2 Fusion Reactor and Fusion Reactor Materials

2.1 Energy Deposition of Energetic Charge Particle in Lithium Vapor①

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Key words Divertor First wall Vapor of liquid lithium

Investigation on the new idea and technology application to the high fusion power density is the key issue for development of economically competitive fusion energy system. The free surface of liquid lithium to be used as energy depletive first wall and divertor plate in fusion reactor is a promising scheme. The heat of evaporation of lithium atom is about 10 times higher than water (≈ 1.5 eV per atom for lithium). A simple calculation can show boiling lithium at 1437 K has the saturated pressure about 0.035 MPa, that is equivalent to evaporation rate $\approx 10^{22}$ atoms $\cdot$ cm^{2} $\cdot$ s^{-1}[1]. Therefore 6 MW $\cdot$ m^{-2} surface heat fluxes can be removed through vaporization and vapor plasma radiation. However overmuch evaporation rate can jeopardize plasma normal operation. Generally speaking, evaporation rate should be limited to 10^{20} atoms $\cdot$ cm^{2} $\cdot$ s^{-1} or less in order to maintain plasma normal operation. The key problem is whether liquid lithium vapor cloud can sufficiently absorb the energy of plasma particles impinging onto first wall and divertor plate making their all energy deposited into lithium vapor cloud and radiated to the much larger vacuum vessel area via soft X ray emission. As a result the surface temperature of liquid lithium couldn't rise as high as boiling temperature and hence evaporation rate is limited. Preliminary investigations are presented in this paper.

1 Calculations of stopping power for different energy ranges

Under the intense deposition of heat flux, the liquid lithium first wall and divertor plate rapidly evaporate and create large amount of lithium vapor cloud. The vapor cloud will be heated by incident plasma particles and be-

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come lithium vapor plasma. The interaction model between lithium vapor plasma and incident plasma particles mainly concerns about the energy deposition of charge particles from SOL, that is the stopping power of lithium vapor plasma to the incident particles. The energy loss of incident plasma particles travelling through lithium vapor is primarily resulted from ionization and excitation of lithium atoms or not fully ionized ions. For low energy plasma ions, elastic scattering also can contribute to an appreciable energy loss. For nonrelativistic plasma ions, the bound electron stopping power can be given by the Bethe equation [2]:

$$\left.\frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}s}\right|_B=\frac{4\pi N_{\mathrm{A}}Z_{\mathrm{eff}}^2\rho e^4 Z_{\mathrm{Li}}}{m_e c^2\beta^2 A_{\mathrm{Li}}}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{\tilde{I}}\right)-\beta^2-\sum_i c_i/Z_{\mathrm{Li}}\right] \quad (1)$$

where Z_{eff} is the effective charge of incident ion, W_{i} is the kinetic energy of incident ion, N_{A} is Avogadro's number, ρ is density of lithium vapor, A_{Li} is atomic weight of lithium vapor, Z_{Li} is mean charge number, β is projectile ion velocity over light velocity, m_e is electronic mass, $\tilde{I}$ is average ionization potential of vapor plasma, $\sum c_i/Z_{\mathrm{Li}}$ is sum of the effects of shell corrections on the stopping charge.

For low energy ions, the Lindhard model is used. In this model, not only excitation and ionization of lithium atoms but also the elastic Coulomb collisions of the ion and the nucleus of the lithium atom need to be considered. The electronic stopping power is given by Ref. [3]:

$$\left.\frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}s}\right|_L=C_{\mathrm{Lss}}W_{\mathrm{i}}^{1/2} \quad (2)$$

where C_{Lss} is a constant that depends on both the incident ion and the target material parameters:

$$C_{\mathrm{Lss}}=\frac{N_{\mathrm{A}}\rho}{A_{\mathrm{Li}}}\frac{1.212Z_{\mathrm{eff}}^{7/6}Z_{\mathrm{Li}}}{(Z_{\mathrm{eff}}^{2/3}+Z_{\mathrm{Li}}^{2/3})A_{\mathrm{i}}^{1/2}}$$

