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IAEA-CN-56/G-1-1-3 (R)

NATIONAL INSTITUTE FOR FUSION SCIENCE

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D-^{3}He Fueled FRC Reactor "ARTEMIS-L"

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Abstract

A neutron-lean D-^{3}He fueled FRC fusion reactor is studied on the bases of former high-efficiency ARTEMIS design. Certain improvements such as effective axial contracting plasma heating and cusp-type direct energy converters as well as an empirical scale of the energy confinement are introduced. The resultant total neutron load onto the first wall of the plasma chamber is as low as 0.1 MW/m^2, which enable the life of the first wall or the structural materials to be longer than the whole life of the reactor. The attractive characteristics of the neutron-lean reactor follow in the ARTEMIS design: it is socially acceptable in views of radioactivity and fuel resources, and the cost of electricity appears to be cheap compared with that from a light water reactor. Critical physics and engineering issues for performing the ARTEMIS-L reactor are clarified.

Keywords :neutron-lean fusion, ARTEMIS-L, D-^{3}He,
Reactor Design, Commercial Power Plant

1. Introduction

Progress in fusion research has been achieved mainly on tokamak concept and a scientific feasibility experiment will soon be performed by the use of this concept. Nevertheless, a number of engineering problems have to be resolved before deuterium-tritium fueled fusion become acceptable commercial power reactors. Engineering problems crucial for performing commercial D-T fusion reactors are attributed to huge 14- MeV neutrons. Those problems include neutron damages of the first wall and structural materials of the reactor and disposal of large amount of radioactive wastes and seem to be very hard to resolve.

Deuterium-helium3 fusion fuels are considered to mitigate those engineering problems. With those fuels, the fraction of the power carried by neutrons in the total fusion power can be as small as a few percent, and more than 70 % of fusion power is carried by charged particles such as 14.7-MeV fusion protons and diffused thermal fuel component. By conducting these charged particles to highly efficient direct energy converters, we can achieve an environmentally sound, highly efficient, and cheap fusion plant with D-^{3}He fuels. A very high β-value, a very high plasma temperature, and a good confinement of the plasma energy are required as well as an accessibility of high power direct energy converters to utilize D-^{3}He fuels for a commercial fusion reactor. In our present knowledge, plasmas confined in a field-reversed configuration (FRC) meet those requirements [see Ref.1].

A comprehensive conceptual design of D-^{3}He fueled FRC fusion reactor ARTEMIS [2] has been carried out for the purpose of examining attractive characteristics of a combination of D-^{3}He fuels and an FRC. Because of its small neutron yields, the engineering problems are drastically mitigated and the estimated cost of electricity from the plant is cheaper than that from a conventional light water reactor. The plasma parameters of ARTEMIS was optimized, however, so as to maximize the overall plant efficiency up to 60 %, and the resultant neutron load onto the first wall is still as large as 0.42 MW/m^2. It may be, therefore, worth examining another version of D-^{3}He fueled FRC fusion reactor by minimizing the neutron yields from the point of views of retaining attractive characteristics of ARTEMIS.

2. Optimization of D-^{3}He burning FRC plasmas

The figures of merit of fusion reactor such as the overall plant efficiency P_{net}/P_f or the ratio of the power carried by neutrons P_n to the net electric power P_{net} can be estimated on the bases of the continuity equations of particle numbers of the respective species and the power balance equation. An averaged beta value <β> is assumed to be 98 % and the particle confinement time τ_p is approximated as twice the energy confinement time τ_E, which can be seen in FRC experiments [3]. Deformation of the velocity distribution of ions from the maxwellian distribution attributed to nuclear reactions are taken into considerations [4]. The power carried by neutrons P_n and the overall plant efficiency are exhibited in Fig.1.(a) and (b), respectively as functions of the density ratio n_{3He}/n_D and the averaged plasma

