Proceedings of ITC18,2008

Development of System Design Code for Heliotron Reactor

Takuya Goto, Akio Sagara, Shinsaku Imagawa

National Institute for Fusion Science

Heliotron reactors inherently have suitable properties for a DEMO reactor; no need of current drive power, easiness in steady state operation. To clarify a possible path to the DEMO reactor with utilizing such properties of heliotron reactors, system design code for heliotron reactors is being developed. Assuming the use for sensitivity analysis over a wide design space, computational time needs to be reduced as much as possible. Whereas calculation of an equilibrium magnetic surface, which requires long computational time including numerical integral, is indispensable to obtain several key engineering and physics variables in a system design. Here magnetic field configuration of heliotron system is considered to be described by geometric configuration of helical coil only. Thus it is expected that magnetic field configuration can be estimated by some empirical scaling laws and approximation formulae. In this paper, current status and some technical issues of code development are reviewed.

Keywords: heliotoron reactor, system design code, simplified calculation method, scaling law

1. Introduction

The construction of international thermonuclear experimental reactor (ITER) has been started and the development of fusion energy source now enters into a quite important phase in which controlled and continuous fusion burn is demonstrated. Then the detailed design study of a DEMO reactor, which succeeds to ITER, should be started in the near future. Helical system, which confines plasma by the magnetic field generated by external conductors only, inherently has suitable properties for a DEMO reactor; no need of current drive power, easiness in a steady state operation. Thus it is quite meaningful to clarify a possible path to the DEMO reactor that fully utilizes such properties. The study of helical system parallel to tokamak is also important from the viewpoint of maintaining flexible developmental strategy of fusion energy.

Generally, sensitivity analysis over a wide design space is an effective way to clarify the design direction of a reactor system. Helical system, however, has high degree of freedom in its design and requires the consideration of complicated three-dimensional effects and fast calculation with simple formulae is difficult. Thus system design code for helical system has not yet been built except for the use in the optimization study within a limited design space. Whereas, heliotron system, which uses 2 continuous helical coils for the plasma confinement, has achieved excellent plasma properties through the experimental studies by Large Helical Device (LHD) [1], and the design of a DEMO reactor can be extrapolated from these achievements. Thus design study of a DEMO reactor with heliotron system is quite significant. We can reduce a degree of freedom in design by specializing for heliotron reactors. The probable design space has been also narrowed down through the past experimental studies. In such a restricted area, we can obtain a valid estimation of the reactor performance by using several empirical scaling laws or approximation formulae. Then it becomes possible to build a system design code for heliotron reactors. In this paper, current situation and several critical issues of code development are reviewed.

2. Application and Required Performance of System Code

As described in the previous section, we assume the use of a system design code for sensitivity analyses over a wide design space. Then system code needs to be able to calculate core plasma performance, engineering design criteria, and plant performance (i.e., electric power output, cost, the amount of radioactive waste, etc.) simultaneously and with a consistent manner. Whereas computational time is required to be reduced as much as possible. Since scanning of 6 patterns of each 6 parameters yield 46,656 design points and only 3 patterns of 10 parameters yield 59,049. Then the computational time per one parameter set point is limited to be <1 sec to carry out a parametric scan with sufficient design points (more than 100,000) within reasonable computational time (e.g., about a day). However, in heliotron system, the position, shape, and current of helical and poloidal coils are the critical factors that determine its design feasibility. For example, the information of magnetic surface structure including ergodic layer is indispensable for the blanket and shield design. The design of vacuum vessel also cannot be fixed without the information of divertor strike points. Magnetic surface structure can be changed by adjusting position and

---

author's e-mail:goto.takuya@LHD.nifs.ac.jp

current of poloidal coils. But its degree of freedom is also limited by stored magnetic energy of the coil system. Then we need to consider these effects even in preliminary phase of the parametric scan to find viable design points. Though it is not described in this paper, we also need to consider feasibility of the sufficient TBR (tritium breeding ratio) achievement, the effect of maintenance time and frequency on plant availability, and operation scenario including transient phase (e.g., plasma lump-up and shutdown).

