Effects of a liquid lithium curtain as the first wall in the Fusion Experimental Breeder (FEB-E) reactor plasma†

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Abstract

We study the effects of a liquid lithium curtain used as the first wall for the engineering outline design of the Fusion Experimental Breeder (FEB-E). Relationships were obtained between the surface temperature of a liquid lithium curtain and the effective plasma charge, fuel dilution, and fusion power production. Results indicate that, under normal operation, the evaporation of liquid lithium does not seriously affect the effective plasma but that the effects on fuel dilution and fusion power are more sensitive. As an example, we investigated the relationships between the flow velocity of the liquid lithium curtain and the rise of surface temperature based on operation option II of the FEB-E design with reversed shear configuration and high power density. Our studies 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 liquid lithium curtain on plasma are negligible. In the present design, the sputtering of liquid lithium curtain and the particle removal effects of the divertor are not considered in detail. Further studies are in progress, and in this work the implications of lithium erosion and divertor physics on the fusion reactor operation are discussed.

Keywords: Liquid lithium curtain, First wall, Fuel dilution, Effective plasma charge, Plasma/wall interaction

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1. Introduction

The goal of fusion energy research is to make fusion energy economically competitive and the cost of electricity low enough to be acceptable by the energy market. Therefore, the fusion plasma has to operate with high power density and the plasma-facing components (PFCs), such as the first wall and divertor plate in a tokamak fusion reactor configuration, have to sustain high surface heat load and bombardment of high particle flux. Such a rigorous environment leads to severe damage and erosion of PFC materials, shortening the lifetime of the PFCs and greatly reducing the economic viability of a fusion reactor because of frequent shutdown for replacement maintenance. This is one of the key issues of concern widely shared by fusion reactor designers. Designing systems to cope with high surface heat load and bombardment from high particle flux, and hence alleviating the damage and erosion of PFC materials, has become one of the most important tasks in fusion engineering reactor research.

In 1971, Christofilos [1] proposed a new idea to replace the solid first wall in the fusion reactor with a rotating liquid metal wall. In 1987, Moir [2] investigated the technical feasibility, and further improvements were made in 1995 [3]. The use of liquid metal as the divertor surface was assessed in 1998 [5, and in 1999 Mattas and Abdou [4] proposed the concept of a flowing liquid divertor target and first wall to handle the high heat flux and particle flux on the PFC surface. Furthermore, the Advanced Limiter-divertor Plasma-facing Systems program in the United States has investigated the feasibility of liquid-metal PFCs for the past five years [6,7]. Studies have included the effects of liquid-metal sputtering, MHD instability and dynamics on liquid-metals, particle recycling and operation, thermal hydraulics, and effects of abnormal tokamak operation (i.e., edge localized modes and disruptions) [8,9,10,11, 12].

A flowing liquid metal curtain offers several advantages: renewable plasma-facing surface, heat load removal, dissipative surface, and protection of both the high-Z solid back wall from radiation damage and plasma contamination from high-Z impurities. The specific application of lithium as a plasma-facing liquid-metal curtain is particularly important because of its uptake of impurities and its affinity for hydrogen in low-recycling regimes [7,8,13].

For the application of flowing liquid-metals we need to find out whether the evaporation of a flowing liquid-lithium curtain will jeopardize the normal operation condition of the core fusion reactor plasma. To this end, we have investigated the FEB-E reactor design [14,15] and determined the relationships between the surface temperature of the liquid-lithium curtain and the effective plasma charge Z_{eff} , fuel dilution, and fusion power production. The sputtering of liquid-lithium curtain and the particle removal effects of divertor are not considered at present. However, exhaustive studies, both experimental and modeling, have demonstrated the feasibility of operating with liquid lithium as a plasma-facing wall or divertor surface. In this work, we analyze the variation relation between the maximum surface temperature rise and flow velocity of the liquid-lithium curtain. We conclude that even though the flow speed of the liquid-lithium curtain is as low as 0.5 m/s, the effects of evaporation from the liquid-lithium curtain on a reactor fusion plasma are negligible.

