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System analysis study for Korean fusion DEMO reactor

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HIGHLIGHTS

- A conceptual design study for a steady-state K-DEMO has been initiated.
- The major radius is designed to be below 6.5 m, considering engineering feasibilities.
- Magnetic field at the plasma center around 8 T is achieved by using Nb_3Sn technology.
- Feasibility of near-future DEMO reactor is studied with a system analysis code.
- A net electric generation on the order of 300 MWe can be achieved below the β_N of 5.

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ABSTRACT

A conceptual design study for a steady-state Korean fusion DEMO reactor (K-DEMO) has been initiated. Two peculiar features need to be noted. First, the major radius is designed to be just below 6.5 m, considering practical engineering feasibilities. But still, high magnetic field at the plasma center around 8 T is expected to be achieved by using current state-of-the-art high performance Nb_3Sn strand technology. Second, a two-stage development plan is being considered. In the first stage, K-DEMO will demonstrate a net electricity generation but will also act as a component test facility. Then, after a major upgrade, K-DEMO is expected to show a net electric generation on the order of 300 MWe and the competitiveness in cost of electricity (COE). Feasibility of such a practical, near-future demonstration reactor is studied in this paper, based on a zero dimensional system analysis code study. It was shown that a net electric generation on the order of 300 MWe can be achieved below the optimistic β_N limit of 5. The elongation of K-DEMO is around 1.8 with single null configuration. Detailed optimization process and the resultant various plasma parameters are described.

1. Introduction

Conceptual design studies for fusion demonstration reactor (DEMO) could be classified into two categories. In one extreme end, the high toroidal magnetic field approach is targeted to achieve maximum fusion power, whereas in the other end, the high β_N approach is aiming at an easier steady-state operation. If we consider another end, faster realization based on realistic near-future engineering constraints, then it may be argued, for example, that the overall size should be relevant to those of the ITER, in order to directly incorporate the progress in tokamak plasma physics during the ITER operation phase [1,2].

A pre-conceptual design study for K-DEMO has been initiated. A National Fusion Development Roadmap had been released in 2005 and Fusion Energy Development Promotion Law was enacted in 2007 to promote a long-term cooperative fusion research. The main design philosophy at the moment can be summarized as faster realization based on realistic near-future engineering constraints. With such a spirit, the major radius is designed to be less than 6.5 m. Plausible radial builds are being studied, including toroidal field (TF) magnets. Based on the physical size of the TF magnets, two options for the radial builds are discussed in our recent work [3].

Another critical feature of the current K-DEMO pre-conceptual design study is a unique two-stage development plan. In its first stage, K-DEMO will be operated partially as a component test facility. Based on the component test results, a major upgrade will be carried out in the second stage development, by replacing relevant in-vessel components in order to achieve a net electricity generation on the order of 300 MWe and the competitiveness in cost of electricity (COE). In this work, the feasibility of such a practical, near-future demonstration reactor will be discussed, mainly to focus on the plausible plasma parameters in order to achieve a net electricity generation on the order of 300 MWe, for two design options, using a 0-dimensional system analysis code [4].

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2. General requirements

In order to demonstrate the competitiveness in COE, the net electricity of at least 300 MWe, hopefully over 800 MWe should be generated assuming ~35% power conversion efficiency. *D–T* fuel system with tritium breeding ratio more than 1.05 for fuel self-sustainability, maintainable reactor structure and plant availability over 70% are other major requirements. At the moment, two options for the K-DEMO design with the main difference in TF magnet sizes are considered. For the option I case, the major and minor radii are 6.0 and 1.8 m, respectively. The major and minor radii for the option II are 6.5 and 2.0 m, respectively. For both options, it was shown that a high toroidal magnetic field of 7.72 T can be achieved at the plasma center by utilizing the current state-of-the-art high performance Nb_3Sn superconducting strand technology [3].

The limit of β_N is determined by the stability of ideal MHD modes, particularly, the low-*n* external kink modes and the $n=\infty$ internal ballooning modes [5]. β_N is limited up to 3.5 even for the ideal MHD limit without wall but can be reached as high as 5 by wall stabilization and the active control of resistive wall modes. Present K-DEMO system analysis has been carried out for the operation at β_N of 4.2 and maximum toroidal field, B_T of 16 T (7.72 T at the plasma core), a sort of a compromise between high β_N and high B_T approach, quite similar to the ARIES-RS case. Before the system analysis for the K-DEMO, benchmark analyses have been carried out for the ITER and ARIES-RS designs, using a zero dimensional system analysis code, in which scaling law has been updated [4,6,7]. The calculated results agree approximately with parameters of ITER and ARIES-RS. Detailed benchmarking results can be found elsewhere [8].