3. Simplified Calculation Method

In the system design of heliotron system, magnetic field calculation is necessary to get several important parameters (e.g., maximum field on coil, minimum minor plasma radius, etc.). However, it requires significant computational time because it cannot be solved analytically and needs numerical integral. Here we only need a moderate accuracy of the calculation result for the application in a parametric scan. The vacuum magnetic field configuration is uniquely determined by the coil geometric configuration and simplified calculation (e.g., approximation formula and inter- or extrapolation of tabulated data) can yield the sufficient accuracy. In the following, a brief description of such simplified calculation methods is given.

3.1 Magnetic filed ratio scaling

The estimation of the maximum magnetic field on coil B_{max} and average toroidal field on magnetic axis $<B_0>$ with reasonable accuracy is indispensable in a system design. $<B_0>$ of tokamak system can be easily calculated from B_{max} and shape of toroidal field coil by using a simple $1/R$ scaling. Whereas $<B_0>$ of heliotron system can be obtained by Ampere's law as

$$\left\langle B_0 \right\rangle = \frac{\mu_0 m I_{\mathrm{c}}}{2\pi R_{\mathrm{c}}} \tag{1}$$

where μ_0, m, I_{c}, R_{c} are vacuum magnetic permeability, toroidal pitch number, helical coil current, and helical coil major radius. But B_{max} of heliotron system cannot be calculated by an analytical way. Here the ratio of these 2 parameters $B_{\mathrm{max}}/<B_0>$ is a non-dimensional parameter and determined by coil geometric configuration only. Thus the magnetic field ratio can be described by a function of several non-dimensional parameters related to geometric factors. Such scaling law has already been proposed by Yamazaki in the design optimization of Large Heclical Device (LHD) [2] as:

$$\frac{B_{\mathrm{max}}}{B_0} = 2.1\left(\frac{j_{\mathrm{c}}}{40}\frac{R_{\mathrm{c}}}{B_0}\right)^{0.40}\left(\frac{10}{m}\right)^{-0.853}\left(\frac{\gamma_{\mathrm{c}}}{1.2}\right)^{0.05}, \tag{1}$$

where j_{c} is helical coil current density and γ_{c} is helical pitch parameter $\gamma_{\mathrm{c}} = m a_{\mathrm{c}} / (\ell R_{\mathrm{c}})$. This scaling well reproduces the magnetic field ratio of heliotron system that has similar coil shape to LHD. However, it cannot reproduce that of recent designed heliotron reactors; FFHR-2m1 and FFHR-2m2 [3]. This is because that the coil cross-sectional shape of FFHR series is different from that of LHD. Thus we tried to build a new magnetic ratio scaling law including this effect. If we assume 2 helical coils has the same rectangular cross-section, the geometrical configuration of helical coils is uniquely determined when the following parameters are given; R_{c}, m, coil minor radius a_{c}, pitch modulation parameter α, coil cross-sectional area S_{c}, and the ratio of coil width to height $x=W/H$. After some consideration, we selected 5 non-dimensional parameters: m, α, γ_{c}, the parameter defined as $\zeta \equiv \sqrt{S_{\mathrm{c}}}/R_{\mathrm{c}}$, and the parameter related to the maximum field on infinite-length linear conductor with rectangular cross-section;

$$\xi = \sqrt{x}\left\{\ln\left(1+\frac{4}{x^2}\right)+\frac{4}{x}\tan^{-1}\left(\frac{x^2}{2}\right)\right\}. \tag{2}$$

Then we calculated magnetic field ratio of various heliotron system by using finite volume current element code developed based on Todoroki's theory [4] and carried out regression analysis of the result. Here we assumed that poloidal coils were located at each vertex of the rectangle that has the inscribed circle with the same radius as the outer edge of the helical coil; $a_{\mathrm{c}}+H/2$.. According to the result of regression analysis, we proposed magnetic ratio scaling as following;

$$\frac{B_{\mathrm{max}}}{\left\langle B_0 \right\rangle} = 0.85(1+\alpha)^{-0.117} m^{-0.853} \gamma_{\mathrm{c}}^{0.156} \xi^{0.796} \zeta^{-0.815}. \tag{3}$$

As shown in Fig. 1, this scaling well reproduce the magnetic field ratio calculated by finite volume current element code within 2% error over wide range of design parameters: $4 \le R_{\mathrm{c}} \le 20$, $m = (8,10,12)$, $1 \le \gamma_{\mathrm{c}} \le 1.4$, $-0.2 \le \alpha \le 0.2$, $0.07 \le \zeta \le 1$, $1 \le \xi \le 2$.

