under the detachment condition. The comparison shows how the 1-D divertor model handles the power loss mechanisms from the outboard mid-plane to the outer divertor target for a DEMO-like condition. Results show good agreement on the calculated value of the total power crossing the separatrix (< 5% difference) and the total impurity radiation power P_{imp} (< 10% difference). However, the 1-D profiles show differences in density and temperature at the upstream of the target (< 10m of connection length to target, corresponding to several 10cm in the poloidal length). One reason for this difference is that the 2-D model calculates impurity transport, which produces a variable impurity fraction along the connection length in the divertor, while the 1-D model uses a single averaged value. The SONIC code also considers physical processes not covered in the 1-D model, such as radial transport in the SOL and divertor region. The integrated values relevant for systems codes showed reasonable agreement while the profiles showed inconsistencies.

Keywords: Nuclear Fusion; Systems Codes; DEMO; Divertor; SOL; PROCESS; SONIC

1 Introduction

In a nuclear fusion demonstration (DEMO) power plant reduction of the large heat load on the divertor target is a key criterion for a viable and consistent design. The power exhaust in the divertor impacts both the operational performance of the machine and the lifetime of the divertor components.

Systems codes form an integral part of the EUROfusion DEMO research programme [1]. The goals of the EUROfusion DEMO programme are for a DEMO reactor that achieves electrical power output (hundreds of MW_e) for long pulse duration (> 2 hrs) [2]. While also demonstrating the technology required for a commercial power station. Reduction of the heat load at the target appropriate for the engineering criterion, such as less the 10 MW/m^2, is a key requirement of a DEMO reactor.

Systems codes are used to analyse large parameter spaces for optimising design solutions that are self-consistent. The models in systems codes are often 0-D and 1-D simplified calculations with the aim of capturing the physics and engineering processes while being computationally fast. Systems modelling is used to design entire fusion power plants and therefore has to be able to provide the divertor heat load and its trade-offs with the other plant systems.

The systems code used for the work reported on here is the UKAEA systems code PROCESS [3, 4]. PROCESS is systems code used to create EUROfusion DEMO (EU-DEMO) baseline designs [5] as well as power plant scoping studies and uncertainty quantification e.g. [6–9]. This work details a comparison of a 1-D SOL and divertor model in the systems code PROCESS with the 2-D divertor simulation code SONIC [10, 11]. The comparison shows how the systems code 1-D divertor model handles the power loss mechanisms from the outboard mid-plane to the outer divertor target for a Japanese DEMO (JA-DEMO) example design [11, 12]. The goal of a divertor model in a systems code is to enforce engineering limits, to determine detachment conditions and to calculate the heat load.

In this paper, we describe the two SOL/divertor models used for the comparison as well as the JA-DEMO input parameters in Section 2, the results from the comparison are outlined in Section 3 and the work is summarised in Section 4.

2 PROCESS Divertor Model and SONIC Code

For reactor design work a number of key divertor protection parameters have been used to try an account for the allowable power going to the target. One commonly used divertor power handling parameter is given below [13, 14].

$$P_{sep}/R_0 <\sim p_{ref} \text{ MWm}^{-1} \quad (1)$$

where P_{sep} is the power crossing the plasma separatrix (MW), R_0 is the plasma major radius (m) and p_{ref} is determined by the power exhaust concepts (17 and 29 MWm^{-1} is defined

Parameter	Value	Units
Plasma temperature at target	1.5	eV
Target total power load ($q_{\|\|}$)	1.718×10^{6}	W/m^2
Connection length from outboard mid-plane to target	166.5	m
Plasma current	13.5	MA
Plasma major radius	8.50	m
Plasma minor radius	2.43	m
Toroidal field on axis	5.94	T
Safety factor (95%)	4.1	-
Distance of flux tube from separatrix at outboard mid-plane	0.002	m
Distance from separatrix at target	0.022	m
Radial position of outer strike point	8.16	m
Target angle	25	degrees
Impurity fraction in SOL (Argon only)	6×10^{-3}	-
Fraction of total separatrix power going towards outboard target	0.44	-

Table 1: *Table of PROCESS inputs parameters for the comparison between PROCESS and SONIC. Note that the temperature of the plasma at the target and the total target power load are inputs in PROCESS. The user can set them to be bounded free parameters, but not in this case.*

for EU and JA DEMO concepts, respectively) [15]. One can also use a limit linked to the peak heat flux in the SOL when the plasma re-attaches to the divertor based on [16]. This protection constraint is defined in PROCESS as:

$$\frac{P_{sep}B_T}{qAR_0} < \left.\frac{P_{sep}B_T}{qAR_0}\right|_{REF} \tag{2}$$

where B_T is the on-axis toroidal field, q is the edge safety factor and A is the aspect ratio ($1/\varepsilon$). Typical reference limits for EU-DEMO are ~ 9 MW.Tm^{-1}. The implementation of a 1-D SOL and divertor model in PROCESS allows the code to capture the divertor conditions in more detail than using these 0-D protection constraints.

