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Problems with p^6Li plasma in a fusion reactor

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Problems of using proton-Lithium-6 (p^6Li) fuel are energy losses that occur in a fusion reactor. Investigating the energy balance equation in this fuel is significant. The p^6Li reaction is termed aneutronic, as it produces relatively few neutrons and requires none for breeding. The energy from the charged reaction products can be directly converted to electrical power at a much higher efficiency than Deuterium-tritium (DT). In this paper, the approach of optimum performance of p^6Li fuel in fusion reactors was presented investigating the energy balance equations for ions and electrons. The optimum fuel mixture is almost $\frac{n_p}{n_{^6Li}} = 3$. The performance was determined to be p^6Li and is favorable for Ti=800 keV.

Key words: Fuel, reactor, energy, radiation.

INTRODUCTION

Choice of suitable fuel for fusion reactors is subject to several conditions especially in terms of economic, safety and environmental parameters, while it is very difficult to satisfy all of them. Risks resulting from the release of radioactive materials run as a result of activation of equipment and presence of tritium in the plasma system. Each fusion plasma Deuterium-tritium (DT) releases 17.6 MeV which turn into a kinetic energy with 3.5 MeV helium and 14.1 MeV neutron (Yu and Yu, 2009).

$$^2_1D + ^3_1T \rightarrow ^4_2He(3.5\text{ MeV}) + n(14.1\text{MeV}) \quad (1)$$

DT reaction has two major disadvantages: (1) It hurts the reactor equipments due to the production of neutron, (2) reproduction of tritium has more problem and it produces a radial space resulting from blanket of lithium (Stott, 2005). The deuteron-deuteron (DD) fusion plasmas are very attractive since deuterium is abundant and it eliminates the need for breed tritium. The produced neutrons are not a lot and they have less energy than DT plasma. However, there is atmospheric pollution due to tritium production through DD fusion plasmas. D^3He plasma is called aneutronic which produces relatively few neutrons and nothing is needed for breeding. Energy resulted from the charged products can directly change into the electric power in a much higher efficiency than DT. Thus, to do the same radioactivity as the DT, higher temperatures 50 to 100 keV are needed. In general, one of the most important alternatives in future fusion reactors

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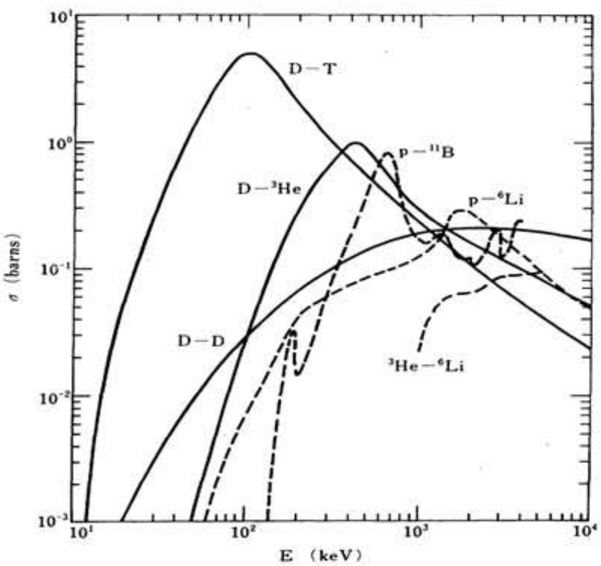


Figure 1. Cross -section as a function of energy for different plasmas (Momota et al., 1980).

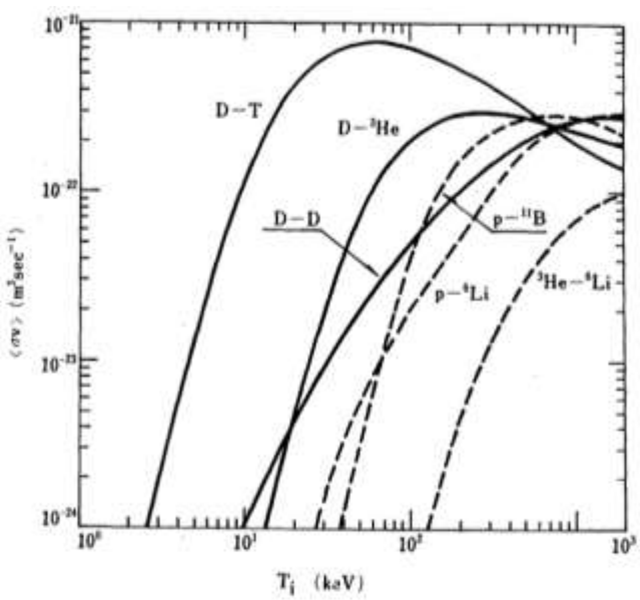


Figure 2. Average reactivity as a function of ion temperature for different plasmas (Momota et al., 1980).