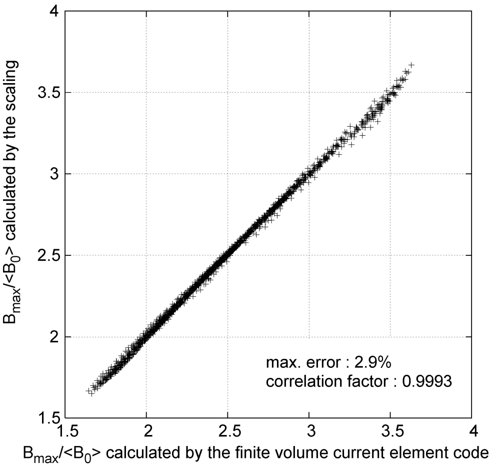

Fig.1 Comparison of magnetic field ratio estimated by the proposed scaling (eq. (3)) and the calculation result by finite volume current element code..

3.2 Calculation of Vacuum Magnetic Surface

To achieve fast calculation in evaluation of plasma performance, we consider the use of ISS (International Stellarator Scaling) [5,6]. ISS scaling law consists of average plasma minor radius $<a_p>$, major radius of last closed flux surface (LCFS) $R_{\rm geo}$, average toroidal field strength B_t, rotational transform ι at normalized radius of ρ=2/3. To obtain these parameters, calculation of an equilibrium magnetic surface is indispensable. But calculation of a magnetic surface needs filed line tracing, which requires long computational time. Whereas magnetic field structures including ergodic layer generated by similar shape 2 coils are always similar to each other. Thus it is expected that parameters related to magnetic configuration can be obtained by inter- or extrapolation of database generated by the detailed calculation with several data points.

To calculate equilibrium magnetic field, the location and current of poloidal coils needs to be determined. Helical coil inevitably generate net vertical field in plasma confinement region. This vertical field is canceled out by poloidal coils symmetrically located against the equatorial plane. Generally two pairs of helical coils, one is located at inner side of torus and the other at outer side, are used to reduce leakage field. Then 6 parameters, radius, height and current of inner and outer poloidal coil, needs to be determined. For simplicity, here we assumed inner and outer poloidal coil has same height and located on the circle that shares its center with helical coil winding center. Then the location of poloidal coil is fixed by two parameters, the radius of circle $R_{\rm PC}$ and angle between outer poloidal coil and equatorial plane $\theta_{\rm PC}$ (see Fig. 2). Once the locations of poloidal coils are given, there remains two degree of freedom; currents of inner and outer poloidal coil. There are two main parameters used to determine the current of poloidal coils: cancellation of dipole field generated by helical coil (BD), that of quadrapole field (BQ). BD value coincides to the shift of vacuum magnetic axis. Here we gave BD value and BQ was fixed to be 100%. And $R_{\rm PC}$ and $\theta_{\rm PC}$ are selected to maximize the volume enclosed by the last closed flux surface.

Table I shows the comparison of the parameter set of LHD at several magnetic axis positions with the calculation result obtained by the interpolation of database. This database is generated by the detailed calculation with parameter set: γ_c=1.1, 1.2, 1.3 and ζ=0.07, 0.08, 0.09, 1.0. As shown in the table, the parameters of LHD with magnetic axis position $R_{\rm ax}$=3.9m and 3.75m (coincides to the BD values of 96.01% and 101.84%) were reasonably reproduced. But the parameters of LHD with $R_{\rm ax}$=3.6m deviate from the result of equilibrium magnetic surface calculation. One reason of this deviation is the difference in the position of poloidal coils. In the case of BD=107.91%, the difference in current and position of poloidal coils from those of LHD is larger than the other cases. The largest deviation of magnetic axis position also shows this difference. Another reason is that the position and current of poloidal coils have not been fully optimized. The magnetic field generated by helical coil is monotonous function of coil geometric parameters. However, magnetic field structure around LCFS strongly depends on the position and current of poloidal coils. Then the volume enclosed by LCFS varies non-monotonically with the coil geometrical configuration. Therefore, the design of poloidal coils need to be optimized to obtain a database that can serve consistent data at any design point by inter- or extrapolation.

