Research on Economics and CO_2 Emission of Magnetic and Inertial Fusion Reactors*)

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An economical and environment-friendly fusion reactor system is needed for the realization of attractive power plants. Comparative system studies have been done for magnetic fusion energy (MFE) reactors, and been extended to include inertial fusion energy (IFE) reactors by Physics Engineering Cost (PEC) system code. In this study, we have evaluated both tokamak reactor (TR) and IFE reactor (IR). We clarify new scaling formulas for cost of electricity (COE) and CO_2 emission rate with respect to key design parameters. By the scaling formulas, it is clarified that the plant availability and operation year dependences are especially dominant for COE. On the other hand, the parameter dependences of CO_2 emission rate is rather weak than that of COE. This is because CO_2 emission percentage from manufacturing the fusion island is lower than COE percentage from that. Furthermore, the parameters dependences for IR are rather weak than those for TR. Because the CO_2 emission rate from manufacturing the laser system to be exchanged is very large in comparison with CO_2 emission rate from TR blanket exchanges.

Keywords: tokamak reactor, inertial fusion reactor, COE, CO_2 emission amount rate, scaling formula

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1. Introduction

For the realization of fusion power plants, an economical and environment-friendly fusion reactor system should be explored. We have assessed cost and life-cycle CO_2 emission amount for toroidal magnetic fusion energy (MFE) reactor designs by the PEC (Physics-Engineering-Cost) system code [1-3]. Recently, this code has been upgraded to apply to the inertial fusion energy (IFE) design for equivalently evaluating both MFE and IFE. To clarify key parameters for the optimization of MFE and IFE, we checked new scaling formulas for cost of electricity (COE) [yen/kWh] and CO_2 emission rate [g-CO_2/kWh] with respect to several design parameters. These scaling formulas might enable us to calculate COE and CO_2 emission rate simply.

2. Assessment Model

In this study, the physics, engineering designs and the economics are evaluated for both tokamak reactor (TR) and IFE reactor (IR) by the PEC system code. The schematic models are shown in Fig. 1, and flow charts of PEC system code are shown in Fig. 2.

2.1 Physics and engineering models

2.1.1 Tokamak fusion reactor

Target electric power output, ignition margin, nor-

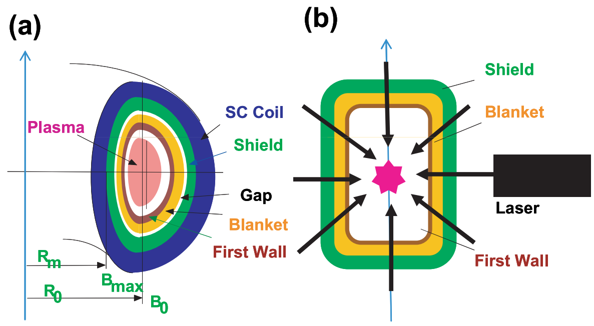

Fig. 1 Schematic drawing of reactor core models; (a) tokamak reactor (TR), (b) IFE reactor (IR).

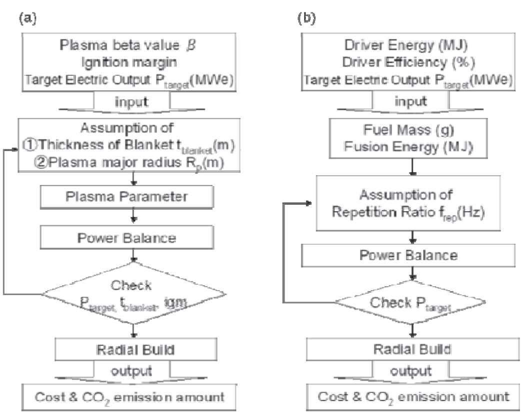

Fig. 2 Assessment flowcharts for (a) tokamak reactor (TR) and (b) inertial fusion reactor (IR).

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Table 1 Base designs for tokamak reactor with 1 GW electric power, 30-year operation and 75% plant availability.

parameters (*: input)	TR-1	TR-2
Confinement model	ITER ELMy H-mode	
β_N^*	3	5
$<T>$ [keV]*	15	15
$<n>$ [10^{20}/m^3]	1.4	1.7
B_t [T]	6.8	5.9
f_{bs} [%]	33	65
R_p [m]	7.1	5.5
H-factor	1.02	1.38
P_{fus} [MW]	4,016	2,851
P_{CD} [MW]	843	259
$L_{neutron}$ [MW/m^2]	3	3.5
Fusion island mass [kt]	9.4	5.9
Capital cost [Byen]	674	473
COE [yen/kWh]	13.13	9.22
CO_2 emission rate [g-CO_2/kWh]	10.8	9.1

Table 2 Base designs for inertial reactors with 1 GW electric power, 30-year operation and 75% plant availability.