is D^3He plasma.

$$ {}_1^2D + {}_2^3He \rightarrow {}_2^4He(3.6MeV) + {}_1^1H(14.7\ MeV) \quad (2)$$

However, the share of "cleanless" has not been done in D^3He completely due to production of neutrons and tritium through the DD side fusion plasma with equal probability as follows:

$$ {}_1^2D + {}_1^2D \rightarrow {}_1^3T(1.01MeV) + {}_1^1H(3.02\ MeV) \quad (3)$$

$$ {}_1^2D + {}_1^2D \rightarrow {}_2^3He(0.82MeV) + n(2.45\ MeV) \quad (4)$$

Since tritium does radioactive decay and neutron irradiation influences the reactor equipment, it is necessary to take some methods to limit the radioactivity caused by neutrons in order to prevent from releasing radioactive tritium. Another aneutronic fusion plasma is the plasma of proton with the lithium-6 (p^6Li). This plasma:

$$ p + {}_3^6Li \rightarrow {}_2^4He(1.7MeV) + {}_2^3He(2.3MeV) \quad (5)$$

is proposed due to the little load of both components. Helium-3 would regress to plasma in the catalyzed mode and the plasma

$$ \frac{d}{dt}\left(\frac{3}{2} n_i T_i\right) = P_{ci} + P_{si} - P_{Li} - P_{ie} = 0 \quad (6)$$

provides a very attractive net Q-value. This plasma is not ignitable in low temperatures and it has a very much energy losses in a fusion reactor. Therfore, the study of problems with p^6Li plasma in a fusion reactor is significant.

THE PROPERTIES OF P^6LI PLASMA

DT fusion reactors inherently encounter with economic and environmental challenges. Therefore, it is strongly emphasized to use a proper alternative among the advanced plasmas. In aneutronic fusion, instead of neutron, most of the energy is released through charged particles. In case of aneutronic plasmas such as D^3He, the released tritium and the problems with radioactive wastes decreased. Neutron is produced indirectly through DD and DT side plasmas. D^3He fusion reactor suffers from the following disadvantages: (1) Helium-3 is only available through the decay of tritium in proton bomb and also in the future space exploitation programs while just a few countries can afford it or it is produced in the fusion of deuterium-tritium; (2) D^3He needs a higher temperature, a more beta and a better containment than DT plasma. p^6Li fusion reaction is an aneutronic advanced fuel. Figures 1 and 2 show a cross-section in terms of energy and average reactivity versus ion temperature for different plasmas, respectively. The p^6Li fusion plasma has advantages: (1) decreases neutron production; (2) no need for Lithium blanket requirement; (3) reduces tritium inventory; (4) direct electrical conversion; (5) optimum chain plasma features. Unfortunately, it has disadvantages including: (1) high bremsstrahlung radiation; (2) produces indirect radioactive ^7Be and ^{11}C; (3) utilizes condensable plasma (^6Li); and (4) high-temperature for ignition (Mily, 1981).

ENERGY BALANCE IN P^6LI PLASMA

It is necessary in the reactors that the input power be sufficiently low when it is compared to the power output for production of a great net power. The study of the p^6Li plasma is important in equilibrium state. The conditions is different for "ideal ignition" and "ignition" cases. In "ideal ignition" which are lower sets for the operating temperature in the plasma. In “ignition” mode is restricted; the pressure, energy confinement time, and temperature for the plasma in stable mode under real condition. The mode of ignition is more practical in this plasma. It is assumed without external power for sustentation of the p^6Li plasma. Here, ion and electron energy balance equations reviewed for this plasma. Ion energy balance equation as:

$$\frac{d}{dt}\left(\frac{3}{2}n_i T_i\right) = P_{ci} + P_{si} - P_{Li} - P_{ie} = 0 \tag{7}$$

where P_{ci} is the amount of energy transferred from charged particles to ions per unit of time, P_{si} is the injected power, P_{Li} is expended energy of each ion per unit of time and P_{ie} is the rate of energy losses by ions as the follow (Spitzer, 1940):

$$P_{ie} = 7.61\times10^{-28} n_e \sum_i \frac{Z_i^2 n_i \ln\Lambda}{\mu_i T_e^{\frac{3}{2}}}\left(1+\frac{m_e}{m_i}\frac{T_i}{T_e}\right)^{-\frac{3}{2}}\left(1+\frac{0.3T_e}{m_e c^2}\right)\left(T_i - T_e\right) \quad \frac{W}{cm^3} \tag{8}$$

