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Tokamak Reactor System Analysis Code for Concept Development of DEMO

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1. Introduction

System analyses are necessary to find device variables which optimize figures of merit such as major radius, ignition margin, divertor heat load, neutron wall load, etc. System analysis incorporates a wide range of the plasma physics and technology assumptions consistently through the use of simple modeling for effects of the plasma physics and technology. In system code, plant power balance equation and the plasma power balance equation are solved to find plant parameters which satisfy the plasma physics and technology constraints simultaneously.

To explore the range of concepts of DEMO and fusion power plant, assumptions on the level of physical and technological development have to be made. The system analyses are intended to capture the range of likely outcomes and to identify necessary R&D areas, both in physics and technology. In this study, as a part of study for developing concepts of DEMO, we investigate the performance in terms of the plasma physics and technology required for steady state operation by using the tokamak reactor system code.

2. Tokamak Reactor System Code

The system code finds the design parameters which satisfies the plasma physics and engineering constraints or optimizes the design depending on the given figure of merits. It includes the range of likely outcomes of development in plasma physics and technology. The parameters arising from the system studies will be used as the basis for further development of DEMO conceptual designs.

2.1 Plasma and plant power balance model

In system code, the mathematical model to capture physics and technologies are overall plant power balance equation and the plasma power balance equation. The first equation is the plasma power balance equation, which is represented as

$$P_{con} + P_{rad} = P_{OH} + P_{\alpha} + P_{CD}$$

where the conduction (P_{con}) and radiation losses (P_{rad}) are balanced by the heating by α particles (P_{α}), auxiliary heating (P_{CD}) and ohmic heating (P_{OH}). These terms have a complex dependence on the plasma parameters, For the confinement scaling, H-mode IPB98y2 scaling law [1] with the confinement improvement factor, H is used.

$$\tau_E = H\tau_E^{IPB98(y,2)}$$

$$\tau_E^{IPB98(y,2)}$$

$$= 0.0562 I_P^{0.93} B_0^{0.15} (P_{con} vol)^{-0.69} n_{19}^{0.41} M^{0.19} R_0^{1.97} (\frac{a}{R_0})^{0.58} \kappa^{0.78}$$

The second is a plant power balance equation, which account for energy multiplication, efficiency of electricity generation and power consumption in current drive, cryogenics and other systems. The overall plant power balance includes complex dependencies on plant parameters, particularly through the current drive and cryogenic powers.

2.2 Physics model

The plasma properties are expressed in zero-dimensional model in this section. A detailed analysis of plasma performance such as MHD equilibrium, stability, transport and current drive analyses are required for further development of a reactor concept.

The total plasma current I_p is limited by a limit on the safety factor q_{95} at the edge.

$$q_{95} = \frac{B_0 R_0}{2\pi} \oint \frac{ds}{R_2 B_p} \cong q_* \frac{(1.17 - 0.65\frac{a}{R})}{(1-(\frac{a}{R})^2)^2}$$

$$q_* = \frac{5 a_2 B_0}{R_0 I_p} \frac{1 + k_{95}^2 (1 + 2\delta_{95}^2 - 1.2\delta_{95}^3)}{2}$$

The plasma beta is limited by

$$\beta \le \beta_T = C_T (I_P / a B_0)$$

with C_T: Troyon coefficient.

Operation at high density is favored but there is a limit at which the plasma becomes disruptive. The density limit is given by Greenwald scaling:

$$n_G = \frac{I_P}{\pi a^2} \quad (10^{20} m^{-3})$$

Steady-state operation requires that the plasma current should be driven by the non-inductive current drive and that the radial distribution of the externally driven current complements the bootstrap current profile so that the total current profile satisfies any global requirements and is robust against MHD instabilities. The bootstrap current is estimated according to ITER physics design guidelines.

2.3 Engineering conditions

There are various engineering constraints such as radial/vertical build, ripple condition, coil critical current density, startup & burn volt-sec capability, the superconducting properties, stress limit, divertor heat load limit, shield requirements, maximum TF field, etc. These constraints will take into consideration of the development of engineering and plasma physics in the future.

The maximum magnetic field on the conductor is expected to be achieved on the basis of current technological expertise. The constraints on the superconducting coils can be a limit on the operating current density at various operating conditions, stress limit.

The position and width for the components of the tokamak reactor such as blankets, shields, central solenoid coils, toroidal field coils, etc. depend on the physics and engineering constraints. The ripple requirement determines the location of outer leg of TF coil. Sufficient space for the blankets and the shields should be maintained to maximize the tritium breeding ratio and the energy multiplication factor. Shield thickness is also closely related to the neutron wall loading (fusion power).

If the plasma current ramp-up is provided with the magnetic flux of central solenoid coils, it has to be bigger than the required magnetic flux and this, in turn, restricts coil position, size and current density. The required magnetic flux is expressed as

$$\Delta\Psi = L_p(l_i, \beta_p) I_p + C_{Ejima}\mu_0 R_0 I_p$$

where L_p and R_p are, respectively, the plasma inductance and plasma resistivity with the Ejima coefficient C_{Ejima}=0.45.

A constraint imposed by the maximum tolerable divertor heat load has a impact on the machine size, plasma current and current drive power. The divertor heat load can be reduced by impurity seeding of the edge plasma and the core by increasing radiated power, or developments of suitable plasma facing material for the divertor target. A maximum peak power flux of 15 MW/m^2 would be permissible and the divertor plasma temperature would need to be reduced below 20 eV to ensure that the erosion rate is acceptable.

The current drive power is required to sustain the plasma current and it is important to develop efficient current drive systems that can run reliably in steady state to reduce the re-circulating power. But the current drive power is limited due to the limit of available ports and the necessity of a low circulating power.

2.4. Development of the system code

In system analysis code, physics and engineering constraints explained in previous sections are modeled into plant power balance equation. The system code finds the design parameters under the plasma physics and engineering constraints or optimizes the design depending on the given figure of merits. The way that the systems code operates is that n variables (usually, physical parameters or device parameters) are found with given n constraints (physical or engineering constraints), or a set of variables which optimize the given figure of merit (object function) are found. In latter case, number of variables can be bigger than the number of constraints.

3. Conclusion

The tokamak reactor system analysis will provide satisfactory results to select the operational region of a reactor design, although the zero-dimensional model cannot precisely consider profile effects such as heating and current drive profile, bootstrap current fraction, advanced tokamak operation with negative shear, and so on. Nevertheless, a detailed analysis of plasma performance such as MHD equilibrium, stability, transport and current drive analyses are required for further development of a reactor concept.

REFERENCES

[1] ITER Physics Basis, Nucl. Fusion 39 (1999), 2175.