At very low ion energies, the nuclear stopping due to elastic coulomb collisions between the ion and lithium nuclei becomes significant, the nuclear stopping power is given by Ref. [4]:

$$\left.\frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}s}\right|_N=\rho c_n W_{\mathrm{i}}^{1/2}\exp[-45.29(c_n' W_{\mathrm{i}})^{0.227}] \quad (3)$$

where

$$c_n=\frac{4.14\times10^6}{A_{\mathrm{i}}^{1/2}}\left(\frac{A_{\mathrm{i}}}{A_{\mathrm{i}}+A_{\mathrm{Li}}}\right)^{3/2}\left(\frac{Z_{\mathrm{eff}}Z_{\mathrm{Li}}}{A_{\mathrm{Li}}}\right)^{1/2}(Z_{\mathrm{eff}}^{2/3}+Z_{\mathrm{Li}}^{2/3})^{-3/4}$$

$$c_n'=\frac{A_{\mathrm{Li}}}{A_{\mathrm{i}}+A_{\mathrm{Li}}}\frac{1}{Z_{\mathrm{eff}}Z_{\mathrm{Li}}}(Z_{\mathrm{eff}}^{2/3}+Z_{\mathrm{Li}}^{2/3})^{-1/2} \quad (4)$$

where A_{i} is mass number of incidention. Hence the total stopping power for an incident ion in lithium vapor cloud is given by taking the minimum of Bethe Eq. (1) or Lindhard Eq. (2) electronic stopping power and then adding to the nuclear stooping power Eq. (3):

$$\left.\frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}s}\right|_{\mathrm{Total}}=\min\left\{\left.\frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}s}\right|_B \left.\frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}s}\right|_L\right\}+\left.\frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}s}\right|_N \quad (5)$$

For the weekly relativistic electrons from SOL region, stopping power is given by Ref. [5]:

$$\frac{\mathrm{d}W_e}{\mathrm{d}s}=\frac{4\pi n_{\mathrm{Li}}Z_{\mathrm{Li}}e^4}{m_e c^2\beta^2}\left\{\ln\left[(\gamma-1)\sqrt{\frac{\gamma+1}{2}}m_e c^2/\tilde{I}\right]-\beta^2/2\right\} \quad (6)$$

where $\gamma = 1/\sqrt{1-\beta^2}$, n_{Li} is the density and Z_{Li} is the effective charge of lithium vapor cloud. Because the incident plasma particles heat and ionize lithium vapor cloud, more free plasma electrons are produced, which will enhance the slowing down process. This contribution is not considered in this paper. For alkali metal, the radii of lithium atoms is least. It has maximum ionization potentials as listed in Table 1.

Table 1 Ionization potentials of lithium atom (or ions)/eV

Neutral lithium atom($Z_{Li}=0$)	5.39
Lithium ion($Z_{Li}=1$)	75.62
Lithium ion($Z_{Li}=2$)	122.42

2 Mean ionization potential calculation of lithium vapor

Ionization equilibrium model of lithium vapor cloud plasma generally can be described by Saha equilibrium:

$$\frac{n_e n_1^*(Z_{Li})}{n_n^*(Z_{Li}-1)} = 6.0\times 10^{21}\frac{g_1^Z T_e^{3/2}}{g_n^{Z-1}} \exp\left[-\frac{E_\infty^Z(n,l)}{T_e}\right] \quad (7)$$

where g_1^Z is the statistical weight for level n of charge state Z and $E_\infty^Z(n,l)$ is the binding energy of outer shell electron of lithium atom initially in level labeled by quantum numbers (n, l):

$$E_\infty^Z(n,l) = \frac{Z^2 E_\infty^H}{(n-\Delta l)^2} \quad (8)$$

where $E_\infty^H = 13.6$ eV is the hydrogen ionization energy and $\Delta_l = 0.75\ l^{-5}$, $l\approx 5$, is the quantum defect. In steady state at high electron density, Eq. (7) becomes:

$$\frac{n_e n^*(Z_{Li})}{n^*(Z_{Li}-1)} = \frac{S(Z_{Li}-1)}{\alpha_3} \quad (9)$$

