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# Study of the effects of liquid lithium curtain as first wall on plasma

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**Abstract**

A global model analysis of the effects of a liquid lithium curtain, which is utilized as the first wall for the Engineering outline design of the Fusion Experimental Breeder (FEB-E), on plasma has been performed. The relationships between the surface temperature of a liquid lithium curtain and the mean effective plasma charge, fuel dilution and the produced fusion power have been obtained. Studies indicate that under normal operation circumstances, the evaporation of liquid lithium does not affect the mean effective plasma charge seriously, but the effects on the fuel dilution and fusion power are more sensitive. We have investigated the relationships between the flow velocity of the liquid lithium curtain and the rise of surface temperature based on the operation scenario II of FEB-E design with reversed shear configuration and higher power density. Results show that even if the flow velocity of the liquid lithium curtain is as low as 0.5 m/s, the effects of evaporation from the curtain on plasma are negligible.


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*Keywords:* Liquid lithium curtain; First wall; Fuel dilution; Mean effective plasma charge; Plasma-wall interaction

## 1. Introduction

The final goal of fusion energy research is to make it economically competitive and to make its cost of electricity (COE) low enough to be acceptable. Therefore the fusion plasma has to be operated with a high power density and the plasma facing components (PFCs), such as the first wall and divertor, have to sustain high surface heat loads and high particle flux bombardment. Such rigorous environments consequently lead to severe damage and erosion of PFC materials. As a result, the lifetime of PFCs would be shortened. The economic capability of a fusion reactor would be greatly reduced by frequent shutdowns and replacement maintenance. This is one of the key issues of concern widely by fusion reactor designers. How to cope with high surface heat loads and bombardment of high particle flux, hence to alleviate the damage and erosion of PFC materials, has turned out to be one of the most important tasks in fusion engineering research.

A new idea to replace the solid first wall in a fusion reactor with a rotating liquid metal wall was proposed first by Christofilos [1] in 1971. Later in 1987, Moir [2] had investigated the technical feasibility and further improvement had been made in 1995 [3]. In 1999, Mattas and Abdou [4] proposed a concept of a flowing liquid divertor target and first wall to handle the high heat flux and particle flux on the PFC surface coming from the plasma operating with a high power density. Zhou et al. [5] made an assessment of liquid metal as the divertor surface. The advantages of such a flowing liquid metal curtain are renewability, heat load removability, dissipative characteristics, and it both protects the high $Z$ solid back wall from radiation damage and prevents the plasma from being contaminated by the high $Z$ impurities. However from the viewpoint of a fusion reactor designer, we need to find out whether the evaporation of this flowing liquid lithium curtain will increase the mean effective plasma charge of the bulk plasma severely. For

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instance, we have investigated our FEB-E reactor [6,7] using a global model analysis and obtained the relationships between the surface temperature of a liquid lithium curtain and the mean effective plasma charge $Z_{eff}$, fuel dilution and the produced fusion power. The sputtering of the liquid lithium curtain, thermally enhanced erosion and the lithium particle removal due to MHD forces are not yet considered at present. In the mean time, the relation between the maximum surface temperature rise and the flow speed of liquid lithium curtain has been calculated. We concluded that even for a flow speed of the liquid lithium curtain as low as 0.5 m/s, the effects of evaporation from the liquid lithium curtain on the mean effective plasma charge $Z_{eff}$ are negligible.

## 2. Effects of lithium curtain temperature on $Z_{eff}$

From the viewpoint of fusion reactor design, we are only interested in the mean effective plasma charge $Z_{eff}$, which is associated with energy balance, rather than the $Z_{eff}$ profile and how it depends on the lithium curtain temperature. Therefore a global analysis for a system, which consists of lithium curtain and facing plasma, has been performed. Generally the mean effective plasma charge $Z_{eff}$ is defined as

$$Z_{\mathrm{eff}} = \frac{\sum_i n_i Z_i^2}{\sum_i n_i Z_i} = \frac{\sum_i n_i Z_i^2}{n_e}, \tag{1}$$