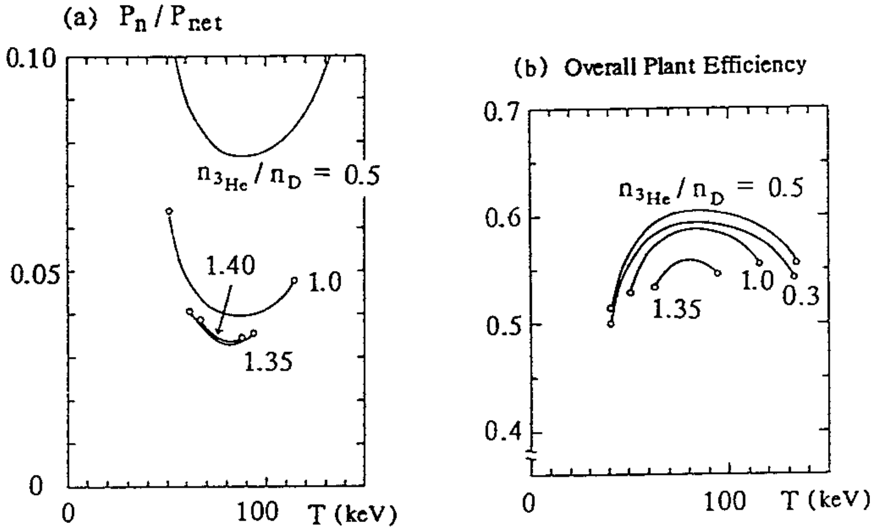


Fig.1.(a) The ratio of power carried by neutrons P_n to the net electric power P_{net}, and (b) the overall plant efficiency as functions of the density ratio n_{3He}/n_D and the averaged plasma temperature T: Neutron yields take their minimum at $T = 83.5$ keV and $n_{3He}/n_D = 1.35$, whereas the overall plant efficiency takes it maximum at $T = 85$ keV and $n_{3He}/n_D = 0.5$. The averaged beta $\langle\beta\rangle = 98\,\%$ and $\tau_p = 2\,\tau_E$ are assumed.

temperature T. The power ratio of the neutron P_n/P_{net} takes its minimum value 0.033 and resultant overall plant efficiency is 55.8 % as the density ratio $n_{3He}/n_D = 1.35$ and averaged plasma temperature $T = 83.5$ keV.

The required confinement parameter $n_e\tau_E = 3.5\times 10^{21}$ sec/m^3 can be obtained by a choice of the plasma radius r_s according to the empirical confinement scaling [5]:

$$\tau_E(sec) \cong 3.0\times 10^{-5} \; \{r_s(m)/\sqrt{\rho_{i0}}\,(m)\}^{2.7}\, T\,(keV)$$

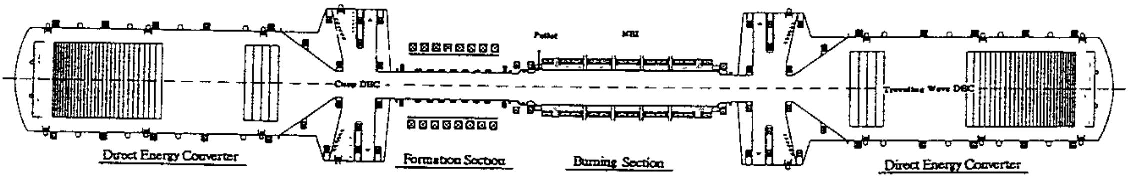
and the external magnetic field. Quantities r_s and ρ_{i0} denote respectively the plasma radius and "gyro-radius" estimated by the external magnetic field. Since a strong external magnetic field or high plasma density gives a small plasma radius and consequently a large heat flux, we reasonably applied the maximum heat flux to be 2 MW/m^2. Thus we have the plasma radius $r_s = 1.7$ m of the optimized FRC plasma. The representative parameters of this D-^{3}He burning FRC plasma are annexed to Fig.2.

3. Constitution of ARTEMIS-L

The whole view of the neutron-lean D-^{3}He fueled FRC reactor

ARTEMIS-L is exhibited in Fig.2. The reactor consists of a formation section, a burning section, and a pair of direct energy converter sections, which are connected linearly so as to easy to disjoin or repair the device.

An initial FRC plasma is produced in the formation section. The chamber is arranged axisymmetrically so as to produce D-^{3}He/FRC plasmas reliably even for a case of very low gas pressure. A fast rising theta-pinch discharge in a filling gas pressure of 0.05 Pa and cusped bias field of 0.035 T produces an FRC plasma. At the latest phase of the pinch discharge, an axial contraction of the plasma is triggered [6], which induces collisionless shock heating giving a plasma temperature $T_i = 3$ keV. As the electron density n_e is $4.1\times10^{20}/\mathrm{m}^3$ and the external magnetic field B_e is 0.7 T, an ion temperature of 3 keV is obtained. The FRC plasma is then translated to the adjacent burning section along lines of force.



Net Electric Power : P_{net}	1.0 GWe
Fusion Power : P_f	1.79 GW
Power to TWDEC	0.55 GW
Power to CDEC	0.58 GW
Power to Heat Converter	0.67 GW
First Wall Radius	2.28 m
Heat Flux	2.00 MW/m^2
Wall Load of Neutrons	0.10 MW/m^2

D^{3}He Fusion Reactor [ARTEMIS-L]

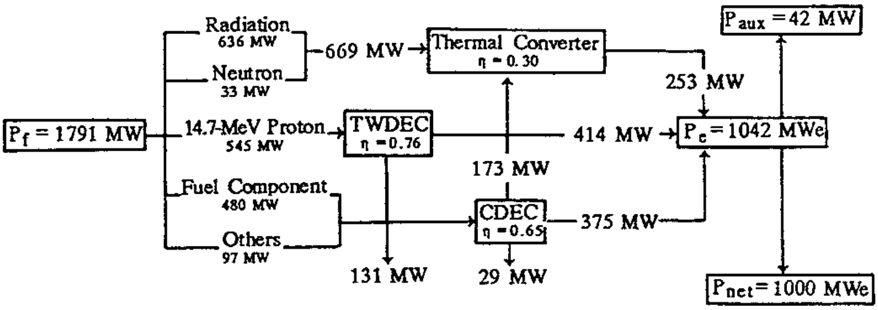
Electron Density	5.12×10^{20} m^{-3}
Density Ratio : $n_{^3He}/n_D$	1.35
Averaged Temperature	83.5 keV
Magnetic Field	5.36 T
Averaged Beta Value	0.98
Plasma Radius × Length	1.68 m × 22.2 m
Plasma Current	190 MA
Energy Confinement Time	6.87 sec

Fig.2.The whole view of D-^{3}He fueled FRC reactor ARTEMIS-L composed of formation section, burning section, and direct energy converters.