It is only a function of T. If the electron temperature and density satisfy the following inequality:

$$10^{12} t_I^{-1} < n_e < 10^{16} T_e^{3.5} \quad (10)$$

where t_I is the ionization time, then steady state Corona equilibrium model can be used:

$$\frac{n(Z_{Li}-1)}{n(Z_{Li})} = \frac{\alpha_r}{S(Z_{Li}-1)} \quad (11)$$

where α_r is electron-ion radiative recombination rate given by

$$\alpha_r(Z_{Li}-1) = 2.7\times 10^{-13}(Z_{Li}-1)^2 T_e^{-1/2} \quad (12)$$

while

$$S(Z_{Li}-1) = 10^{-5}\frac{(T_e/E_\infty^{Z_{Li}-1})^{1/2}}{(E_\infty^{Z_{Li}-1})^{3/2}(6.0+T_e/E_\infty^{Z_{Li}-1})} \exp\left(-\frac{E_\infty^{Z_{Li}-1}}{T_e}\right) \quad (13)$$

where $E_\infty^{Z_{Li}-1}$ is ionization energy of lithium ion with charge state $Z_{Li}-1$. α_3 is collisional three-body recombination rate of singly ionized plasma:

$$\alpha_3 = 8.75\times 10^{-27} T_e^{-4.5} \quad (14)$$

Given the temperature T_e of lithium vapor cloud plasma and ionization potentials of lithium atom and ions in Table 1. We can estimate the probabilities of three charge states:

$$f_0 = \frac{n(Z_{Li}=0)}{n(Z_{Li}=0)+n(Z_{Li}=1)+n(Z_{Li}=2)}$$

$$f_1 = \frac{n(Z_{Li}=1)}{n(Z_{Li}=0)+n(Z_{Li}=1)+n(Z_{Li}=2)} \quad (15)$$

$$f_2 = \frac{n(Z_{Li}=2)}{n(Z_{Li}=0)+n(Z_{Li}=1)+n(Z_{Li}=2)}$$

Then we can obtain:

$$\Rightarrow \tilde{I} \approx f_0 \times I_0 + f_1 \times I_1 + f_2 \times I_2.$$

3 Results and discussion

Assuming that lithium vapor plasma has been formed and an uniform distribution with thermal equilibrium has been reached. The lithium vapor pressure $p_{Li} = 2.67 \times 10^7$ Pa and averaged temperature 4 eV, denstiy $n_{Li} = 6 \times 10^{18}$ atoms · cm^{-3}. As can be shown the Corona equilibrium condition can not be met, we have to calculate mean ionization potential from Eq. (9) and got $\tilde{I} = 31.2$ eV. The atom mass $A_{Li} = 6.94$ and the average effective charge number of lithium vapor plasma $\langle Z_{Li} \rangle = 2.3$. We calculated the stopping power of fusion produced energetic α particle in lithium vapor cloud as shown in Fig. 1. During the major disruption event, a large number of energetic run-away electrons are produced, slowing down in lithium vapor. For our interested case, the most of electrons are in weekly relativistic range. The stopping power of lithium vapor varies with electron energy are shown in Fig. 2. At the early time of a disruption event, the temperature of lithium vapor cloud is about a few eV and density also low. The vapor cloud only can expand to a few centimeters. Most of incident particle energy will be still deposited on the first wall and target plate. As the time development of disruption event, the vapor cloud will be expanding and extending to the scale of 70 cm or so and the most of energy below 1 MeV α particles and energetic run-away electrons will be absorbed by the vapor. For normal case of high surface heat

