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Environmental and economical assessment of various fusion reactors by the calculation of CO_2 emission amount

S. Uemura, K. Yamazaki, H. Arimoto, T. Oishi, T. Shoji

Department of Energy Engineering and Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 466-8603, Japan

We compared several fusion rectors from the view point of CO_2 emission amount. Magnetic confinement systems we evaluated are Tokamak Reactor (TR), Helical Reactor (HR) and Spherical Tokamak reactor (ST). These models are calculated by Physics Engineering Cost (PEC) code. Parameters of Inertial confinement fusion Reactor (IR) is simply calculated by given pellet gains. In addition, different blanket modules and fuels are considered in TR designs. To calculate CO_2 emission amount of fusion reactor defined by plasma parameters and radial build, we used basic unit for CO_2 weights (k-t-CO_2/t-material). Calculation results indicate that CO_2 is the most emitted from the construction stage of coil systems for magnetic confinement fusion reactors. For the IR design, the construction stage of driver system and pellet purification stages involve much CO_2 emission. By comparing fusion reactors with other power generation systems from the view point of CO_2 emission amount, we confirmed that fusion reactor emits less CO_2. Therefore, there is little influence on economics of fusion reactors by introducing carbon tax.

Keywords: Tokamak Reactor (TR), Helical Reactor (HR), Spherical Tokamak reactor (ST), Inertial confinement fusion Reactor (IR), blanket, CO_2 emission amount, Cost Of Electricity (COE)

1. Introduction

Fusion reactor is expected to be one of abundant energy resources in the future. However there are many technological problems to be solved. In addition it is essential to assess safety, economics and environmental burden of fusion reactor. In this paper we calculated the Cost Of Electricity (COE) and CO_2 emission amount for several types of fusion reactors. And to assess economics and environmental issues at once, we considered the case of introduction of carbon tax.

2. Assessment procedure

Confinement systems we evaluated here are three types of magnetic confinement fusion reactors (Tokamak Reactor (TR), Helical Reactor (HR) and Spherical Tokamak reactor (ST)) and Inertial confinement fusion Reactor (IR). Several blanket modules and fuel systems (D-T or D-^{3}He) are considered in TR. We used Physics Engineering Cost code (PEC code) [1, 2] to calculate COE of magnetic confinement fusion reactors. PEC code is a code which calculates plasma parameters and radial build of fusion reactor with input parameters such as net electric power output and ignition margin.

The calculation flow of IR parameter is shown in Fig.1. Driver systems quoted here are Kr-F laser of SIRIUS-P [3] (driver energy is 3.4 MJ with 7.5% efficiency) and heavy ion beam (HIB) [4] (driver energy is 7 MJ with 20.4% efficiency). Repetition rate is calculated

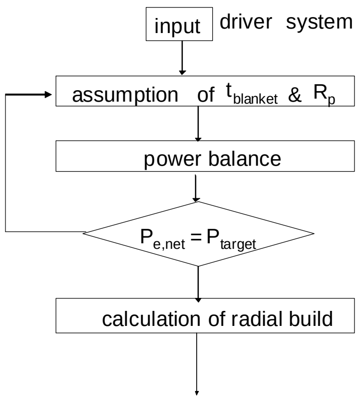

Fig.1 Calculation flow of IR.

by given driver energy and pellet gain. Chamber size is approximated by some other reactor designs [3, 4]. Cost of plant systems except for driver system and pellet production are calculated by the same scaling as PEC code. Driver system and pellet production cost are given by the scaling described in Ref. [4].

To estimate CO_2 emission amounts, we used basic unit for CO_2 weight (k-t-CO_2/t-material) [2, 5, 6]. CO_2 emissions from mining, transport and fabrication are included in this factor.

