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Development of a systems analysis code for fusion DEMO reactor design
核融合原型炉設計に向けたシステムコードの開発

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We report recent efforts towards improvement of a systems analysis code TPC for DEMO reactor design. As a first step of such improvement, the calculated results from the two systems codes, TPC and PROCESS, are compared. The main result is that most of the calculation outputs from the two codes are in good agreement while the radiation power losses calculated are somewhat different between the two codes because of difference in the impurity radiation and spatial profile models. Some issues for development/improvement of systems codes relevant to DEMO plasma physics are discussed.

1. Introduction

For fusion research directed at electricity generation in the ITER and post-ITER era, it is necessary to define development targets toward DEMO including plasma parameters and engineering requirements such as magnetic field and divertor heat flux. These parameters and requirements are strongly dependent on design concepts such as whether the operation is steady state or pulsed, the target net electric power, assumed advancement in physics parameters and so on. Moreover, such parameters and requirements are determined self-consistently. In general as a first step of systematic reactor design, systems analysis is performed in order to estimate reactor operation windows with engineering constraints (e.g. [1]). More detailed physics and engineering analyses are performed as following steps.

Systems analysis codes consists of a large number of algebraic formulae representing plasma physics phenomena and fusion engineering components. Most of these formulae are coupled with each other. Although many systems analysis codes have been developed and applied to ITER and commercial fusion reactor designs so far, there are some issues for fusion DEMO reactor design.

1) Benchmarking existing systems codes and comparison of the calculation results from the codes are lacked. Some physics and engineering models, approximations and solution methods are different among existing systems codes, so that there are often disagreement in calculation results from these codes and it is difficult to find root causes of such disagreement because systems analysis codes consists of a large number of algebraic formulae.
2) It is still unclear weather existing physics models used in the existing systems codes can be applicable to a fusion reactor since most of physics models in the systems codes are based on ITER Physics Guidelines [2].

Purposes of our work are to establish physics and engineering basis on DEMO design and to develop (or improve) a DEMO systems analysis code. For these purposes it is important to resolve the above issues.

2. Benchmark of the systems codes

The systems code TPC is being improved in Japan Atomic Energy Agency (JAEA) [3]. This code was used for analysis of ITER operation points [4]. To resolve the former issue described in Section 1, we compared calculation results from the two systems codes, TPC and PROCESS [5]. PROCESS is being developed in Culham Centre for Fusion Energy (CCFE) and was benchmarked against ITER-TAC costs. Comparison showed good agreement in general [6]. In this presentation we focus on comparison of the calculation results from the modules relevant to plasma physics in TPC and PROCESS. Comparison of the modules of fusion engineering and cost evaluation will be reported elsewhere.

The plasma physics calculation modules consist of two balance equations: the plasma power and current balance equations. Each term in the balance equations is evaluated based on the ITER Physics Design Guidelines [2]. In the benchmark reported here we used Nevins formula [7] for the bootstrap current fraction. The fitting formula proposed by Bosch and Hale [8] was used for the D-T fusion reaction rate parameter $<\sigma v>_{DT}$. The ITER IPB98(y,2) scaling [9] was used for the global energy confinement time. The plasma temperature and density profiles were assumed to be in a parabolic form characterized by the shaping factors α_T and α_n, respectively.

The benchmark model parameters are summarized in Table 1. While the plasma geometry is the same as ITER, the target fusion power is of the order of gigawatt, which is higher than in ITER. The calculation results from PROCESS and TPC are summarized in Table 2. Outputs from the computation modules relevant to plasma physics in the two systems codes are in good agreement, except for radiation power losses [10].

A possible cause of difference in the calculated $P_{\rm brem}$ and $P_{\rm lin}$ values is difference in the impurity radiation and spatial profile models. The models used in TPC and PROCESS is summarized in Table 3. In the present benchmark calculation case, fortunately, the calculated values of the *HH* factor from the two codes are in good agreement, as shown in Table 2. Thus, the difference in the calculated impurity radiation power losses is not so large to crucially affect the plasma power balance. However, it would become large in a fusion reactor in which impurities are actively seeded to reduce divertor heat load, e.g. the DEMO reactor SlimCS [11].

3. Further works

In the presentation comparison of the calculation results from the two codes will be discussed more extensively. We will also discuss about the second issue described in Section 1; we will examine applicability of calculation models for some physical phenomena, e.g. the synchrotron radiation, impurity radiation and bootstrap current, to DEMO design.

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Table 1 Input plasma parameters in the benchmark calculation.

Major radius	R_p (m)	6.28
Aspect ratio	A	3.00
Elongation at the 95 % flux surface	κ_{95}	1.60
Triangularity at the 95 % flux surface	δ_{95}	0.33
Toroidal field at axis	B_t (T)	6.58
Safety factor at the 95 % surface	q_ψ	3.00
Density-averaged plasma temperature	$<T>_{DA}$ (keV)	22.91
Temperature profile index	a_T	1.50
Density profile index	a_n	0.70
Diameter of central solenoid	R_{CS} (m)	2.00
Distance between TF coil & plasma surface	Δ_{TF} (m)	1.18
Impurity He density fraction	f_{He} (%)	10
Impurity O density fraction	f_O (%)	0.2
Impurity Fe density fraction	f_{Fe} (%)	0.065

Table 2 Output calculation results from TPC and PROCESS.

		PROCESS	TPC
Fusion power	P_{fus} (MW)	2501	2501
Total plasma current	I_p (MA)	18.5	18.5
Normalized thermal beta value	$\beta_{N,th}$	2.88	2.89
Normalized total beta value	$\beta_{N,tot}$	3.77	3.89
Poloidal beta value	β_p	1.32	1.24
Volume-averaged electron density	$<n>$ (10^{20}/m^3)	1.01	1.02
Greenwald density fraction	n/n_{GW}	0.93	0.94
plasma volume	V_p (m^3)	892	889
HH factor	H_{98y2}	1.21	1.23
Current drive power	P_{CD} (MW)	117.00	116
bootstrap current fraction	I_{BS}/I_p (%)	55.2	55.8
Z-effective	Z_{eff}	1.70	1.71
Bremsstrahlung power loss	P_{brem} (MW)	51.5	48.7
Syncrotron power loss	P_{syn} (MW)	47.8	47.8
Line radiation power loss	P_{line} (MW)	38.9	51.1

Table 3 Summary of the $P_{\rm brem}$ and $P_{\rm lin}$ models.

Code		PROCESS	TPC
P_{brem}	fuel	$\propto f_{prof} n_{20}^2 f_k Z_k^2 T_{10}^{1/2} V_p$	$\propto f_{prof} n_{20}^2 f_k Z_k^2 T_{10}^{1/2} V_p$
	impurity	The fitting formulae from transport simulations	$\propto f_{prof} n_{20}^2 f_k Z_k^2 T_{10}^{1/2} V_p$
P_{line}		Give the fraction $P_{line,k}/P_{brem,k}$	The coronal model