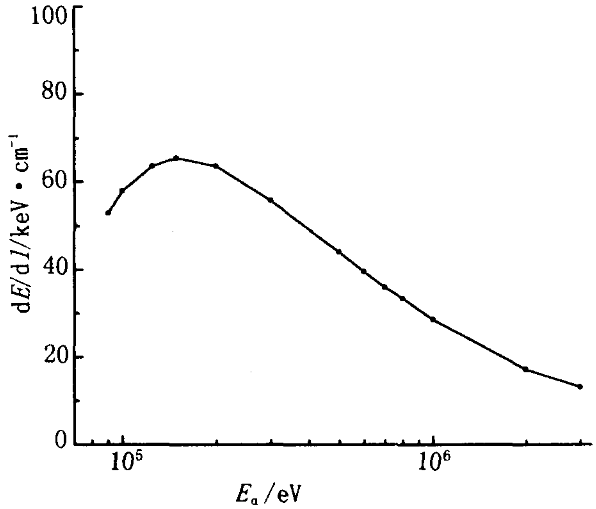

Fig. 1 Bound electron stopping power of α particle in lithium vapor

Lithium vapor temperature 4 eV, density 6×10^{18} cm^{-3}.

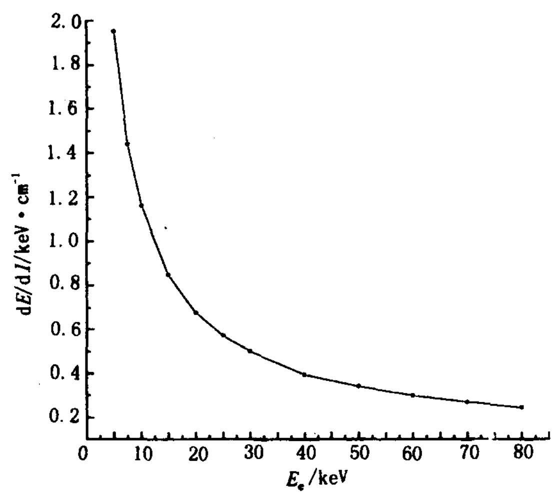

Fig. 2 Stopping power of weekly relativistic electron in Li vapor

Lithium vapor temperature 4 eV, density 6×10^{18} cm^{-3}.

flux (non-disruption case), the liquid lithium vapor cloud also can absorb a large fraction of kinetic energy of the incident charge particles.

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2.2 Least Tritium Storage Required to Start up FEB

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Key words Mean residence time Tritium cycle subsystems Tritium inventory

To investigate what the least tritium inventory is to start up a fusion experimental reactor of 143 MW fusion power. A dynamic subsystem model of tritium fuel cycle system and mean residence time method are utilized to simulate tritium fuel cycle system of fusion experimental breeder (FEB) in which lithium is used as tritium breeder and helium as coolant. The plasma burn-up fraction $\beta = 2.08\%$ and tritium-breeding ratio $\Lambda = 1.10$ are designed. Based on the details of core plasma and blanket design of FEB, a dynamic subsystem model is constructed to describe the tritium distribution in reactor system. A computer code-SWITRIM has been developed to simulate tritium fuel cycle system. The tritium inventories in 10 subsystems are calculated during one-year operation period. This code is utilized to predict the required minimum initial tritium storage to start up an experimental breeder of 143 MW fusion thermal power. Calculation results show that the least initial tritium storage is about 319 g to start up and operate FEB and it strongly depends on the mean residence time in the subsystems of plasma exhaust gas, FCU (fuel clean up unit) and ISS (isotope separation system). Besides, the minimum initial tritium inventory depends on the tritium permeability in the first wall, limiter, divertor and blanket, also on the tritium production and implantation in the beryllium neutron multiplier as well.

1 Subsystems

FEB tritium cycle system is divided into 10 subsystems, the simulation has been treated as time-dependent problem and 100% availability is assumed. The physics bases of SWITRIM code are based on the following assumptions: (1) Tritium storage and fuelling subsystem has initial tritium storage $Y_0(0) = 0.5$ kg. The tritium storage container has been coated with permeation-proof barrier to