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

In this section we analyze the effect a liquid lithium curtain has on plasma impurity dilution, mainly on the effective plasma charge, Z_{eff}. We also briefly discuss the implications of particle-induced erosion and transport of lithium in the liquid state .Generally, the effective plasma charge Z_{eff} is defined as

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

Assuming that the α particle concentration is 10%; fuel mixture ratio is 50%D -50%T, and lithium impurity ion density is n_{Li} in plasma, we have

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

Since

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

and

$$n_{DT} + 0.4 n_e = 1.2 n_e - Z_{Li} n_{Li} ,$$

therefore

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

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

Assuming lithium impurity and fuel ions have a common temperature T_i ,we can give the partial pressure contributed from lithium impurity ions by

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

We have calculated the bound electron stopping power of α particles in the lithium vapor cloud [16]. The sputtered lithium atom flux may be smaller than the evaporated lithium atom flux because of the shielding effects of lithium vapor clouds [17]. The sputtering yields of lithium bombarded by charged particles H^+, D^+, T^+, and He^{++} are calculated by application of sputtering theory based on a bipartition model of ion transport. The sputtering yield of the α particle is the largest [18]. Our results have only 20%–50% differences compared with the experimental data given by Allain and Ruzic [19] at the incident He^+ particle energies between 200 and 1000 eV of the He^+ particle.

Two issues merit discussion: the particle-induced erosion of liquid lithium and its transport in a fusion plasma. The sputtering of liquid lithium as a function of temperature has been extensively studied both in linear plasma devices and in particle-beam facilities [9,11]. Typically, liquid-Li surfaces used as PFCs are saturated with fuel particles, namely, hydrogen isotopes, because of the high hydrogen retention properties of lithium. The result is diluted Li emission into the fusion plasma [20]. In addition, almost two-thirds of the sputtered Li particles are emitted as ions; and with the presence of a plasma sheath in at the fusion reactor wall, they are immediately accelerated back to the surface. Those Li atoms that are removed as neutrals are readily ionized; see, for example, [13,21,22]. Therefore, the contribution of particle-induced sputtered atoms into the core fusion plasma is likely to be small and thus can be neglected, assuming that plasma edge conditions remain similar to the studies presented in the literature. For plasma edge conditions substantially different (i.e., magnetic field strength at PFCs, edge temperature, etc.), further assessment of lithium sputtering and its implications must be investigated.

We also do not consider particle removal effects due to MHD forces and or off-normal events. These effects are important; but because these effects are not well understood, their inclusion is problematic and awaits further study [8,13].

With these limitations, then, the relation of the saturated vapor pressure and surface temperature T_{Li} of a liquid lithium curtain can be expressed by the fitting formula given by Douglas [23]:

$$\lg p_{Li} = 12.992 - \frac{8442.53}{T_{Li}} - 1.64098 \lg T_{Li}$$

$$+ 2.5968 \times 10^{-4} T_{Li}\ , \qquad (5)$$

where the pressure p_{Li} is in unit of torr and T_{Li} in K. By combining equations (4) and (5), one obtains the following.

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

For convenience, we convert the unit of plasma pressure $n_e kT_i$ to 10^{20} keV/m^3. Given 1torr $=$ 133 Pa $= 8.3 \times 10^{19}$ keV/m^3, we get the identity 1×10^{20} keV/m$^3 = 120$ torr.

Then equation (6) takes the following form:

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

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

For instance, we have studied the design option II of FEB-E [14,15]. The reactor parameters are $P_f = 741$ MW, $T_i = 13$ keV, and $n_e = 2.178$ ($\times 10^{20}$/m^3). For different Z_{eff}, equation (7) can be written as

$$a_i T_{Li} + b T_{Li}^2 - c T_{Li} \lg T_{Li} - d = 0\ , \qquad (8)$$

where a_i's are dependent on Z_{eff} and the other coefficients are $b = 2.5968 \times 10^{-4}$, $c = 1.64098$, and $d = 8442.52$. After solving equation (8), we show in Figure q the variation relation of Z_{eff} with respect to T_{Li}. Table 1 also lists this data, along with a_i coefficients.