2.1 PROCESS Divertor Model

The 1-D SOL and divertor model in PROCESS contains a set of ordinary differential equations derived from [17] to describe the physical processes in the SOL. The physical processes that are included in the model are:

- Convected heat flux
- Thermal conduction
- Momentum conservation
- Radiation by D, T and impurities
- Charge exchange
- Electron impact ionization
- Surface recombination
- Assumes all particles striking target are recycled (i.e. no pumping)

The model also assumes that all particles striking target are recycled (i.e. no pumping). The flux tube used in the model begins at the edge of the target sheath and ends at the plasma outboard mid-plane. The PROCESS code takes a number of input parameters 1, and constraints defined by the user. Importantly, the parallel heat flux on the target $q_{||}$ and the target temperature T_{target} are bounded free parameters. This allows the user to constrain both values to ensure the engineering and physics design is valid (i.e. what is the divertor heat flux and plasma detachment). The model then calculates backwards from the target to the outboard mid-plane to determine what upstream parameters produce the prescribed target conditions. Normally this is in the form of the code enforcing consistency between the calculated upstream P_{sep} from the 1-D model and the P_{sep} calculated by the core physics model (e.g. alpha power minus radiation losses).

2.2 SONIC Simulation

The SONIC modelling software is a 2-D divertor and SOL simulation suite that consists of a number of codes that model different physical aspects of the divertor and SOL. SONIC consists of three transport codes:

- IMPMC – a 2-D Monte Carlo impurity code
- SOLDOR – a 2-D plasma fluid code for ion and electron components
- NEUT2D – a 2-D Monte Carlo neutral transport code

The code calculates the properties of the divertor and SOL plasmas for a 2-D geometry and therefore it calculates

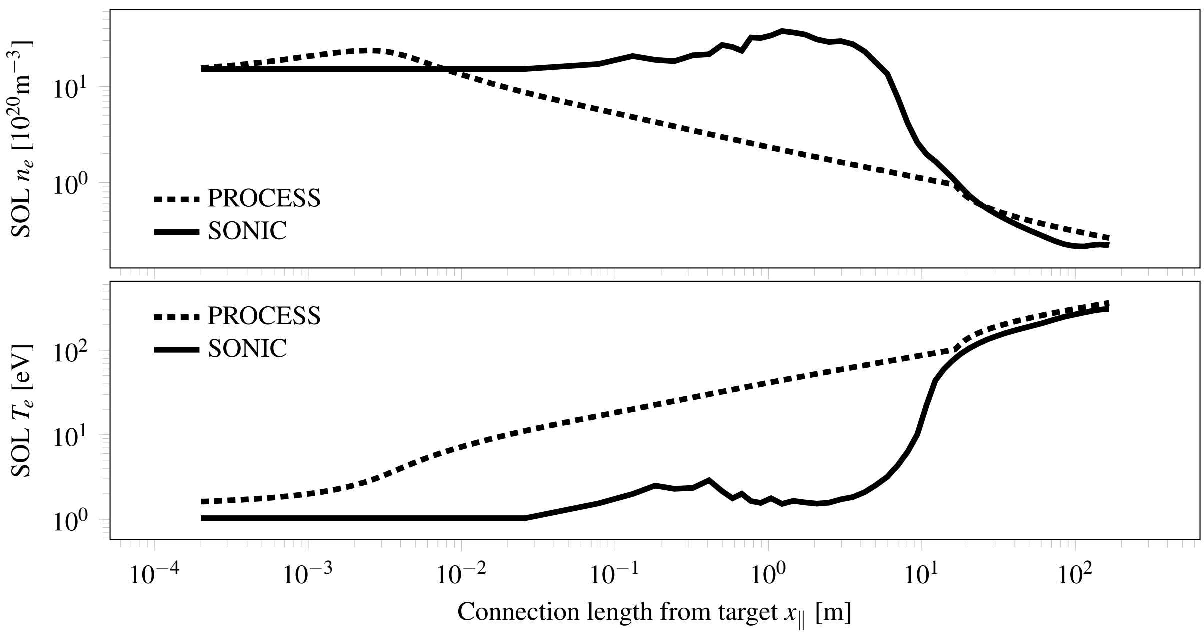

Figure 1: *Top: SOL plasma electron density along the connection length (target=0m, outboard midplane=166m) for PROCESS and SONIC. Bottom: SOL plasma temperature as a fraction of the electron density along the connection length.*