3. System code analysis results

To realize a steady state operation of a tokamak, the plasma current should be driven non-inductively without using a transformer, and it is important to make use of the bootstrap current [2,9]. The bootstrap current is a self-generated current which can reduce the re-circulating power fraction for the current drive and thereby enhance the plant performance. For example, the fusion power is increased at higher values of the bootstrap current fraction (f_{bs}), as shown in Fig. 1. Reasonable values for the plasma current ranges can be estimated from the plasma current scans as a function

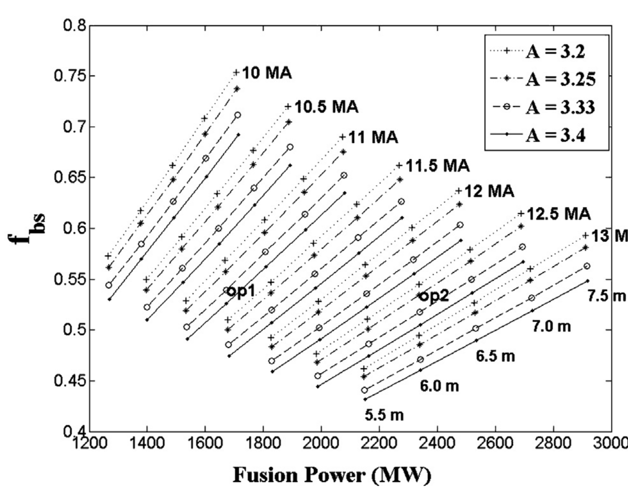

Fig. 1. The bootstrap current fraction and the fusion power for conventional magnetic shear case, with various aspect ratios of 3.2–3.4 and plasma currents in the range of 10–13 MA.

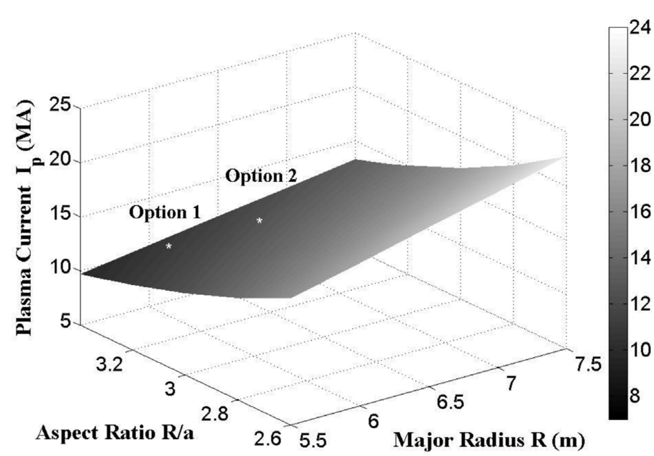

Fig. 2. Plasma current variation as a function of the aspect ratio and major radius when the toroidal magnetic field at the plasma core is 7.72 T.

of the aspect ratio and major radius, presented in Fig. 2. The fusion powers of near 1700 and 2400 MW can be achieved, for options I and II cases, respectively, when the bootstrap current fraction is 53%.

The bootstrap current fraction depends on the safety factor (q) profile. The above calculations, shown in Figs. 1 and 2, are for a conventional operation case. The relevant q profile and the pressure variation for the K-DEMO option II case, for example, are shown in Fig. 3. By only varying the q profile, which corresponds to a weak negative shear operation, the bootstrap current fraction can be enhanced to 0.62. The fusion power is increased from 2338 to 2400 MW and the energy confinement time (τ_E), from 2.32 to 2.35 s, respectively. The thermal energy confinement time is described by the *IPB*98(y,2) scaling as follows:

$$\tau_E = H_{H98}\,\tau_{E,th}^{IPB98(y,2)} \tag{1}$$

where $\tau_{E,th}^{IPB98(y,2)} = 0.05621 \cdot I_p^{0.93} B_T^{0.15} P_{heat}^{-0.69} n_e^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_x^{0.78}$.

The energy confinement time can be increased by the $H_{H98(y,2)}$ ($\geq$1.3) for a steady state operation.

The bootstrap current dominates in the plasma edge region. It was argued that the edge safety factor (q_{95}) over 6 is due to operations with weaker internal transport barriers (ITBs) at edge plasma. Only a weak negative shear with a bit relatively high q_0, about 2.5, may be suitable profiles for advanced operation [10]. In the negative magnetic shear region $s=(r/q)dq/dr<0$, kinetic stability occurs [5].

Further optimization on the q profiles has been carried out and the resultant parameters and operational capabilities of K-DEMO for option I and option II are listed in Table 1. The elongation ($\kappa_{95}=1.8$) of K-DEMO is quite similar to that of KSTAR (major radius 1.8 m, minor radius 0.5 m, plasma current 2 MA, elongation 2.0, triangularity 0.8 and the toroidal field at center 3.5 T). The plasma cross section will be shape-controlled to a triangular shape with a triangularity of 0.4. The ratio of the averaged electron density over the Greenwald limit (n/n_G) is limited to a value near unity in order to reduce the probability of plasma disruption (Greenwald density limit, $n_G = I_p/\pi a^2$) [11]. The L–H transition powers, $P_{LH} = 0.042\, {n_{20}}^{0.73} {B_T}^{0.74} S^{0.98}$ MW [12], for the options I and II are 98 MW and 113 MW, respectively.

Total core synchrotron and bremsstrahlung radiation power, for example, for the option II, are 103.6 MW and 38.7 MW, respectively. The total net electron and ion temperature sources are

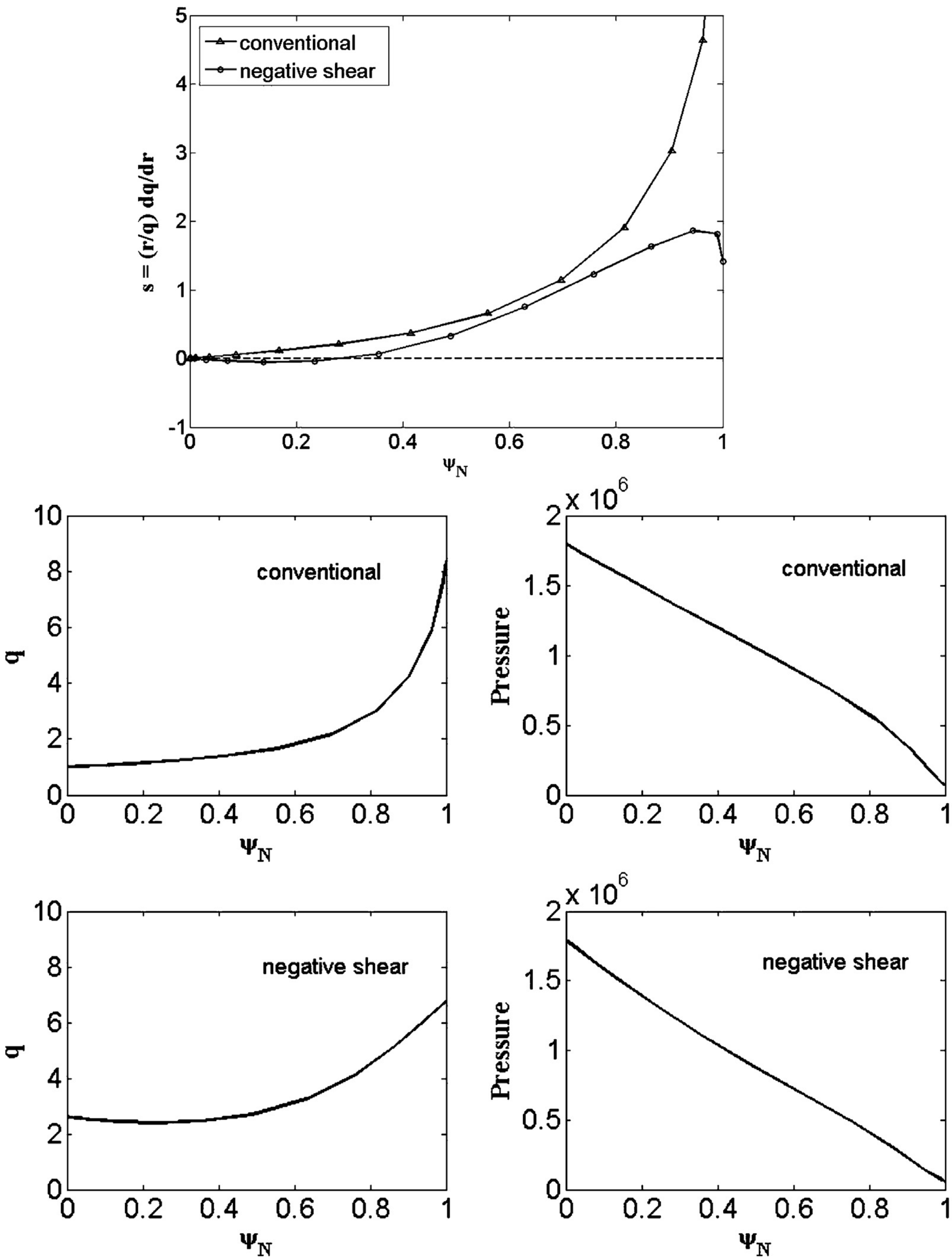

Fig. 3. The safety factor, pressure, and magnetic shear $s = (r/q)dq/dr$ profiles for the conventional magnetic shear (triangles) and negative shear cases (circles).