Results show that, in order to guarantee the effective plasma charge $Z_{eff} \le 1.5$, it is necessary to keep the lithium curtain temperature $T_{Li} \le 1415$ K. This result does not account for particle-induced sputtering, temperature-dependent erosion [11,24], or particle removal effects due to MHD forces or off-normal events in a fusion reactor device. As stated earlier, however, the former assumption is viable because of lithium's high redeposition fraction.

2.1 Effects of evaporation on Z_{eff}, fuel dilution and fusion power

The fusion power can be expressed as usual:

$$p_f = (n_{DT}/2)^2 < \sigma V > E_{DT} \,. \tag{9}$$

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

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

For convenience, the fractional fuel dilution factor of each impurity species is 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 mixtures are assumed, the fusion power density without any impurities is

$$\begin{aligned} P_f^0 &= (n_{DT}/2)^2 < \sigma V > E_{DT} \\ &= \tfrac{1}{16} n^2 < \sigma V > E_{DT} \,. \end{aligned} \tag{13}$$

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

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

where n_{Li} is given by

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

and from the charge neutrality requirement

$$n_e = n_{DT} + 2n_\alpha + 3n_{Li}. \quad (16)$$

Then Z_{eff} can be described as

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

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

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

Figure 2 shows the fusion power reduction with respect to f_{Li}, with $f_\alpha = 0.1$ fixed. The effective plasma charge Z_{eff} varies with T_{Li} and is tabulated in Table 2 with f_α = 0.1 fixed.Figure 3 shows 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 $\frac{P_f}{P_f^0}$.

2.2 Maximum temperature rise of lithium curtain after passing vacuum chamber

First, we examine the maximum temperature rise of an element of the liquid-lithium curtain after passing through the vacuum chamber. In particular, we consider the FEB-E design option II: with fusion power $P_f = 741MW$, auxiliary heating power $P_f = 37MW$, plasma major radius $R = 4m$ and minor radius $a = 0.854m$, and elongation $\kappa = 1.8$. If one assumes the fraction of plasma exhaust power to the 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 can be regarded as a fraction $\varepsilon_{div} = 0.15$ of the area of the first wall that is recessed a given depth (channel height); then the peak heat flux on the first wall can be calculated as follows.

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

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

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

where Δ_{SOL} is the thickness of scrape-off layer (SOL). The temperature of liquid lithium curtain T_{Li} can be determined by solving the equation:

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

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

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

where q_{fw} is the wall loading. Let the inlet temperature of the lithium curtain be

$T_{Li0} = 500\,\mathrm{K}$, and set $T_{Li} = T'_{Li} + T_{Li0}$, $\dot{q}(r,t) \cong 0$. From eq. (21), we have the following.

$$\frac{\partial^2 T'_{Li}}{\partial r^2} = \frac{\rho c_p}{k}\frac{\partial T'_{Li}}{\partial t} \quad . \qquad (23)$$
$$T'_{Li} = 0, \qquad t = 0$$

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

$$\frac{\partial T'_{Li}}{\partial r} = -\frac{1}{k} q_{fw} . \qquad r = 0 . \qquad (24)$$

Let $\chi = \dfrac{k}{\rho c_p}$, and make the Laplace transform. Then

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

From eq. (23), we get

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

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

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

and the solution of eq. (26) is

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

where $c(p)$ is integration constant. Taking the differential of eq. (28) with respect to r, we obtain

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

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

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

The solution of eq. (29) is

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

(31)

Inverting above eq. (31), we get

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

(32)

We set $\xi=\frac{r}{2\sqrt{\chi t}}$ and

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

where $erfc(\xi)$ is related with the common error function $erf(\xi)$ by

$$erfc(\xi)+erf(\xi)=1 . \qquad (34)$$

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 is given by

$$(T'_{Li})_{\max}=q_{fw}\sqrt{\frac{4\tau}{\pi\rho kc_p}} . \qquad (35)$$

The maximum temperature rise $(T'_{Li})s_{\max}$ of an element of the liquid curtain varies with the flowing speed of the curtain for the 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, even though the curtain flowing speed is as low as 0.5 m/s.