3. Assessment models

Models of confinement systems and blanket models adopted here are explained below. To compare all of fusion

author's e-mail:s-uemura@ees.nagoya-u.ac.jp

Table1 Main parameters of several magnetic confinement fusion reactors calculated by PEC code

	TR		ST	HR
confinement scaling	ITER Elmy H mode			ISS mode
fuel	D-T	D-^{3}He	D-T	D-T
normalized β value β_N average β value <β> (%)*	β_N=4	β_N=6	β_N=6	<β>=4%
Aspect ratio <A>*	3.5	3.5	1.6	7.8
Average temperature <T> (keV)*	15	42.5	15	10
Plasma major radius R_p (m)	6.3	13.9	4.3	14.9
Toroidal field B_t (T)	6.2	8.4	2.5	4.7
Total fusion power P_{fus} (MW)	3478	4823	4188	2346
Average density <n> ($10^{20}/m^3$)	1.5	1.5	1.0	1.0

* input parameter

Table2 Main parameters of inertial confinement fusion reactors. Driver systems considered here are Kr-F laser system and Heavy Ion Beam (HIB).

laser system	Kr-F	HIB
Driver energy (MJ)*	3.4	7
Driver efficiency*	0.075	0.206
Pellet gain*	120	120
Repetition rate f_{rep}(Hz)	6.5	2.7
Chamber size R_{fw} (m)	4.4	5.8
Total fusion power P_{fus} (MW)	2644	2260

* input parameter

Table.3 Several blanket parameters in TR design

Blanket module	Li/V	Flibe/FS	LiPb/SiC	Li2O/SiC	F-F hybrid
Thermal efficiency*	0.46	0.4	0.5	0.49	0.4
FW/Blanket lifetime W_{life} (MWy/m^2)*	18	15	20	20	15
Toroidal field B_t (T)	6.1	6.2	6.1	5.9	4.7
Total fusion power P_{fus} (MW)	2909	3478	2618	2682	592
Thickness of FW/Blanket $t_{blanket}$ (m)	0.4	0.6	0.8	0.5	0.9
Thickness of shield t_{shield} (m)	0.8	0.7	0.4	0.8	0.6
Neutron wall load L_{wall} (MW/m^2)	3.0	3.3	2.8	2.7	0.9

* input parameters

reactors under the same conditions, 1000MWe net electric power output, 30 years operation period and 0.75 utilization factor are assumed.

In the reference case normalized beta value (average beta value for HR) is determined by the technical performance of reactor models which is considered now. When TR employs D-^{3}He fuel, high temperature and high maximum toroidal field is required to design sufficiency compact and economical reactor. So D-^{3}He fuel reactor is assumed to have high performances (high temperate, magnetic field and beta). Because of the low neutron generation rate of D-^{3}He fuel, we assumed that there is no blanket exchange during D-^{3}He fuel fusion reactors. Main parameters of magnetic confinement fusion reactors calculated by PEC code are listed in Table1.

Pellet gain of IR is given as an input in our calculation. And pellet gain is selected same value for Kr-F laser system reactor and HIB reactor. Li breeder liquid wall chamber is adapted to IR and we assumed that there is no blanket exchange during its operation period. The main parameter of the reference case of IR is listed in Table2.

Blanket modules we adapted to TR are Li breeder with V structural material blanket (Li/V), Flibe breeder with ferrite steel structural material blanket (Flibe/FS), LiPb breeder with SiC structural material blanket (LiPb/SiC), Li_2O breeder with SiC structural material blanket (Li_2O/SiC) and fission fusion hybrid (F-F hybrid) blanket [7]. There is UO_2 in F-F hybrid blanket model so its neutron energy multiplication rate is very high (We assumed 6.0). Each model has a difference in thermal efficiency and wall life time in PEC code [2]. Main parameter of the TR reactor which has different blanket is shown in Table3.

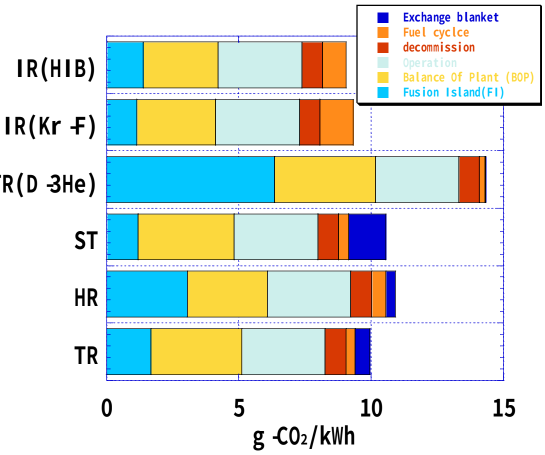

Fig.2 CO_2 emission amount of several fusion reactors.