where the notations are defined as usual. Assuming the α particle concentration is 10%; fuel mixture ratio is 50%D–50%T, and the lithium impurity ion density is $n_{Li}$ in plasma, $Z_{Li}$ is the charge of the lithium ion, $n_{DT}$ is the fuel ion density, then

$$Z_{\mathrm{eff}} n_e = n_{Li} Z_{Li}^2 + n_{DT} + 0.4 n_e. \tag{2}$$

Since

$$n_{DT} + 0.2 n_e = n_e - Z_{Li} n_{Li},$$

therefore

$$Z_{\mathrm{eff}} n_e = n_{Li} Z_{Li}^2 + 1.2 n_e - Z_{Li} n_{Li}$$

and

$$n_{Li} = \frac{(Z_{\mathrm{eff}} - 1.2) n_e}{Z_{Li}(Z_{Li} - 1)}. \tag{3}$$

Suppose the lithium impurity and fuel ions have a common temperature $T_i$, the partial pressure contributed from lithium impurity ions can be given by

$$p_{Li} = n_{Li} k T_i = \frac{(Z_{\mathrm{eff}} - 1.2) n_e}{Z_{Li}(Z_{Li} - 1)} k T_i. \tag{4}$$

We have calculated the bound electron stopping power of a $He^+$ particle in lithium vapor cloud [8]. The sputtered lithium atom flux may be smaller than the evaporated lithium atom flux due to the shielding effects of lithium vapor clouds [9]. The sputtering yields of solid lithium bombarded by charged particles $H^+$, $D^+$, $T^+$ and $He^+$ are calculated by the application of sputtering theory based on a bipartition model of ion transport. The sputtering yield of the $He^+$ particle is the largest [10]. Our results have only 20–50% difference as compared with the experimental data given by Allain and Ruzic [11] at the incident $He^+$ particle energies between 200 and 1000 eV of the $He^+$ particles. If the particle removal effects due to MHD forces and erosion are not considered, then the relation of the saturated vapor pressure and surface temperature $T_{Li}$ of the liquid lithium curtain can be expressed by the fitting formula given by Douglas [12]:

$$\lg p_{Li} = 12.992 - \frac{8442.53}{T_{Li}} - 1.64098 \lg T_{Li} + 2.5968 \times 10^{-4} T_{Li}, \tag{5}$$

where the pressure $p_{Li}$ is in units of Torr and $T_{Li}$ in K. We make a trial assumption:

$$p_{Li} = n_{Li}^{\mathrm{curtain}} T_{Li}^{\mathrm{curtain}} \approx n_{Li}^{\mathrm{core}} T_{Li}^{\mathrm{core}},$$

where $p_{Li}$, $n_{Li}$ and $T_{Li}$ are the partial pressure, density and temperature of the lithium species respectively, the superscript curtain refers to the value at the curtain and core to that at the plasma core. The reason for this assumption can be explained as that the lithium density at the curtain (the source is at the curtain) is much greater than that at the core; but the lithium temperature at curtain is much lower than that at core. The pressure is a product of the density and temperature. The total plasma pressure mainly is contributed from the bulk plasma ion species and electrons. By combining the Eqs. (4) and (5), one obtains

$$\lg\left[\frac{(Z_{\mathrm{eff}} - 1.2) n_e k T_i}{Z_{Li}(Z_{Li} - 1)}\right] = 12.9992 - \frac{8442.53}{T_{Li}} - 1.64098 \lg T_{Li} + 2.5968 \times 10^{-4} T_{Li}. \tag{6}$$

For convenience, we convert the unit of plasma pressure $n_e k T_i$ to $10^{20}$ keV/m$^3$, and given 1 Torr = 133 Pa = $8.3 \times 10^{19}$ keV/m$^3$, thereby, we get the identity $1 \times 10^{20}$ keV/m$^3$ = 120 Torr. Then Eq. (6) takes the following form

$$T_{Li} \lg\left[\frac{120(Z_{\mathrm{eff}} - 1.2) n_e k T_i}{Z_{Li}(Z_{Li} - 1)}\right] - 12.9992 T_{Li} + 1.64098 T_{Li} \lg T_{Li} - 2.5968 \times 10^{-4} T_{Li}^2 + 8442.53 = 0, \tag{7}$$

where the pressure $n_e k T_i$ is in units of $10^{20}$ keV/m$^3$ and $T_{Li}$ in K.