3. Discussion and Conclusions

We have shown that when the inlet liquid lithium temperature is 500 K, even though the flow speed is as low as 0.5 m/s, the outlet temperature rises only to 740 K. Under such low temperature the evaporation rate of liquid lithium is not high [15], since the evaporation heat of a liquid lithium atom is 10 times that of a water atom. We therefore conclude that if the sputtering of liquid lithium can be omitted, even without considering the divertor removal effects of evaporated lithium atoms, the liquid lithium curtain will not seriously jeopardize the core plasma. Flowing liquid lithium provides the benefit of a low-Z renewable first wall; and not only does it remove the thermal energy, but it protects the back solid first wall from damage. The core plasma will not be contaminated by high-Z impurities, especially since lithium is a strong getter of impurities, as has been demonstrated in CDX-U experiments with liquid Li [12]. If we do consider the removal effects of evaporated lithium atoms by the divertor, then a much higher lithium temperature can be allowed, resulting in a lower flow speed required, or lower pumping power.

Nevertheless, the assumptions currently made weigh heavily on how MHD effects and off-normal events affect the use of flowing liquid lithium curtains or similar PFC systems in a high-density fusion reactor. Encouraging results have shown that particle-induced sputtering of lithium particles into the plasma edge of current tokamak experimental reactors remains negligible up to temperatures near 700 K. Beyond these temperatures, thermal evaporation dominates, and significant lithium vapor is generated. The vapor is, however, fully ionized near the edge and provides power shielding protecting PFCs. An additional benefit of using liquid lithium is that low-recycling regimes can be achieved [7,12,13], leading to steep temperature profiles at the edge. Moreover, in future fusion reactors MHD-induced effects, leading to unusually large influx of lithium into the fusion plasma, can be mitigated with novel advanced systems such as the lithium capillary-pore system [13].

Off-normal events present in pulsed and quasi-steady-state fusion devices could also present a challenge for the application of a flowing liquid-lithium curtain. This topic has important implications for the effective plasma charge and fuel dilution calculated in this study. Additional studies are in progress, including: liquid-lithium sputtering, lithium atom transport in the SOL region, and divertor-pumping effects and their effect on parameters.

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Figure Captions:

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

Fig. 2. Fusion power reduction due to fuel dilution

Fig. 3. The effects of T_{Li} on Z_{eff} , P_f/P_0 and f_{Li}

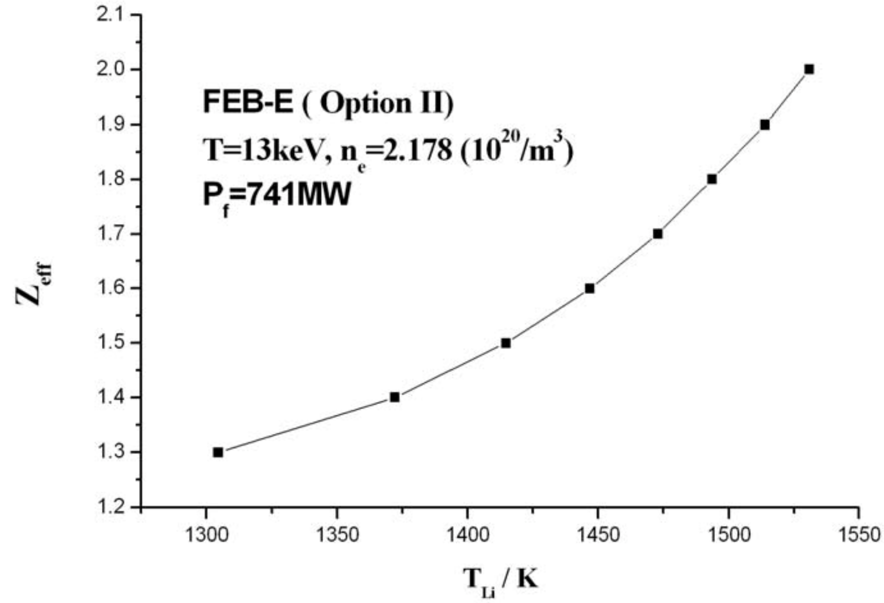

Fig. 1. The variation relation between Z_{eff} and T_{Li}

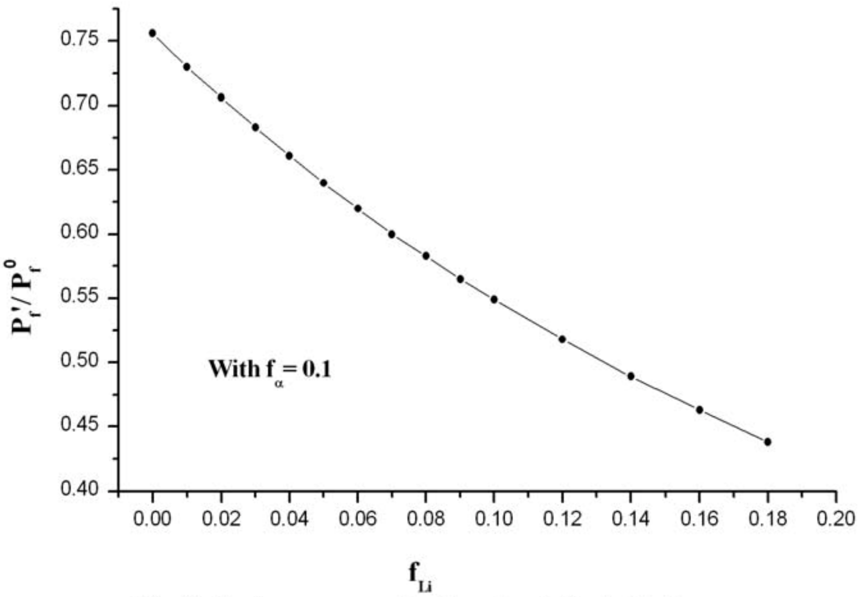

Fig. 2 Fusion power reduction due to fuel dilution

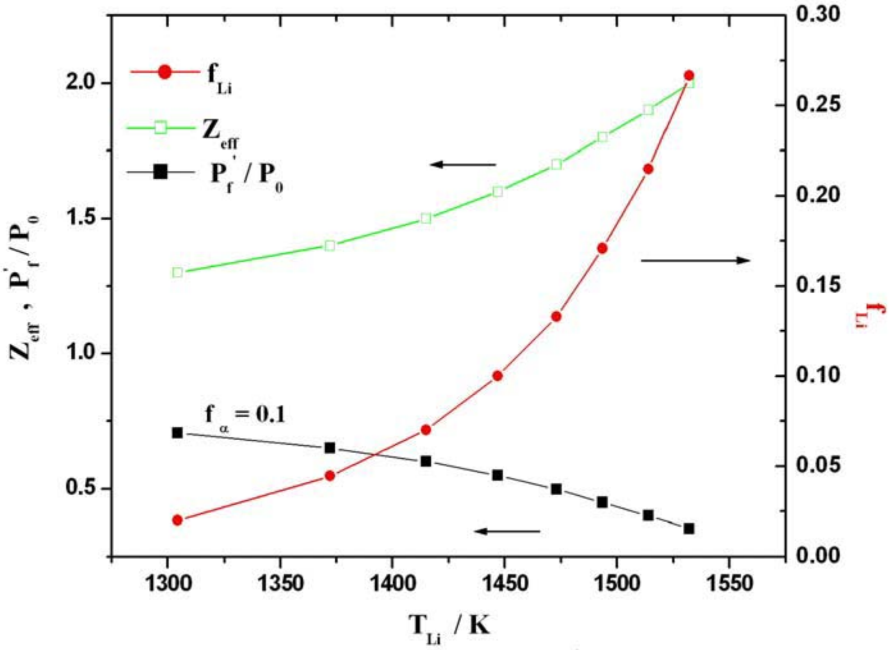

Fig.3 The effects of T_{Li} on Z_{eff} , $P_f^{'}/P_0$ and f_{Li}

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

Z_{eff}	a_i	T_{Li} (K)
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

Table 2. Z_{eff} variation with f_α 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

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

v (m/s)	$(T'_{Li})_{\max}$ (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