206.5 MW and 196.2 MW. Power from core plasma to entire scrape off layer (SOL) is 545 MW and the peak heat flux to the divertor plate will be about 24.5 MW/m^2 if the power is directly transferred to an ITER-like-shaped divertor. When a power distribution between inboard and outboard targets is assumed 1:4 (ITER assumes 1:2), a surface heat power is 136.25 MW and 408.75 MW, respectively. If a 7.5° divertor cassette of which outboard target plate is about 0.8 m × 1 m (toroidal × poloidal) then an average heat load is about 7.1 MW/m^2 (peak heat load is about 10.6 MW/m^2) [13]. With the improvement of tokamak operation, increasing the confinement time will be able to reduce the divertor heat load.

The overall power balance of the K-DEMO are shown in Table 2. The net electricity of 90 and 294 MWe are expected, for the options I and II, respectively. Due to the relatively high value of the bootstrap current fraction of 0.6, less heating and current drive power (P_{heat}) is required and thus high Q value of 24–30 can be achieved. But still around 70 MW of heating and current drive power will be needed for the current profile control in the startup phase of a steady state K-DEMO operation. In order to increase heating and current drive efficiency further study is needed. The recirculating fraction is defined as the ratio of the required electrical power for the operation of the plant to the gross electric power of the power plant. A conservative value of 0.5 was

Table 1
Parameters and operational capabilities of K-DEMO.

Parameter	Option I	Option II
Major radius, R_0 (m)	6.0	6.5
Minor radius, a (m)	1.8	2.0
Aspect ratio, A	3.33	3.25
Toroidal field on axis, B_T (T)	7.72	7.72
Plasma current, I_P (MA)	11	12.5
Elongation, κ	1.8	1.8
Triangularity, δ	0.4	0.4
Normalized beta, β_N (%)	4.2	4.2
Safety factor, q_{95}	3.5–6.0	3.5–6.0
Energy confinement time, τ_E (s)	2.27	2.36
Bootstrap current fraction, f_{bs}	0.6	0.6
Averaged electron temperature (keV)	19	19
Averaged electron density (10^{20} m^{-3})	1.08	1.12
Greenwald limit, n_{GW} (10^{20} m^{-3})	1.08	0.99
n/n_{GW}	1.0	1.13
Total fusion power (MW)	1708	2400
Q-value	24.4	30
Total H&CD power (MW)	70	80
L–H mode transition power (MW)	98	113
Average wall loading (MW/m^2)	2.0	2.34
Z_{eff}	1.4	1.4

Table 2
Power balance of K-DEMO.

Power balance	Option I	Option II
Fusion power, P_{fus}	1708 MW	2400 MW
Heating and current drive power, P_{heat}	70 MW	80 MW
Total heat, $(0.8f_m$[a] $+ 0.2)P_{fus} + P_{heat}$	2325 MW	3248 MW
Q (P_{fus}/P_{heat})	24.4	30.0
Thermodynamic efficiency, η_{th}	0.35	0.35
Gross electric power	598 MWe	840 MWe
Recirculating fraction	0.85	0.65
Recirculating electric power	508 MWe	546 MWe
Net electric power	90 MWe	294 MWe

[a] Energy multiplication factor of blanket f_m is 1.4.

used for the estimation. However, a typical target value is less than 0.2 [14], which will further increase the net electric power generation.

4. Summary

In summary, a system analysis study on the current two options for the K-DEMO has been carried out. The main design philosophy at the moment can be stated as faster realization based on realistic near-future engineering constraints. With such a spirit, the feasibility of such a practical, near-future demonstration reactor was mainly focused. In order to demonstrate the competitiveness in COE, at least, the net electricity of 300 MWe can be generated. System analysis has been carried out for the operation at a reasonably practical value for β_N of 4.2 and maximum toroidal field, B_T of 16 T (7.72 T at the plasma core), a sort of a compromise between high β_N and high B_T approach. First, the plasma and bootstrap currents were roughly scanned and then detailed q profile variations are considered. Only a weak negative shear with a bit high q_0 of 2.5 seems to be good enough for the required net electric generation on the order of 300 MWe.

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