4. Results

The CO_2 calculation results of reference fusion reactors are shown in Fig.2. The coil construction phase is the most CO_2 emitting stage of magnetic confinement fusion reactors. CO_2 emission amounts from coil system construction account for 10%, 8% and 20% of lifetime CO_2 emission amount of TR, ST and HR, respectively. HR and D-^{3}He fuelled TR needs rather larger coil than D-T fuelled TR and ST, and more CO_2 are emitted at the Fusion Island (FI) construction stage. ST needs more re-circulating power including ohm loss at the normal conducting coil, and more CO_2 are emitted at the Balance Of Plant (BOP) construction stage. On the contrary, HR requires less re-circulating power, and less CO_2 is emitted at the BOP construction stage. Dependence of CO_2 emission amount and plasma major radius on beta value is shown in Fig.3. The achievement of higher beta value leads to more compact system and less CO_2 emission.

CO_2 emission amounts of tokamak reactors with different blanket module are shown in Fig.4. Thermal efficiency is an influential factor to design fusion reactor. A

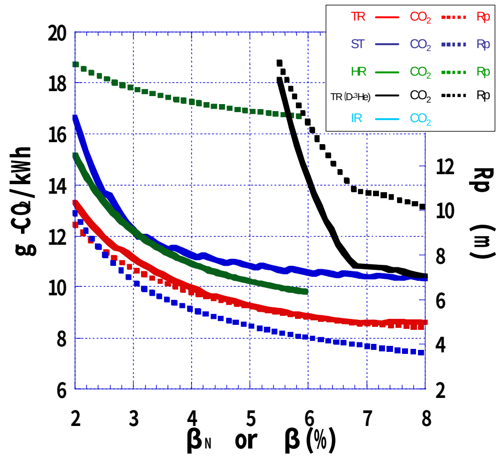

Fig.3 Dependence of CO_2 emission amount and plasma major radius on beta value.

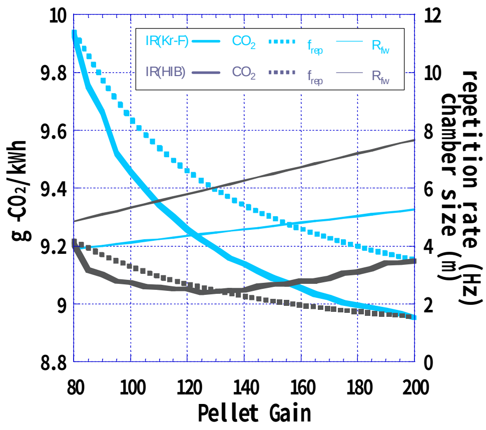

Fig.5 Dependence of CO_2 emission amount, laser repetition rate and chamber size on pellet gain.

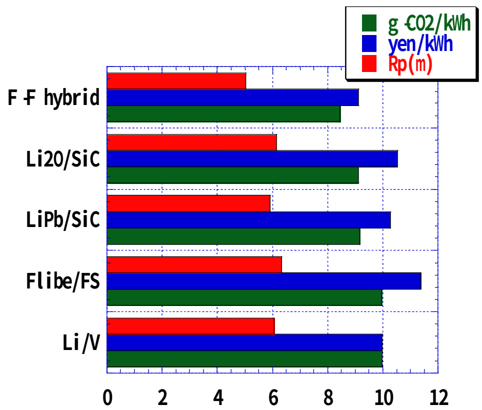

Fig.4 CO_2 emission amount, Cost Of Electricity (COE) and plasma major radius Rp of several TR designs with different blanket modules.