Electron and ion temperature T_e, T_i and the electron rest energy $m_e c^2$ are in eV, m_i is the ion mass ($m_i = \mu_i m_p$, m_p is the proton mass) and density n is in cm^{-3}. The Coulomb logarithm is $\ln\Lambda \approx 31 - \ln(\frac{\sqrt{n_e}}{T_e})$ (Fundamenski and Garcia, 2007). Electron energy balance equation is:

$$\frac{d}{dt}\left(\frac{3}{2}n_e T_e\right) = P_{ce} + P_{se} + P_{ie} - P_{Le} - P_B - P_C = 0 \tag{9}$$

In comparison with Equation 8, bremsstrahlung and cyclotron power are the different quantities. P_B is bremsstrahlung radiation power as follows (Nevins, 1998):

$$P_B = 1.62\times10^{-32} n_e^2 \sqrt{T_e}\left\{\sum_i \frac{Z_i^2 n_i}{n_e}\left[1+0.7936\frac{T_e}{m_e c^2}+1.874\left(\frac{T_e}{m_e c^2}\right)^2\right]+\frac{3}{\sqrt{2}}\frac{T_e}{m_e c^2}\right\} \quad \frac{W}{cm^3} \tag{10}$$

P_C is cyclotron radiation. This can be confined by the magnetic field in an inertial fusion reactor. The calculations show that the amount of $T_i = 800 keV$ and $T_e = 300 keV$ are almost ideal conditions with considered criteria. Fusion power per unit volume produced is:

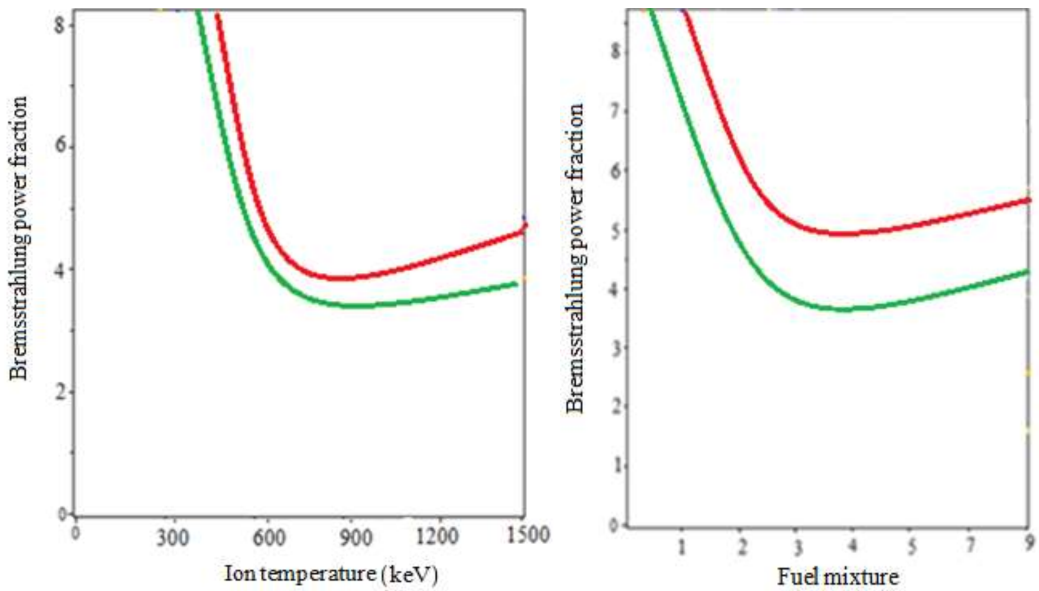
$$P_f = n_p n_{^6Li} \langle \sigma\upsilon \rangle E_{fus} = 1.602.10^{-19}\frac{\varepsilon}{(\varepsilon+3)^2} n_e^2 \langle \sigma\upsilon \rangle E_{fus} \quad \frac{W}{cm^3} \tag{11}$$