parameters (*: input)	IR(a)	IR(b)
Ignition model	fast ignition	
Isentrope α^*	3	
Laser energy E_{in} [MJ]	1.2	
LD peak power P_{LDc} [GW]	14.4	
ρR [g/cm^2]	3.5	
Target gain G	180	
Laser repetition rate f_{rep} [Hz]*	12	
Reactor module number N_{mdl}	3	
Explosion output/shot E_{fus} [MW]	216	
$L_{neutron}$ [MW/m^2]	2.8	
Fusion island [kt]	6.6	
Laser diode unit cost C_{LD} [yen/W]	5	1
Capital cost [Byen]	593	478
COE [yen/kWh]	13.01	9.62
CO_2 emission rate [g-CO_2/kWh]	14.9	11.1

malized beta value and so on, are used as input parameters. ITER ELMy H-mode [4] with improvement factor is checked for optimizing the ignition margin. The alpha-particle confinement fraction is assumed to be 0.95. Two tokamak base designs are considered; tokamak reactor-1 (TR-1) with normalized beta value β_N of 3.0 and tokamak reactor-2 (TR-2) with β_N of 5.0.

As for engineering assessment, the maximum field strength of the superconducting magnet system is assumed 13 T, made of Nb_3Sn conductors. The superconducting magnet design model is described in Ref. [5]. The tolerable neutron wall fluence is assumed to be 20 MWyr/m^2 in the case of LiPb/SiC blanket system, which determines the replacement cycle of blanket modules. The blanket thickness and the relevant gaps are critical parameters to determine the reactor radial build. We assume the reference scaling law of total blanket thickness as a function of neutron wall loading L_{wall}. The ratio of LiPb/SiC blanket thickness to total thickness is 0.3. The thermal efficiency is assumed as 35% for the base designs.

Table 1 shows main parameters of TR-1 and TR-2 by the PEC code with the same electric power of 1 GW$_e$. The required current drive (CD) power might significantly contribute to the circulating power flow, and the bootstrap fraction f_{BS} is important parameter to reduce CD power.

2.1.2 Inertial fusion reactors

Recently the PEC system code has been upgraded to apply to IFE designs (Fig. 2 (b)). In the case, the fast ignition concept as IFE reactor is adopted here based on KOYO-Fast design and other system designs [6, 7]. The driver energy and relevant efficiencies (driver efficiency η_{driver} ~0.12, compression efficiency η_c ~0.05 and heating efficiency η_h ~0.10) critically determine the fusion core system. Mass of fuel M_{fuel} which would be compressed and heated is estimated by given driver energy E_{driver} and η_{driver} as follows.

$$E_{driver} = \frac{E_c}{\eta_c} + \frac{E_h}{\eta_h}, \quad (1)$$

$$E_c = 0.324\rho_c^{2/3}\alpha M_{fuel}, E_h = 115T_h\left(\frac{0.5}{\rho_c R}\right)^3 M_{fuel}, \quad (2)$$

$$M_{fuel} = \frac{4\pi}{3}\frac{(\rho_c R)^3}{\rho_c^2}, \quad (3)$$

where R, ρ_c, α and T_h are plasma radius, compressed density, isentrope parameter (~3) and hot plasma temperature (~20 keV), respectively. The compression and heating efficiencies are η_c(~0.05) and η_h (~0.1), respectively. Fusion energy E_{fus} is calculated by the fuel mass M_{fuel} and burn-up fraction Φ,

$$E_{fus} = \frac{17.6}{2}\Phi\frac{M_{fuel}}{m_{DT}}, \quad (4)$$

and the repetition rate f_{rep} is adjusted to satisfy the following power balance,

$$P_{net} = f_{elect}P_{th}(1 - f_{plant}) - \frac{E_{driver} \times f_{rep}}{\eta_{driver}}. \quad (5)$$

The radius of IR cylindrical chamber R_{fw} should be determined by the detailed design analysis and might be a function of the neutron wall load $L_{neutron}$ and fusion energy E_{fus}. Here we assumed the scaling laws derived based on previous ICF conceptual design works.

The economics of IR design depends strongly on the laser diode unit cost C_{LD} [yen/W]. We assumed inertial reactor (IR(a)) with C_{LD} = 1 [yen/W] and inertial reactor (IR(b)) with C_{LD} = 5 [yen/W]. These unit costs are much lower than the present cost of 100 [yen/W]. The reactor parameters of these base IR designs are shown in Table 2.

The power/energy of implosion laser is 13.6 GW/1.13 MJ and that of heating laser is 0.8 GW/0.07 MJ.