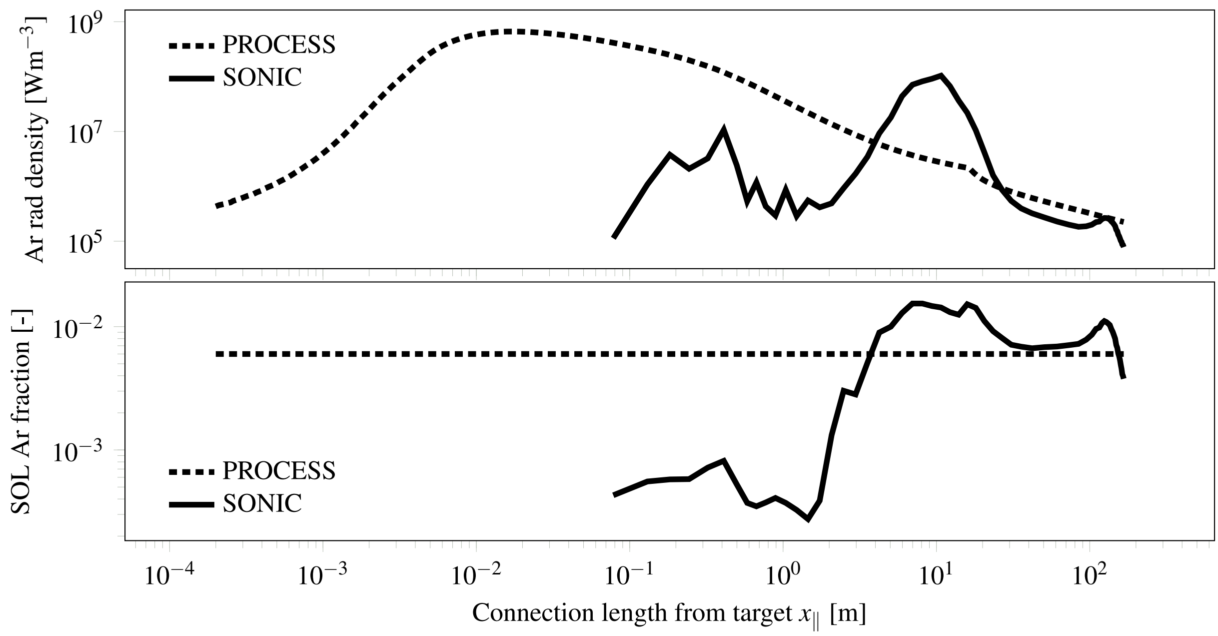

Figure 2: *Top: SOL argon impurity radiation density along the connection length (target=0m, outboard midplane=166m) for PROCESS and SONIC. Bottom: SOL argon impurity as a fraction of the electron density along the connection length.*

over multiple flux tubes, from the separatrix to $\sim$3 cm outer SOL. Diffusion coefficients of $\chi_i = \chi_e = 1\text{m}^2\text{s}^{-1}$ and $D = 0.3\text{m}^2\text{s}^{-1}$ are the same in the ITER simulation, The drift transport across the flux tubes is not included. For this comparison a single flux tube was chosen that is the same radial distance from the separatrix at the outboard mid-plane as PROCESS is used (2mm). The integrated quantities for the comparison, such as the total impurity radiation power in the whole outer divertor, use quantities from SONIC that include all of the outer divertor flux tubes. As SONIC captures the physics process across multiple flux tubes it can simulate the radial distribution of the detachment, i.e. “full” or “partial”, unlike the 1-D model.

In the Japanese DEMO case used in the comparison [11], the plasma is attached radially away from the strike point along the target (> 12 cm), and the electron temperature at the target increases radially from 1-2 eV in the detached area to 20-30 eV in the attached area. The peak heat load appears in the attached area. For the purpose of power handling, this comparison will show appearance of the detachment near the strike point, as most of the power is transported near the separatrix, where the power falls off in DEMO size machines is normally of the order 2mm [16]. Comparison of the peak heat load in the outer flux tube (mid-plane radius of $\sim$1 cm) will be future work.