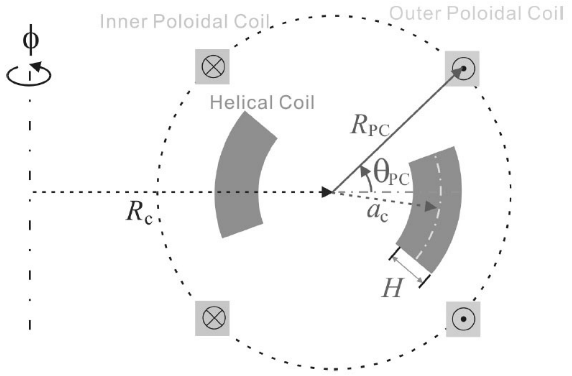

Fig.2 Schematic viewing of poloidal cross-section of heliotron system.

Table I Comparison of parameters related to magnetic surface structure of LHD at several vacuum magnetic axis positions with the value obtained by interpolation of database. The values in left row are results of equilibrium magnetic surface calculation, those in right row are obtained by interpolation of database.

	LHD $R_{\rm ax}$=3.9m		LHD 3.75m		LHD 3.6m	
BD	0.9601	←	1.0184	←	1.0791	←
$<a_p>$	0.535	0.552	0.589	0.593	0.636	0.584
ι_0	0.432	0.402	0.349	0.334	0.378	0.306
ι_a	0.964	1.049	1.214	1.257	1.571	1.229
$R_{\rm ax}$	3.9	3.903	3.75	3.767	3.6	3.651
$R_{\rm geo}$	3.816	3.811	3.740	3.738	3.672	3.694

4. Conclusion

System design code for heliotron reactors is being developed. To reduce computational time, we introduced several simplified calculation methods. For calculation of magnetic field ratio (the ratio of maximum field on coil $B_{\rm max}$ to average toroidal field on magnetic axis $<B_0>$), we proposed a new scaling described by exponential law of non-dimensional parameter related to coil geometrical configuration. We also tried to establish tabulated database of parameters related to magnetic field and magnetic surface structure at several specific design point. We expected that we can obtain these parameters at any design point by inter- or extrapolation of the database. Magnetic field components generated by helical coils can be well reproduced. But magnetic surface structure strongly depends on current and position of poloidal coils and we have not yet established perfect database that can be installed in the system code. Though we need further optimization of them to establish a consistent database, we had a perspective to build system design code that satisfies the required performance.

To achieve high reliability of the system design code, we plan to refine ISS scaling law by considering the effect of vacuum magnetic axis position and density/temperature profile and build it into the system code. We also need to consider finite beta effect on the magnetic configuration. Simplified evaluation method of tritium breeding ratio (TBR), plant availability, and operation scenario is also required to find viable design window. It is also quite important to clarify the design space with high robustness to the model uncertainty for assured development to a DEMO and commercial reactor instead of local optimization. To install procedures that can achieve these analyses, we can find the design point of the heliotron reactor that has high reliability and feasibility.

Acknowledgement

The authors appreciate the all members of helical reactor design group in National Institute for Fusion Science for provide valuable advises.

References

[1] O. Motojima *et al.*, Nucl. Fusion **40**, 599 (2000).

[2] K. Yamazaki *et al.*, Fusion Technology **21**, 147 (1992).

[3] A. Sagara *et al.*, Nucl. Fusion **45**, 258 (2005).

[4] J. Todoroki, Kakuyugo Kenkyu **57** (1987) 318 [*in Japanese*].

[5] U. Stroth *et al.*, Nucl. Fusion **36**, 1063 (1996).

[6] H. Yamada *et al.*, Nucl. Fusion **45**, 1684 (2005).