Impurity Accumulation and Particle Behaviour with the Presence of Transport Barriers in ITER and DEMO

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In this work, impurity accumulation, plasma particle behaviour, plasma profiles and fusion performance of ITER- and DEMOs-like plasmas in the presence of both edge transport barrier (ETB) and internal transport barrier (ITB) are investigated using a 1.5D BALDUR integrated predictive modelling code. For all simulations, the core transport is computed by a combination of a neoclassical transport model called NCLASS and an anomalous transport model called Mixed Bohm/gyro-Bohm (Mixed B/gB). Mixed B/gB transport model includes ITB formation through the assumption that ITB is formed by the suppression of anomalous transport due to to the ω_{ExB} flow shear and magnetic shear. The details of how the model computes transport coefficients can be seen in Ref. [1]. The transport reduction occurs when the shearing rate $\omega_{ExB} = \frac{(RB_\theta)^2}{B}\frac{\partial(E_r/RB_\theta)}{\partial\psi}$ surpasses the instability growth rate. The radial electric field $E_r = \frac{1}{Zen_i}\frac{\partial p_i}{\partial r} - v_\theta B_\phi + v_\phi B_\theta$ is calculated from the force balance equation of plasma species. The pressure gradient term is computed self-consistently, the poloidal flow term is calculated from NCLASS module and the toroidal rotation term is calculated based on the neoclassical toroidal viscosity (NTV) model. The NTV model is based on the idea that the offset toroidal rotation can be produced by the NTV dissipation, which is caused by symmetry breaking via application of a non-axisymmetric field [2, 3]. The toroidal velocity can be calculated as: $v_\phi = \frac{1}{eZB_\theta}\left(3.54 - \frac{r}{R}K_1\right)\frac{dT_i}{dr}$, which implies that the offset velocity is driven by the temperature gradient. The details of how the model was implemented into BALDUR can be seen in Ref. [4]. The boundary condition of the simulations is taken to be at the top of pedestal, where the pedestal temperature is calculated using the pedestal model based on the magnetic and flow shear stabilization width model combining with the ballooning mode instability used to set the pressure gradient limits [5].

ITER Simulations

In this work, standard type I ELMy *H*-mode ITER simulations are investigated using BALDUR. The design parameters used in simulations are major radius *R* of 6.2 m, minor radius *a* of 2.0 m, plasma current I_p of 15.0 MA, toroidal field of 5.3 T, elongation κ of 1.7, triangularity δ of 0.33, RF heating of 7.0 MW, NBI heating of 33.0 MW and line average density n_l of 1.0×10^{20} m^{-3}. Figure 1 illustrates simulation results of ITER-like plasma. The left panels show central ion temperature (top) and central electron temperature (bottom). It can be seen that initially the central temperatures are slowly increasing until around 100 seconds where the plasma has reach quasi-stationary state. This is because the plasma current has been designed to slowly increase to the designated value. At quasi-stationary state, the temperatures are fluctuated around 10% of average values. This is due to sawtooth instability. In particular, the ion temperature fluctuates around 40 keV and electron temperature around 35 keV.

The right panels of figures 1 illustrates profiles of ion temperature (T_i), electron temperature (T_e), deuterium density (n_D), tritium density (n_T), beryllium density (n_{BE}), and helium density (n_{HE}) as a function of normalized minor radius *r/a* at arbitrary time during quasi-stationary state (2,900 seconds). Obviously, the plasma temperatures are highest at plasma center and decrease toward the edge. It appears that a fairly wide ITB are formed from *r/a* = 0.2 to 0.6. Moreover, deuterium and tritium densities have roughly the similar profiles, which is quite flat, just above 4×10^{19} m^{-3}, with strong gradient near the edge. Interestingly, Beryllium is found to be able to penetrate into the plasma core, though its profile is rather flat. Whereas, helium is found to accumulate in the plasma core so it is also affected by ITB formation.

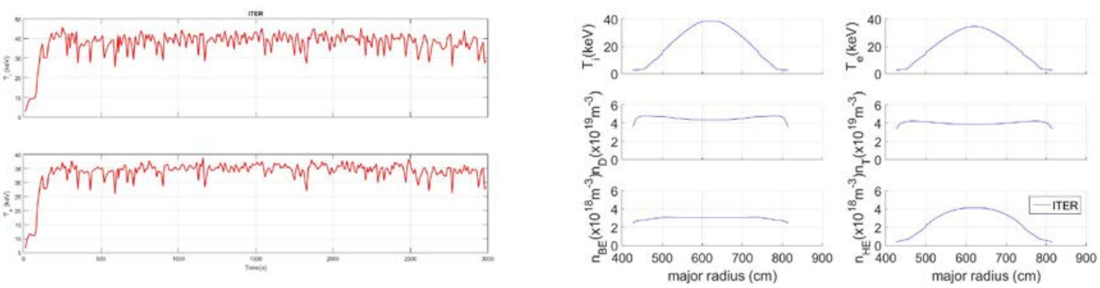

Figure 1: Time evolution of temperatures at plasma center (left) and plasma profiles during quasi-stationary state (right) for ITER

DEMO Simulations

Two different DEMO projects are investigated in this work; Korean DEMO (K-DEMO) and Japanese DEMO. The design parameters of K-DEMO used in simulations are R = 6.8 m, minor a = 2.1 m, I_p = 12 MA, toroidal field of 7.4 T, κ = 2.0, and δ = 0.625 [6]. For Japanese DEMO, three different models are investigated; model A, model B and model C. The design parameters used in simulations can be seen in Ref. [7]. Example of DEMO simulations are shown in figure 2, which is the simulation results from K-DEMO.