Table 1
$Z_{eff}$ variation with $T_{Li}$ for FEB-E reactor (design option II)

| $Z_{eff}$ | $a_i$ | $T_{Li}$ |
|---|---|---|
| 1.3 | 11.246 | 1304.4 |
| 1.4 | 10.945 | 1372.0 |
| 1.5 | 10.770 | 1414.7 |
| 1.6 | 10.645 | 1447.0 |
| 1.7 | 10.548 | 1473.0 |
| 1.8 | 10.470 | 1493.5 |
| 1.9 | 10.402 | 1514.0 |
| 2.0 | 10.343 | 1531.0 |

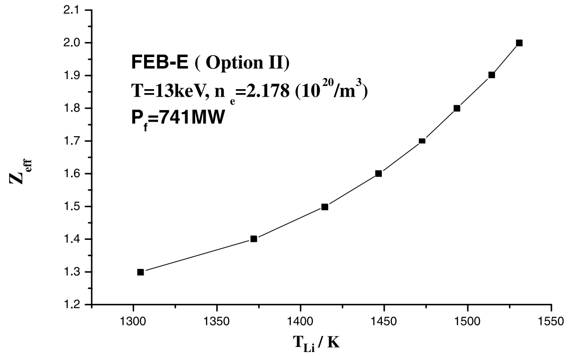


Fig. 1. The variation relation between $Z_{eff}$ and $T_{Li}$.

As an example, we have studied the design option II of FEB-E [6,7]. The designed reactor parameters are $P_f = 741$ MW, $T_i = 13$ keV, $n_e = 2.178(\times 10^{20}/\mathrm{m}^3)$. For different $Z_{eff}$, the Eq. (7) can be written as

$$a_i T_{Li} + bT_{Li}^2 - cT_{Li}\lg T_{Li} - d = 0, \tag{8}$$

where $a_i$ is dependent on $Z_{eff}$ and the other coefficients are given as $b = 2.5968 \times 10^{-4}$, $c = 1.64098$, and $d = 8442.52$. After having solved the Eq. (8), the variation relation of $Z_{eff}$ with respect to $T_{Li}$ and $a_i$ are given in the Table 1 and shown in Fig. 1.

Results show that to guarantee the effective plasma charge $Z_{eff} \leqslant 1.5$, it is necessary to keep the lithium curtain temperature $T_{Li} \leqslant 1415$ K. This result does not account for sputtering, temperature-dependent erosion [13] nor particle removal effects due to MHD forces.

## 3. Effects of evaporation on $Z_{eff}$, fuel dilution and fusion power

As usual, the fusion power can be expressed as

$$P_f = (n_{DT}/2)^2 \langle \sigma V \rangle E_{DT}. \tag{9}$$

For helium ash and lithium ion contaminated fusion plasma, the total particle number density can be written as

$$n = 2n_{DT} + 3n_\alpha + 4n_{Li}. \tag{10}$$

For convenience, the fractional fuel dilution factors of each impurity species are defined as

$$f_\alpha = \frac{n_\alpha}{n_{DT}}, \quad f_{Li} = \frac{n_{Li}}{n_{DT}}, \tag{11}$$

then

$$n = n_{DT} \times (2 + 3f_\alpha + 4f_{Li}). \tag{12}$$

If $f_\alpha = 0$, $f_{Li} = 0$, and equal fuel mixture are assumed, the fusion power density without any impurities is

$$P_f^0 = (n_{DT}/2)^2 \langle \sigma V \rangle E_{DT} = \frac{1}{16} n^2 \langle \sigma V \rangle E_{DT}. \tag{13}$$