2.2 Cost accounting model

The cost analysis is mainly based on the unit costs per weight which values are based on those of Refs. [8-11]. The cost of superconducting toroidal coil with weight W_{TFC} is assumed as $0.114W_{TFC}$(t) [M$]. The typical value of W_{TFC} is 1,926 [t] for the TR-1 design ($\beta_N = 3$) and 1,102 [t] for the TR-2 option ($\beta_N = 5$). The cross-section of inboard-side TF coil is determined by ~ 30 MA/m^2 and the total coil weight is calculated by this cross-section and the circumference. The other main detailed cost accounting values used here are described in Ref. [3]. Relevant to IR designs, costs of plant systems except driver and pellet fabrication systems are calculated by the same scaling data in the PEC code for MFE models. Here, the driver system cost is based on KOYO and KOYO-Fast [11]. The laser system cost is a summation of laser glass optics $C_{LG} = U_{LG,E} \times (E_{Lc}[\text{MJ}] + 2 \times E_{Lh}[\text{MJ}])$, laser diode $C_{LD} = U_{LD,P} \times (P_{LD,c}[\text{MW}] + P_{LD,h}[\text{MW}])$ and other laser equipment. Here, subscripts c and h denote implosion and heating processes in the fast ignition scheme, respectively. We assume that the unit cost of laser glass $U_{LG,E}$ is 100 [M$/MJ], and the unit cost of laser diode $U_{LD,P}$ is 0.01 [$/W] for IR(a) design or 0.05 [$/W] for IR (b) design. The pellet fabrication cost $\left[132(f_{rep}\,[\text{Hz}]/5.6)^{0.7} + 66)\,[\text{M\$}]\right]$ are given by the scaling law described in Ref. [3].

2.3 CO_2 emission analysis model

To estimate life-cycle CO_2 emission amounts equivalently including methane gas, we used basic unit for CO_2 weight (k-t-CO_2/t-material) based on input-output table [3, 12-15]. GHG emissions from mining, transportation and fabrication of various components are totally included in this table. The CO_2 emission amount of superconducting toroidal coil with weight W_{TFC}(t) is assumed as $99W_{TFC}$(t) [t-CO_2], and that of the laser systems with the cost C_{laser} (M¥) is assumed as $1.98C_{laser}$ (M¥) [t-CO_2].

3. Assessment Results

3.1 Economic and Environmental Assessments

3.1.1 Economic assessment

The economic assessment results for the base designs are shown in Fig. 3 (a) and (b). By Fig. 3 (a), high-beta operation design is superior to low-beta design with respect to the manufacturing cost of the TR fusion island (47% cost reduction). The costs of the superconducting coil and the current drive system mainly are reduced. Because fusion island is made compact and the CD power is reduced due to increasing f_{BS}. On the other hand, the costs of the fusion island for low C_{LD} design is 40% lower than that for high-C_{LD} design. As shown in Fig. 3 (b), COEs of TR-1 and IR(a) are almost same, and COEs of TR-2 and IR(b) are also almost same. Both advanced designs (TR-2 and IR(b)) have 30% lower COE than conventional designs.

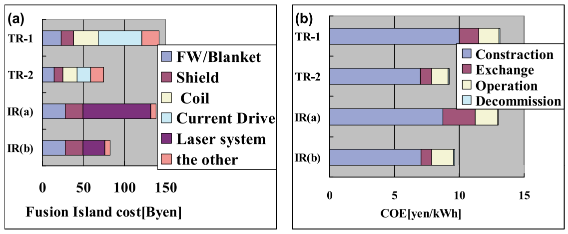

Fig. 3 (a) Cost of manufacturing the fusion island, including laser system, (b) COE (Cost Of Electricity) analysis results.

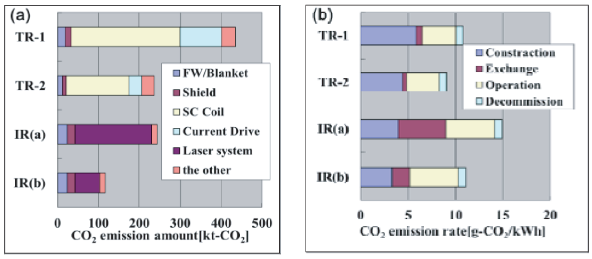

Fig. 4 (a) CO_2 emission amount of manufacturing the fusion island, including laser system, (b) life-cycle CO_2 emission rate analysis results.

3.1.2 CO_2 emission assessment

The CO_2 emission amount assessment results for the base designs are shown Fig. 4 (a) and (b). In Fig. 4 (a), CO_2 emission amount of manufacturing the fusion island of advanced designs are about 50% lower than that of conventional ones. The CO_2 emission form blanket system depends on the type of coolant and structural materials [3]. In the present Flibe/FS (Ferritic Steel) case, the CO_2 fraction of the blanket system shown in Fig. 3 (a) is small compared with the cost fraction of the blanket shown in Fig. 4 (a). In the case of the Li/V blanket system, CO_2 emission is ten times larger than the present Flibe/FS model.