2.3 Inputs

For the comparison, an output of SONIC run for a Japanese DEMO design [11] was provided. The data contained the SONIC output for all of the flux tubes in the 2-D equilibrium. The flux tube that matched the single flux tube modelled in PROCESS was used. This was the flux tube that was just outside the separatrix and 2mm in radial thickness at the outboard mid-plane. The input data for PROCESS is listed in Table 1.

3 Results

Figure 1 shows distributions of the plasma temperature (T_e) and density (n_e) along the flux tube, where left and right ends correspond to the target and outboard mid-plane, respectively. Values of T_e and n_e by PROCESS and SONIC are similar at the both ends. Two profiles by PROCESS and SONIC show similar values in the upstream part of the X-point, and different behavior below the X-point. This is due to the fact that SONIC includes physical processes that are not incorporated in the System code; SONIC simulates impurity transport along the flux tube as well as diffusion process, whereas PROCESS uses a fixed value of the impurity fraction (see Figure 2).

It is noted that SONIC simulation results including the values of T_e and n_e are still not consistent with those of the plasma detachment in experiments, in particular, significant reduction of the plasma density and momentum. Improvement of the plasma detachment modelling will be necessary. The 1-D model can have multiple impurities in the vessel (e.g. xenon in the plasma core and argon and small amounts of tungsten in the SOL). For this comparison only argon in the SOL is considered. In reality there will be a mixture of elements present in the core and SOL depending on the seeded impurity choice and first wall/divertor material choice.

Figure 2 shows profiles of the argon impurity radiation power density and the impurity fraction along the flux tube. Note that values of impurity parameters at the sheath entrance (corresponding to the left end mesh), is not shown, and values at the left end correspond to 3 mm above the target. For the SONIC results, the Ar radiation power density is significantly increased at the middle of the divertor leg due to increase in Ar density, n_e and the Ar fraction. Impurity transport, i.e. balance of the thermal force and friction force on the impurity, and thermal instability of the background plasma produce the increase of the peaking of the plasma and impurity densities. Thus, T_e is reduced to the detached plasma level, i.e. 1-2 eV in the downstream of the peak. On the other hand, T_e and n_e in the PROCESS 1-D model are gradually decreased from the X-point to the target. Argon radiation power density is increased gradually and has a peak just above the target.

The total impurity radiation integrated along the flux tube for outer divertor in reasonable agreement, provided that we give an value of the impurity concentration comparable to that in the core plasma, i.e. 0.6% (see Table 2). It is worth noting that the SONIC profile shown in Figures 1 and 2 are for a single flux tube out of a number, whereas PROCESS is using the single flux tube to provide results for the entire outer divertor.

The calculated power crossing the separatrix P_{sep} is in reasonable agreement as well as the plasma parameters such as n_e and T_e at the target and mid-plane, once we give an reasonable value of the impurity concentration, although the plasma distributions in the divertor is not accurately simulated by the 1-D code without the impurity transport.

4 Conclusions

One dimensional divertor model in PROCESS was investigated, compared to results of SONIC simulation under the partial detachment condition. Comparison of the plasma parameters along the flux tube near the separatrix showed agreement on the total power crossing the separatrix and rough agreement on the upstream mid-plane values of the SOL density and temperature, provided that we gave an value of the impurity concentration comparable to that in the core plasma.

Good agreement of the total outer divertor impurity radiation power was also seen. However, differences of the plasma and impurity profiles were seen along the divertor leg, since the SONIC code simulated numbers of physical processes not accounted for in simple 1-D model with a fixed value of the impurity fraction. User inputs are used to constrain the boundary conditions such as the target SOL temperature and the allowable maximum heat load on the target. As a result, we found that the simple divertor model in PROCESS will predict a formation of the divertor detachment

Parameter	PROCESS	SONIC	Units
Total power crossing the plasma separatrix	241	258	MW
SOL electron density at outboard target	122	195	$10^{19}m^{-3}$
SOL electron temperature at outboard mid-plane	364	303	eV
SOL electron density at outboard mid-plane	2.6	2.2	$10^{19}m^{-3}$
Total Argon impurity radiation (outer divertor)	72.6	79	MW

Table 2: *Table of PROCESS and SONIC output parameters for the comparison.*

simulated by 2-D divertor code.

A database of the parameter scan by the 2-D simulation will be required for the 1-D model to determine robust selection of the detachment plasma parameters. At the same time, additional 1-D modelling will be developed to evaluate the peak heat load in the attached plasma area. A comparison of the 1-D model to the European 2-D SOL and divertor modelling code SOLPS [18] for EU-DEMO would also be beneficial and is currently planned.

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