Now we turn to considering the effects of fuel dilution resulting from the helium and lithium on fusion power, $f_\alpha \neq 0$, $f_{Li} \neq 0$ so that

$$n_{DT} = n/(2 + 3f_\alpha + 4f_{Li}). \tag{14}$$

In Section 2 $n_{Li}$ is given by

$$n_{Li} = \frac{(Z_{eff} - 1.2)n_e}{Z_{Li}(Z_{Li} - 1)} \tag{15}$$

and from the charge neutrality requirement

$$n_e = n_{DT} + 2n_\alpha + 3n_{Li}, \tag{16}$$

then $Z_{eff}$ can be described as

$$Z_{eff} = 1.2 + \left( \frac{6f_{Li}}{1 + 2f_\alpha + 3f_{Li}} \right). \tag{17}$$

The reduction factor of the fusion power due to fuel dilution can be given by

$$\frac{P_f}{P_f^0} = \left( \frac{4}{(4 + 6f_\alpha + 8f_{Li})} \right)^2. \tag{18}$$

Fig. 2 shows the fusion power reduction with respect to $f_{Li}$, with $f_\alpha = 0.1$ fixed. The mean effective plasma

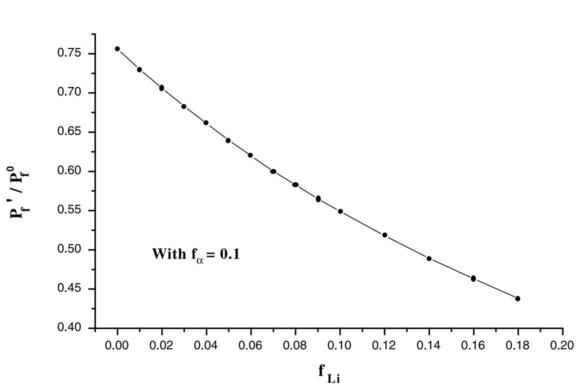


Fig. 2. The fusion power reduction due to fuel dilution.

Table 2
$Z_{eff}$ variation with $f_\alpha$ for FEB-E reactor, with $f_\alpha = 0.1$ fixed

| $f_{Li} = n_{Li}/n_{DT}$ | $Z_{eff}$ |
|---|---|
| 0.00 | 1.2 |
| 0.01 | 1.25 |
| 0.02 | 1.30 |
| 0.03 | 1.34 |
| 0.04 | 1.38 |
| 0.06 | 1.46 |
| 0.08 | 1.53 |
| 0.10 | 1.60 |
| 0.12 | 1.66 |
| 0.14 | 1.72 |
| 0.16 | 1.77 |
| 0.18 | 1.82 |
| 0.20 | 1.87 |
| 0.22 | 1.91 |
| 0.24 | 1.95 |
| 0.26 | 1.99 |

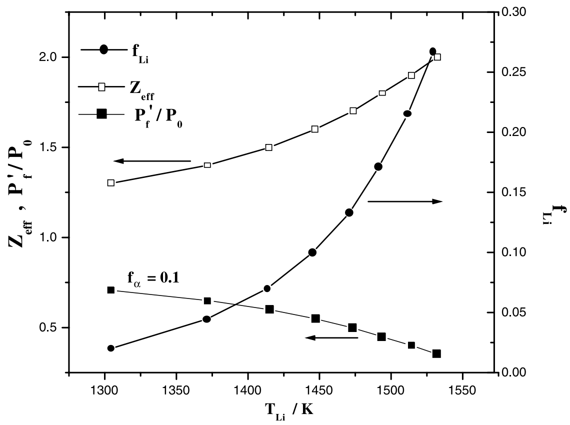


Fig. 3. The effects of $T_{Li}$ on $Z_{eff}$, $f_{Li}$ and $P_f/P_f^0$.

charge $Z_{eff}$ variation with $T_{Li}$ is listed in Table 2 with $f_\alpha = 0.1$ fixed. The effects of the temperature $T_{Li}$ of the liquid lithium curtain on $Z_{eff}$, the fuel dilution factor $f_{Li}$ resulting from liquid lithium atoms, and the reduction factor of the fusion power density $P_f/P_f^0$ are shown in Fig. 3.