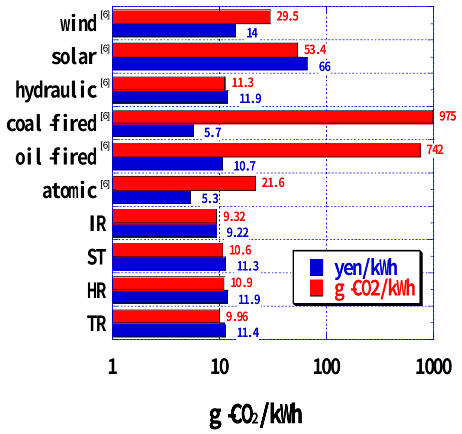

Fig.6 Comparison among fusion reactors and other conventional power plants from the aspect of COE and CO2 emission amount.

higher thermal efficiency model, such as LiPb/SiC or Li_2O/SiC model, can give rise to more compact system and less CO_2 emission than other blanket models. Vanadium needs much electric power to fabricate, so the CO_2 emission amount of Li/V blanket model is rather higher than others. F-F hybrid blanket model modify FI requirements because of its high neutron multiply factor. Therefore it is possible to construct with lower cost and less CO_2 emission amount. But there exists another problem; high level radioactive waste disposal.

Driver construction stage is the most CO_2 emitting stage of IR. Additionally IR emits more CO_2 than magnetic confinement fusion reactor at the fuel cycle stage. However, total CO_2 emission amount from IR is lower than that from magnetic confinement fusion reactors because of its compactness and the assumption that no blanket exchange is required during its operation period. Dependence of CO_2 emission amount, laser repetition rate and chamber size on pellet gain is shown in Fig.5. When pellet gain is low, high laser repetition rate is necessary to attain desired net electric power. High laser repetition rate requires many pellets, and CO_2 emission during fuel cycle is increased. Whereas, when high pellet gain is assumed, large chamber size is necessary to tolerate high fusion heat pulse.

Figure 6 shows the comparison of fusion power pants and other power generation systems from the view point of COE and CO_2 emission amount. Fusion reactors emit less CO_2 than other conventional power plants do [6]. When comparing fusion reactor with atomic power plant, atomic power plant emits more CO_2 in its fuel cycle. Atomic power plant needs uranium concentration, whereas fusion power plant needs tritium separation. In this paper, tritium separation of fusion reactor is optimistically evaluated, so it might be necessary to reconsider it well.

COE of fusion reactor and other power plants in the case of carbon tax introduction is shown in Fig.7. CO_2

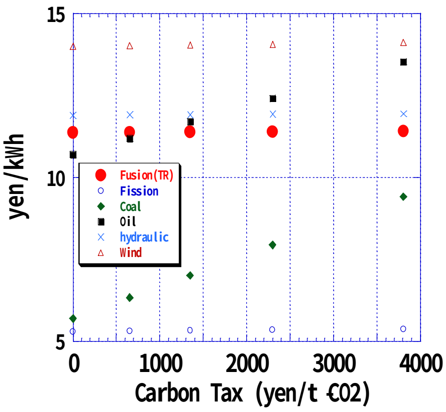

Fig.7 COE of fusion reactor and other power plants in case some carbon tax is introduced

emission amount from fusion reactor during its life time is far less than those from thermal power plants. Introduction of carbon tax has little impact on COE of fusion reactors alike conventional clean energy recourses like solar and wind power etc. Carbon taxes assumed here are 1350, 3808, 655 and 2300 yen/kWh (actual example of Norway, actual example of Sweden, a plan of Japanese environment ministry and recommendation of Central Research Institute of Electric Power Industry [8], respectively.)

5. Conclusion

We calculated CO_2 emission amount from various fusion reactors including inertial confinement fusion reactor. CO_2 is emitted mainly at the magnet system construction stage for magnetic confinement fusion reactors. So HR and D-^{3}He fuelled fusion reactors with bigger magnet system emits more CO_2 during its construction stage. FI of ST is so compact that CO_2 is less emitted during its construction, but BOP construction stage involves much CO_2 emission because of its large re-circulating power. For inertial confinement fusion reactors CO_2 is emitted mainly at the driver system construction stage. The chamber size and quantity of pellet decided by repetition rate are also strongly related to CO_2 emission amount. After comparing fusion reactors with other power generation systems from the view point of CO_2 emission amount, we conclude that fusion reactor emits less CO_2. There is little influence on economics of fusion reactors even by introducing carbon tax.

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