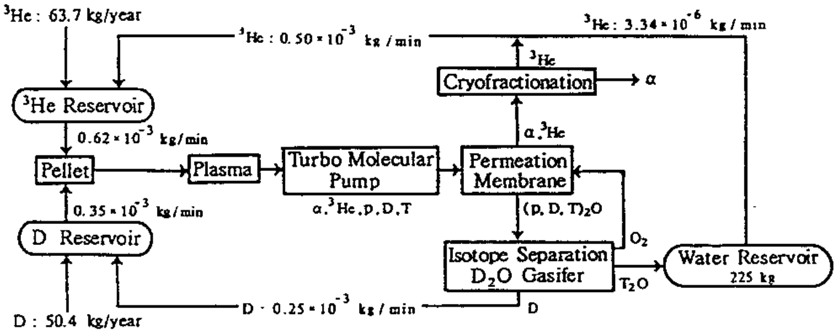
A D-^{3}He burning FRC plasma is evolved for 50 sec after the translation with the aid of a combination of neutral beam injection of 1 MeV/100 MW, fueling, and a slow magnetic compression up to $B_e = 5.4$ T. Concerning the fueling, we introduced the "Pac-Man" method: A small deuterium ice pellet inside which liquid ^{3}He is contained is injected into the burning section. At the moment, FRC moves towards the pellet with a speed of 5×10^5 m/sec and put it deep inside the FRC before the evaporation of the pellet.

A large fraction in the D-^{3}He fusion energy is carried by charged particles along the lines of force to a pair of direct energy converters (DEC) section. The power 577 MW carried by diffused fuel components is induced to positive-biased plates located closed to line cusps and the power 545 MW carried by 14.7-Mev protons is converted to electricity through the traveling wave direct energy converters. Another fraction in the fusion power is 669 MW and converted to heat in the first wall as well as the neutron shielding blanket with borated heavy water and ultimately converted to electricity.

The power and particles flows are illustrated in Fig.3. Approximately equal amount of thermal power, power carried by 14.7-MeV protons, and power carried by thermal diffused fuel components are respectively induced to thermal converters, traveling wave direct energy converters, and cusp type direct energy converters. Conversion efficiencies of respective converters are estimated as 30 %, 76 %, and 65 %. Thus, we obtain an net electric power of 1,000 MWe. The estimated overall plant efficiency is approximately 55.8 %, which should be compared with the value 60.1 % from the high-efficiency ARTEMIS.



(a) Power Flow



(b) Particle Flow

Fig.3.(a) The power flow chart and (b) the particle flow chart of D-^{3}He fueled FRC reactor ARTEMIS-L: The overall plant efficiency is estimated as 56 % with helium fuel of 63.7 kg/year. The duty factor is assumed to be 75 %.

Approximately 63.7 kg of helium3 and 50.4 kg of deuterium are consumed for 9 month's operation a year. Diffused fuel helium3 and deuterium are pumped out with turbo molecular pumps together with fusion products: ^{4}He, ^{1}H, and T. Helium3 and deuterium are separated severally from others and fed back to the fuel reservoirs. Tritium is oxidized to form T_2O whose total content of 225 kg is stored in a water reservoir. A small quantity 3.3×10^{-6} kg of helium3 is produced in the water reservoir through $T(\beta^-)^3He$ reaction, which is fed back also to the helium3 reservoir.

4. Discussions of the results

All the bases of the engineerings applied to our reactor design are conventional. No fuel breeding is necessary and the neutron flux is as low as 2.9×10^{16} n/m²·sec. The applied maximum of the magnetic field and stress of materials are respectively less than 6.5 T and 350 MPa. No development of new materials, therefore, is needed to perform the reactor. A straight structure and low radioactivity allows us an easy maintainability.

Because of a simple and compact structure of the D-^{3}He fueled FRC reactor ARTEMIS-L, the total direct cost and the total plant capital cost estimated after the ESECOM studies are respectively as cheep as 1,030 M$ and 1,800 M$; and the cost of electricity (COE) is estimated as 30.5 mill/kW·h, which is cheaper than that from a light water reactor. We assumed the cost of fuel ^{3}He to be 0.2 M$/kg. The fraction of the fuel cost in the COE is only 0.3 % and uncertainty in the fuel cost doesn't affect the COE significantly.

It appears that the neutron-lean D-^{3}He fueled FRC reactor ATREMIS-L is attractive in views of the social acceptability and the cost of electricity. Nevertheless, developments of highly efficient neutral beams of 1 MeV and high power direct energy converters are needed to perform ARTEMIS-L reactor. The detailed physics on plasma transports and microinstabilities relating to the anomalous electron transport are the important problems to be studied.

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