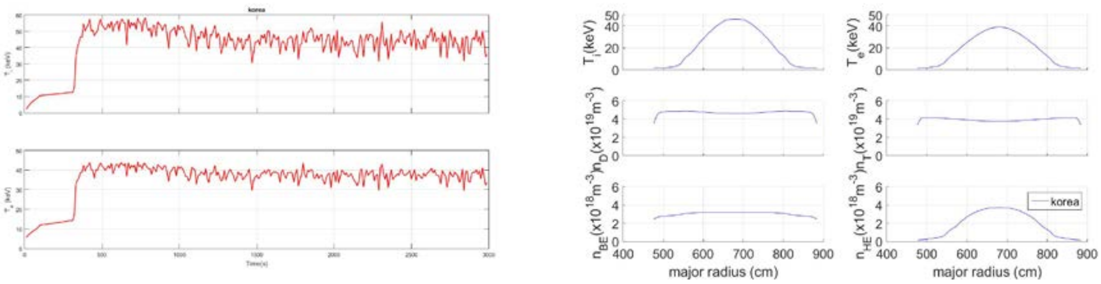

Figure 2: Time evolution of temperatures at plasma center (left) and plasma profiles during quasi-stationary state (right) for K-DEMO

Figure 2 shows that the plasma has reached quasi-stationary state at around 400 seconds. where the plasma has reach quasi-stationary state. The ion temperature fluctuates around 45 keV and electron temperature around 40 keV. Furthermore, in K-DEMO a wide ITB formation can be found from r/a = 0.1 to 0.5. It also appears that deuterium, tritium, and beryllium densities profiles are relatively flat, with a sharp gradient at plasma edge for deuterium and tritium. Similarly, helium is also accumulated inside the ITB. Japanese DEMO models A, B and C simulation results also yield similar profiles except that there exists a more local ITB but the gradients inside the ITB is quite large. This can be seen in figure 3, which shows results from Japanese DEMO model C.

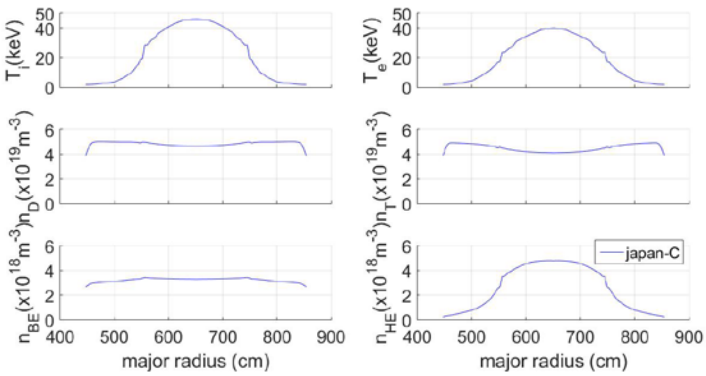

Figure 3: Plasma profiles during quasi-stationary state for Japanese DEMO model C

Table 1: Comparison of simulation results from ITER and DEMOs (average values during quasi-stationary state).

Parameters	ITER	K-DEMO	J-DEMO A	J-DEMO B	J-DEMO C
$T_{i,0}$ (keV)	37.99	43.42	38.66	44.43	51.00
$T_{e,0}$ (keV)	34.15	37.27	34.45	37.86	41.35
W_{TOT} (MW)	426	441	404	461	534
P_{AUX} (MW)	40	40	63	59	54
P_{α}(MW)	133	153	151	187	176
Q	16.63	19.13	11.98	15.85	16.30
$n_{BE,0}$ (10^{18} m^{-3})	3.03	3.12	3.90	4.01	3.37
$n_{HE,0}$ (10^{18} m^{-3})	4.13	3.59	4.25	5.16	5.02

Table 1 summarizes the performance of each tokamak in this work. Overall, Japanese DEMO C yields the highest temperatures at plasma center, while ITER yields the lowest. The same machine also yields highest fusion power, but Japanese DEMO B yields the most alpha heating power. On the other hand, Japanese DEMO A yields lowest fusion power and ITER yields the least alpha heating power. Nevertheless, considering for fusion performance is best through the fusion Q, which has highest value for K-DEMO. Japanese DEMO A is the worst in term of fusion performance comparison. For impurity accumulation, it is found from simulations that beryllium concentration at plasma center is highest in Japanese DEMO B and lowest in ITER. Helium accumulates the highest in Japanese DEMO B and the lowest in K-DEMO.

Acknowledgments

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