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Problems with \textsuperscript{6}Li plasma in a fusion reactor

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Problems of using proton-Lithium-6 (\textsuperscript{6}Li) fuel are energy losses that occur in a fusion reactor. Investigating the energy balance equation in this fuel is significant. The \textsuperscript{6}Li 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 \textsuperscript{6}Li fuel in fusion reactors was presented investigating the energy balance equations for ions and electrons. The optimum fuel mixture is almost \( \frac{n_{\text{p}}}{n_{\text{\textsuperscript{6}Li}}} = 3 \). The performance was determined to be \textsuperscript{6}Li 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).

\[ \text{\textsuperscript{2}}D + \text{\textsuperscript{3}}T \rightarrow \text{\textsuperscript{4}}He(3.5 \text{ MeV}) + n(14.1 \text{MeV}) \]  

(1)

DT reaction has two major disadvantages: (1) It hurts the reactor equipment 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. \textsuperscript{3}He 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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is D³He plasma.

\[ _{2}^{2}\text{D} + _{2}^{3}\text{He} \rightarrow _{2}^{4}\text{He}(3.6\text{MeV}) + _{1}^{1}\text{H}(14.7\text{MeV}) \]  (2)

However, the share of “cleanless” has not been done in D³He completely due to production of neutrons and tritium through the DD side fusion plasma with equal probability as follows:

\[ _{2}^{2}\text{D} + _{1}^{2}\text{D} \rightarrow _{2}^{3}\text{T}(1.01\text{MeV}) + _{1}^{1}\text{H}(3.02\text{ MeV}) \]  (3)

\[ _{2}^{2}\text{D} + _{1}^{3}\text{H} \rightarrow _{2}^{4}\text{He}(0.82\text{MeV}) + _{0}^{1}\text{n}(2.45\text{ MeV}) \]  (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 (p⁶Li). This plasma:

\[ p + _{3}^{4}\text{Li} \rightarrow _{2}^{4}\text{He}(1.7\text{MeV}) + _{2}^{3}\text{He}(2.3\text{MeV}) \]  (5)

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

\[ \frac{d}{dt} \left[ -n_{T} \right] = P_{\text{in}} + P_{\text{Li}} - P_{\text{ef}} = 0 \]  (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. Therefore, the study of problems with p⁶Li plasma in a fusion reactor is significant.

THE PROPERTIES OF P⁶LI 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 D³He, the released tritium and the problems with radioactive wastes decreased. Neutron is produced indirectly through DD and DT side plasmas. D³He 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) D³He needs a higher temperature, a more beta and a better containment than DT plasma. p⁶Li 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 p⁶Li 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 ¹¹C; (3) utilizes condensable plasma (⁶Li); and (4) high-temperature for ignition (Mily, 1981).
ENERGY BALANCE IN $^{6}\text{Li}$ 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 $^{6}\text{Li}$ 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 sustention of the $^{6}\text{Li}$ plasma. Here, ion and electron energy balance equation are reviewed for this plasma. Ion energy balance equation as:

$$\frac{d}{dt}\left(\frac{3}{2}n_{i}T_{i}\right) = P_{ci} + P_{si} - P_{Li} - P_{ie} = 0$$

(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):

$$P_{i} = \frac{7.61 \times 10^{-3}n_{i}}{m_{i}c^{2}}\sum_{n}Z_{i}^{2}n_{i}^{2}\ln \Lambda \left(\frac{T_{i}}{T_{e}}\right)^{2} \left(1 + \frac{m_{i}}{m_{p}}\right)\left(1 + \frac{0.3T_{i}}{m_{e}c^{2}}\right)(T_{i} - T_{e}) \frac{W}{cm^{3}}$$

(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 ( $m_{i} = \mu m_{p}$, $m_{p}$ is the proton mass) and density $n$ is in cm$^{-3}$. The Coulomb logarithm is $\ln \Lambda = 31 - \ln \left(\frac{\sqrt{m_{e}}}{T_{e}}\right)$ (Fundamenski and Garcia, 2007). Electron energy balance equation is:

$$\frac{d}{dt}\left(\frac{3}{2}n_{e}T_{e}\right) = P_{ce} + P_{se} + P_{ie} - P_{Bi} - P_{Bc} = 0$$

(9)

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

$$P_{B} = 1.62 \times 10^{-3}n_{i}\sqrt{T_{i}} \left[\sum_{n}Z_{i}^{2}n_{i}^{2}\left(1 + 0.7936 \frac{T_{i}}{m_{e}c^{2}} + 1.874(\frac{T_{i}}{m_{e}c^{2}})^{2}\right) \left(\frac{3}{2} \frac{T_{i}}{m_{e}c^{2}}\right)\right] \frac{W}{cm^{3}}$$

(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 $T_{e}$=800keV and $T_{i}$ = 300keV are almost ideal conditions with considered criteria. Fusion power per unit volume produced is:

$$P_{i} = n_{i}n_{e} < \sigma \nu > E_{\text{max}} = 1.602 \times 10^{19} \frac{e}{(\varepsilon + 3)^{2}} < \sigma \nu > E_{\text{max}} \frac{W}{cm^{3}}$$

(11)

where $E_{\text{max}}$ is the released energy (in eV) and $\varepsilon = \frac{n_{e}}{n_{i}}$. $P_{i}$ is equal with $P_{\text{fus}}$. Investigations indicate that $P_{i}$ is maximized for $^{6}\text{Li}$ plasma by assuming $\varepsilon = 3$ with $T_{e}$ = 300keV 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 $P_{i}$. Figure 4a shows that $P_{b}$ reduces with low $T_{e}$. Figure 4b indicates that $\frac{P_{e}}{P_{f}}$ decreases with $T_{e}$ and low $\ln \Lambda$.

The investigations show $T_{i}$ is also important in $\frac{P_{e}}{P_{f}}$ value. $\frac{P_{e}}{P_{f}}$ reduces with in low $T_{i}$. $P_{b}$ decreases in low $T_{e}$ and it makes an enhancement in $\frac{P_{e}}{P_{f}}$.

CONCLUSION

This study is showed that for the ignition of $^{6}\text{Li}$ fuel in a fusion reactor, two important problems would emerge; the losted 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 $^{6}\text{Li}$ 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 impressive in $\frac{P_{e}}{P_{f}}$.
CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES


