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Fusion Engineering and Design 81 (2006) 1145–1149

Fusion Engineering and Design

www.elsevier.com/locate/fusengdes

Impact of plasma, magnet and wall performances on tokamak and helical reactor economics

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Received 10 March 2005; received in revised form 22 September 2005; accepted 22 September 2005
Available online 27 December 2005

Abstract

For the assessment of both tokamak and helical reactors, the base case reactor models are introduced, and parameter scan analyses on plasma beta, electric power output, maximum magnetic field strength and neutron wall loading are carried out. The assessment shows that high temperature operation is appropriate in tokamak reactors to increase bootstrap current fraction and current-drive (CD) efficiency. In contrast, low-temperature high-density operation is feasible and desirable in helical system to reduce helical ripple transport. The capital cost of helical reactors is rather high; however, the cost of electricity (COE) is not much higher than that of tokamak reactors especially in the case of low beta design, because of smaller re-circulation power (no current-drive power) and less-frequent blanket replacements due to lower neutron wall load. The engineering improvement of increasing maximum magnetic field strength gives rise to the compact designs with lower construction cost. However, it does not lead to the strong reduction in COE because of the increase in the neutron wall loading. The COE critically depends on the system availability which is determined by the wall lifetime and the blanket maintenance time.

Keywords: Fusion reactor; Economic analysis; Tokamak; Helical system; Cost of electricity

1. Introduction

For the realization of attractive fusion power plants we need high-beta, good-confinement, steady-state plasma characteristics and high-field, high-wall-load, efficient-blanket engineering performances. The tokamak system has better plasma confinement properties; however, the current-drive re-circulation power and the plasma current disruption events are problematic. In contrast, the helical system is expected as a steady-state reactor, but a rather big and expensive system should be improved. To search for a favorable toroidal fusion reactor, we have evaluated fusion reactor economics using the physics–engineering–cost (PEC) code [1–3]. Its assessment models and comparative results for both tokamak and stellarator systems are reported here.

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0920-3796/$ – see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.fusengdes.2005.09.038

2. Assessment model

System assessments have been done using the physics, engineering and costing code. This code was originated for helical system reactors [1–4] using relevant physics and engineering design scaling laws [5], and was upgraded for the comparisons between tokamak and helical reactors [2]. The benchmark test of this code has been successfully performed [6] comparing with ARIES-AT advanced tokamak [7] and ARIES-SPPS stellarator [8] power plant models.

As for physics models, the reactor plasma performance can be determined by beta limits, confinement scaling laws and density limits. These physics databases for tokamak and helical systems are checked comparatively [9]. As for engineering design, we compared several blanket designs (reduced activation ferritic steel (RAF)-flibe, V–Li, SiC–PbLi) in the PEC code. The reference magnet system is assumed made of Nb_3Sn conductor, and its typical maximum magnetic field is assumed to be 13 T depending on coil current density. The coil electromagnetic force, coil stress, wall loading and other engineering items are also evaluated. These assumptions and relevant physics/engineering models determine the plasma-coil space and the scale of the reactor system with the requirement of a target electric power output. As for cost analysis, various unit costs are defined in the same manner of Refs. [10,11] and the operation, maintenance and replacement costs are also added for calculating the cost of electricity (COE).

The system configurations of tokamak and helical reactors are given in Fig. 1. In this paper, a LHD-type heliotron reactor (LHR: large helical reactor) with *L* (poloidal periodic number) = 2, *M* (toroidal periodic number) = 10 configuration is considered for helical reactors. The RAF-flibe blanket option is assumed in both tokamak and helical systems for the present comparative studies.

3. Base case designs

As for base case designs, we introduced four reactor design options; tokamak reactor-1 (TR-1) and heliotron reactor-1 (HR-1) with 5% plasma beta and 1 GW electric output power, and tokamak reactor-2 (TR-2) and heliotron reactor-2 (HR-2) with 3% plasma beta and 2 GW electric power. These reactor parameters are shown in Table 1. In the case of helical reactors, rather large system is required. The TR-1 and HR-1 correspond to higher beta, standard power reactors, and TR-2 and HR-2 are assumed as conventional beta and higher electric power plants. Here required confinement improvement factors (*H*-factors) are given with respect to the ITER scaling law [12] for tokamaks, and with respect to the international stellarator scaling (ISS) [13] and the new LHD #1 (NLHD1) scaling laws [2] for helical reactors.

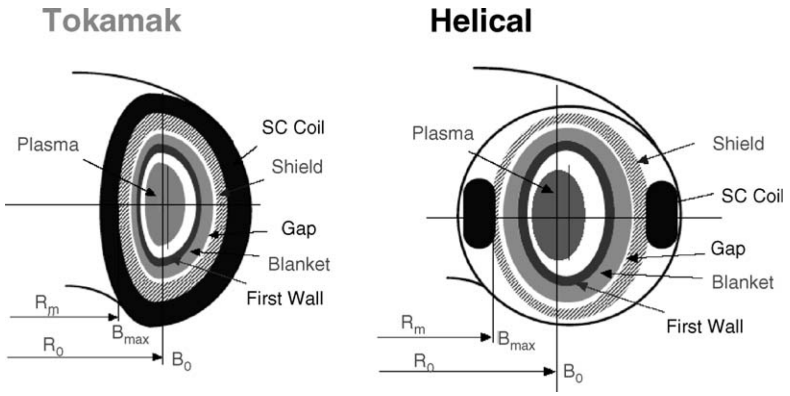

Fig. 1. Model of tokamak and helical (heliotron) reactor systems.