where E_{fus} is the released energy (in eV) and $\varepsilon = \frac{n_p}{n_{^6Li}}$. P_f is equal with P_{p^6Li}. Investigations indicate that P_f is maximized for p^6Li plasma by assuming $\varepsilon = 3$ with $T_e = 300 keV$ and $n_e = 10^{25} cm^{-3}$. The results show that P_f and P_B increase with high T_e and n_e. Figure 3a displays the ideal T_i is 800 keV. In this state, P_B is minimized. Figure 3b shows that the ideal fuel mixture is $\varepsilon = 3$. In this factors, P_B is more than P_f. Figure 4a shows that P_B reduces with low T_e. Figure 4b indicates that $\frac{P_{ie}}{P_f}$ decreases with T_e and low $\ln\Lambda$.

The investigations show T_i is also important in $\frac{P_{ie}}{P_f}$ value. $\frac{P_{ie}}{P_f}$ reduces with in low T_i. P_B decreases in low T_e and it makes an enhancement in $\frac{P_{ie}}{P_f}$.

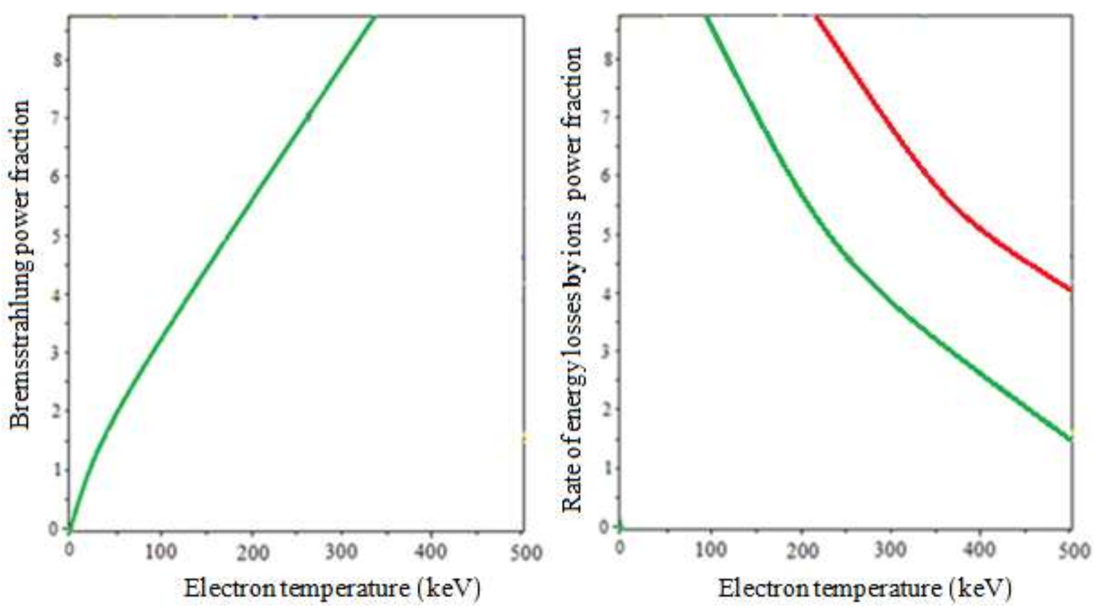
CONCLUSION

This study is showed that for the ignition of p^6Li fuel in a fusion reactor, two important problems would emerge; the lossed energy and the need for high-temperature electrons and ions. T_i is obtained by the use of $\frac{P_B}{P_f}$. It has been determined that the operation T_i is almost 800 keV. Coulomb logarithmic decreased to $\ln\Lambda = 5$ and improved p^6Li plasma performance. In this case, P_B is more than P_f. At high T_e, radiation losses are very much. Calculations show P_B and P_f increase with high T_e and n_e. P_B is minimized with creating appropriate fuel composition. P_B increases with high T_e. Also, T_e and T_i are impressible in $\frac{P_{ie}}{P_f}$.



a **b**

Figure 3. P_B/P_f as a function of (a) T_i (b) ε (red color for $\ln\Lambda = 20$ and green color $\ln\Lambda = 5$).



a **b**

Figure 4. (a) P_B/P_f ; (b) P_{ie}/P_f ; as a function of T_e (red color for $\ln\Lambda = 20$ and green color $\ln\Lambda = 5$).

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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