As shown in Fig. 4 (b) the β_N dependence of CO_2 emission rate is rather weak than that of COE for TR. That is because the CO_2 emission from the operation and BOP construction are rather dominant. On the other hand, the C_{LD} dependence of CO_2 emission rate is equivalent to that of COE for IR. That is because CO_2 emission from manufacturing the laser system products to be exchanged is dominant in addition to that from manufacturing initial laser system. We confirmed that reducing C_{LD} is important to reduce CO_2 emission rate in the assessment model.

3.2 Scaling formula for COE and CO_2 emissions

After wide parameter scans, we obtained the following new COE and life-cycle CO_2 emission rate scaling formulas for TR and IR. All the scaling formulas are derived as functions of electric power P_e ($1 \sim 3$ GW), plant availability f_{avail} ($0.65 \sim 0.85$), thermal efficiency f_{th} ($0.35 \sim 0.60$) and operation year t_{oper} ($30 \sim 60$ years). In addition normalized beta β_N ($3 \sim 6$) and maximum magnetic field strength B_{max} ($10 \sim 16$ T) are included for TR and isentrope parameter α_F ($2 \sim 4$) and laser diode unit costs C_{LD} ($1 \sim 5$ yen/W) are checked for IR;

$$COE^{TR} = \frac{10.3}{\left(\frac{\beta_N}{5}\right)^{0.56}\left(\frac{B_{max}}{13}\right)^{0.01}\left(\frac{P_e}{1000}\right)^{0.46}\left(\frac{f_{th}}{0.35}\right)^{0.46}\left(\frac{f_{avail}}{0.75}\right)^{0.84}\left(\frac{t_{oper}}{30}\right)^{0.67}}, \quad (6)$$

$$CO_2^{TR} = \frac{9.36}{\left(\frac{\beta_N}{5}\right)^{0.21}\left(\frac{B_{max}}{13}\right)^{0.00}\left(\frac{P_e}{1000}\right)^{0.21}\left(\frac{f_{th}}{0.35}\right)^{0.24}\left(\frac{f_{avail}}{0.75}\right)^{0.34}\left(\frac{t_{oper}}{30}\right)^{0.35}}, \quad (7)$$

$$COE^{IR} = \frac{10.4 \cdot \left(\frac{\alpha_F}{3}\right)^{0.35}\left(\frac{C_{LD}}{1}\right)^{0.21}}{\left(\frac{P_e}{1000}\right)^{0.46}\left(\frac{f_{th}}{0.35}\right)^{0.42}\left(\frac{f_{avail}}{0.75}\right)^{0.80}\left(\frac{t_{oper}}{30}\right)^{0.63}}, \quad (8)$$

$$CO_2^{IR} = \frac{11.2 \cdot \left(\frac{\alpha_F}{3}\right)^{0.32}\left(\frac{C_{LD}}{1}\right)^{0.20}}{\left(\frac{P_e}{1000}\right)^{0.25}\left(\frac{f_{th}}{0.35}\right)^{0.35}\left(\frac{f_{avail}}{0.75}\right)^{0.23}\left(\frac{t_{oper}}{30}\right)^{0.25}}. \quad (9)$$

The root mean square errors of these scaling lows are less than 2%. The parameter dependence of COE for TR is as same as that for IR. The COE dependence on plant availability and operation year is especially strong. That is because the plant construction cost is very large in the life-cycle cost (about 80%). As for CO_2 emission rate, the parameter dependences are rather weak than those of COE. This is because CO_2 emission percentage from manufacturing the fusion island is lower than its COE percentage. And the plant availability and operation year dependences for IR are rather weak than those for TR. Because the CO_2 emission amount of manufacturing the laser system to be exchanged is very large.

4. Summary

We upgraded PEC (Physics-Engineer-Cost) system code to apply to the inertial fusion energy (IFE) design in order to search for economically and environmentally optimized fusion reactors, and to find out scaling formulas of cost of electricity and CO_2 emission rate on key parameters for TR and IR.

As for COE (Cost-Of-Electricity) assessment, the advantage of high-beta tokamak reactors and the inertial reactors with low laser diode unit cost are clarified. The plant availability and operation year dependences are especially dominant. We clarified long and efficient operation system is very attractive for reducing COE.

As for CO_2 emission assessment, the normalized beta dependence of CO_2 emission rate is rather weak than that of COE. On the other hand, the laser diode unit cost dependence of CO_2 emission rate and that of COE are almost same. This is because the CO_2 emission amount of manufacturing the laser system to be exchanged is dominant. Due to the same reason, the plant availability and operation year dependences of IR are rather weak than those of TR.

From these analysis results, we clarified the key parameters for the realization of economical and environment-friendly future fusion power reactors.

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