## 4. Maximum temperature rise of the lithium curtain after passing vacuum chamber

At first, we examine the maximum temperature rise of an element of the liquid lithium curtain after passing through the vacuum chamber. For instance, we consider the FEB-E design option II: the fusion power $P_f = 741$ MW, auxiliary heating power $P_{aux} = 37$ MW, plasma major radius $R = 4$ m and minor radius $a = 0.854$ m, elongation $\kappa = 1.8$. Assuming the fraction of plasma exhaust power to divertor is $f_{div} = 0.55$ and the peaking factor of heat flux on the first wall is $\hat{f}_{fw} = 1.5$, the divertor target area of the first wall can be regarded as a fraction $\varepsilon_{div} = 0.15$ of the area of first wall that is recessed a depth (channel height), then the peak heat flux on the first wall can be calculated [14]:

$$q_{fw} = \frac{(0.2P_f + P_{aux})(1 - f_{div})\hat{f}_{fw}}{(2\pi R)\left[2\pi a\sqrt{0.5(1+\kappa^2)}\right](1 - \varepsilon_{div})}. \tag{19}$$

Suppose we can keep the liquid curtain flowing with constant speed by making use of MHD effects. Because of the continuity requirement, the liquid curtain should follow $(d/dz)(v\delta) = 0$ in the flowing process. The product $(v\delta)$ is a conserved quantity. Therefore the curtain will become thinner as it is flowing down due to gravity acceleration. Here $z$ is the flowing direction, $v$ is the velocity, and $\delta$ is the thickness of the curtain. Then the time exposed to the plasma heat load for the liquid curtain element can be given by

$$\tau = 2 \times (a + \Delta_{SOL})k/v, \tag{20}$$

where $\Delta_{SOL}$ is the thickness of the SOL region. The temperature of the liquid lithium curtain $T_{Li}$ can be determined by solving the equation:

$$\rho c_p \frac{\partial T_{Li}}{\partial t} = \nabla \cdot (k \nabla T_{Li}) + \dot{q}(r,t), \tag{21}$$

where $\dot{q}(r,t)$ is the volumetric heat source. Assume the $r$ direction is from curtain to blanket, then the boundary condition at $r = 0$ is given by

$$-k\frac{\partial T_{Li}}{\partial r}(0,t) = q_{fw}, \tag{22}$$

where $q_{fw}$ is the wall loading. Let the inlet temperature of lithium curtain be $T_{Li0} = 500$ K, and set $T_{Li} = T'_{Li} + T_{Li0}$, $\dot{q}(r,t) \cong 0$. From Eq. (21), $T_{Li}$ follows the equations

$$\begin{aligned} &\frac{\partial^2 T'_{Li}}{\partial r^2} = \frac{\rho c_p}{k}\frac{\partial T'_{Li}}{\partial t}, \\ &T'_{Li} = 0, \quad t = 0. \end{aligned} \tag{23}$$

For a fixed flowing element of the curtain during the time interval $t \leqslant \tau$ from inlet to outlet of the chamber, Eq. (22) can be written as

$$\frac{\partial T'_{Li}}{\partial r} = -\frac{1}{k}q_{fw}, \quad r = 0. \tag{24}$$

Let $\chi = k/\rho c_p$ and take the Laplace transform, then

$$T'_{Li}(r,p) = \int_0^\infty T'_{Li}(r,t)\exp(-pt)\,dt. \tag{25}$$

From Eq. (23), we get

$$\frac{\partial^2 T'_{Li}(r,p)}{\partial r^2} = \frac{p}{\chi}T'_{Li}(r,p). \tag{26}$$

Taking the Laplace transform again for the boundary condition at $r = 0$, we get

$$\frac{\partial T'_{\mathrm{Li}}(r,p)}{\partial r} = -\frac{1}{k}(q_{\mathrm{fw}})\frac{1}{p} \tag{27}$$

and the solution of Eq. (26)

$$T'_{\mathrm{Li}}(r,p) = c(p)\exp\left(-r\sqrt{\frac{p}{\chi}}\right), \tag{28}$$

where $c(p)$ is an integration constant. Taking the differential of Eq. (28) with respect to $r$, one obtains

$$\frac{\partial T'_{\mathrm{Li}}}{\partial r}(r=0) = -\sqrt{\frac{p}{\chi}}c(p). \tag{29}$$

From Eqs. (27) and (29), we have

$$c(p) = \frac{1}{k}(q_{\mathrm{fw}})\frac{\sqrt{\chi}}{p^{3/2}}. \tag{30}$$

The solution of Eq. (29) is

$$T'_{\mathrm{Li}}(r,p) = \frac{1}{k}(q_{\mathrm{fw}})\frac{\sqrt{\chi}}{p^{3/2}}\exp\left(-r\sqrt{\frac{p}{\chi}}\right). \tag{31}$$

Inverting Eq. (31) above, we get

$$T'_{\mathrm{Li}}(r,t) = \frac{1}{k}(q_{\mathrm{fw}})\sqrt{\chi}\left[2\sqrt{\frac{t}{\pi}}\exp\left(\frac{-r^2}{4\chi t} - \frac{r}{\sqrt{\chi}}\mathrm{erfc}\left(\frac{r}{2\sqrt{\chi t}}\right)\right)\right] \tag{32}$$

by setting $\xi = r/2\sqrt{\chi t}$ and

$$\mathrm{erfc}(\xi) = \frac{2}{\sqrt{\pi}}\int_{\xi}^{\infty}\exp(-\eta^2)\,\mathrm{d}\eta. \tag{33}$$

It is related with the common error function $\mathrm{erf}(\xi)$ by

$$\mathrm{erfc}(\xi) + \mathrm{erf}(\xi) = 1. \tag{34}$$

From Eq. (32), the maximum temperature rise of an element of the liquid lithium curtain within the time interval $t = \tau$ passing through the vacuum chamber can be given by

$$(T'_{\mathrm{Li}})_{\max} = q_{\mathrm{fw}}\sqrt{\frac{4\tau}{\pi\rho k c_p}}. \tag{35}$$

The maximum temperature rise $(T'_{\mathrm{Li}})s_{\max}$ of an element of the liquid curtain varies with the flow speed of the curtain for FEB-E design as listed in Table 3. We find that the outlet temperature of the liquid lithium curtain is much less than 1000 K, at that temperature evaporation become strong, even when the curtain flowing speed is as low as 0.5 m/s.

Table 3
$(T'_{\mathrm{Li}})_{\max}$ variation with flowing speed of the curtain for FEB-E design

| $v$ (m/s) | $(T'_{\mathrm{Li}})_{\max}$ (K) |
|---|---|
| 5.1 | 74.8 |
| 4.0 | 84.4 |
| 3.0 | 97.6 |
| 2.0 | 119.4 |
| 1.0 | 168.9 |
| 0.5 | 238.8 |

## 5. Discussions

Analyses indicate that the application of a flowing liquid lithium curtain in front of the solid first wall would not seriously affect the mean effective plasma charge of core plasma for an FEB-E design with higher power density. For example, if the inlet liquid lithium temperature is 500 K, even when the flow speed is as low as 0.5 m/s, the outlet temperature only rises to 740 K. Under such low temperatures the evaporation rate of liquid lithium is not high [8], because it is much lower than the boiling point. Since the evaporation heat of the liquid lithium atom is 10 times that of the water atom. Our conclusion is if the liquid lithium sputtering, particle removal effects due to MHD force and erosion are not considered the liquid lithium curtain will not seriously jeopardize the core plasma. However it becomes a low $Z$ renewable first wall and it not only removes the thermal energy but protects the back solid first wall from damage. The core plasma will not be contaminated by high $Z$ impurities. On the other hand, a small fraction of evaporated lithium atoms will bring about reactions with neutrons with a high probability once they diffuse into core plasma. These reactions produce tritium and partly play a fueling role. If we consider the removal effects of evaporated lithium atoms due to MHD forces, then a much higher lithium temperature can be allowed, that means a lower flow speed is allowable, or lower pumping power is required. Further studies of liquid lithium sputtering, lithium atom transport in SOL region, and divertor-pumping effects are in progress.

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