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Effects of a liquid lithium curtain as the first wall in a fusion reactor plasma*

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This paper explores the effect of a liquid lithium curtain on fusion reactor plasma, such curtain is utilized as the first wall for the engineering outline design of the Fusion Experimental Breeder (FEB-E). The relationships between the surface temperature of a liquid lithium curtain and the effective plasma charge, fuel dilution and fusion power production have been derived. Results indicate that under normal operation, the evaporation of liquid lithium does not seriously affect the effective plasma charge, but effects on fuel dilution and fusion power are more sensitive. As an example, it has investigated the relationships between the liquid lithium curtain flow velocity and the rise of surface temperature based on operation scenario II of the FEB-E design with reversed shear configuration and high power density. Results show that even if the liquid lithium curtain flow velocity 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 yet considered in detail. Further studies are in progress, and in this work implication of lithium erosion and divertor physics on fusion reactor operation are discussed.

Keywords: liquid lithium curtain, first wall, fuel dilution, effective plasma charge, plasma-wall interaction
PACC: 2852, 2852F, 2852J

1. Introduction

The final goal of fusion energy research is to make it economically competitive and the cost of electricity as low as to be acceptable by the energy market. Therefore the fusion plasma has to operate with high power density and the plasma facing components (PFC), such as 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 rigorous environments consequentially lead to severe damage and erosion of PFC materials. As a result, the lifetime of PFC would be shortened. The economic viability of a fusion reactor would be greatly reduced by the frequent shutdown and replacement maintenance. This is one of the key issues of concern which is 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. A new idea to replace the solid first wall in the fusion reactor with a rotating liquid metal wall was proposed first by Christofilos[1] in 1971. Later in 1987, Moir[2] investigated the technical feasibility and further improvements were made in 1995.[3] 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 established ALPS (Advanced Limiter-divertor Plasma-facing Systems) program in the United States studied the feasibility of liquid-metal PFCs and continues this work for future fusion reactor designs.[5,6] Studies have included the effects of liquid-metal sputtering, Magnetohydrodynamic (MHD) instability and dynamics on liquid-metals, particle recycling and operation, thermal hydraulics, effects of abnormal tokamak operation (i.e., edge localized modes (ELMs) and disruptions).[7−11]

The advantages of a flowing liquid metal curtain are: 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. In ad-

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dition, the specific application of lithium as a plasma-facing liquid-metal curtain is also particularly important due to its affinity for hydrogen to operate in low-recycling regimes and uptake of impurities.[6,7,12] 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. For instance, we have investigated the FEB-E reactor design[13,14] and obtained the relationships between the surface temperature of liquid lithium curtain and the effective plasma charge $Z_{\rm eff}$, fuel dilution and fusion power production. The sputtering of liquid lithium curtain and the particle removal effects of divertor are not yet considered at present. However, exhaustive studies, whether experimental and modelling, have demonstrated the feasibility of operating with liquid lithium as a plasma-facing wall or divertor surface. This point will be discussed in detail in the next section. In this work, the variation relation between the maximum surface temperature rise and the liquid lithium curtain flow velocity has been analysed and calculated. We concluded that even though the liquid lithium curtain flow speed is as low as 0.5 m/s, the effects of evaporation from the liquid lithium curtain on reactor fusion plasma are negligible.

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

In this section we analyse the effect of a liquid lithium curtain on plasma impurity dilution, mainly on the effective plasma charge, $Z_{\rm eff}$. We also briefly discuss the implications of particle-induced erosion and transport of lithium in the liquid state on the analysis carried out in this section and subsequent sections of this paper. Generally the effective plasma charge $Z_{\rm eff}$ is defined as:

$$Z_{\rm eff} = \frac{\sum_{\rm i} n_{\rm i} Z_{\rm i}^2}{\sum_{\rm i} n_{\rm i} Z_{\rm i}} = \frac{\sum_{\rm i} n_{\rm i} Z_{\rm i}^2}{n_{\rm e}}. \tag{1}$$

Assuming α particle concentration is 10%, fuel mixture ratio is 50%D −50%T, and lithium impurity ion density is $n_{\rm Li}$ in plasma, then we get

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

Since

$$n_{\rm DT} + 0.2 n_{\rm e} = n_{\rm e} - Z_{\rm Li} n_{\rm Li},$$

and

$$n_{\rm DT} + 0.4 n_{\rm e} = 1.2 n_{\rm e} - Z_{\rm Li} n_{\rm Li},$$

therefore

$$Z_{\rm eff} n_{\rm e} = n_{\rm Li} Z_{\rm Li}^2 + 1.2 n_{\rm e} - Z_{\rm Li} n_{\rm Li},$$

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

Assuming that lithium impurity and fuel ions have a common temperature $T_{\rm i}$, we can obtain the partial pressure contributed from lithium impurity ions as

$$p_{\rm Li} = n_{\rm Li} k T_{\rm i} = \frac{(Z_{\rm eff} - 1.2) n_{\rm e}}{Z_{\rm Li}(Z_{\rm Li} - 1)} k T_{\rm i}. \tag{4}$$

We have calculated the bound electron stopping power of α particle in the lithium vapour cloud.[15] The sputtered lithium atom flux may be smaller than evaporated lithium atom flux due to the shielding effects of lithium vapour clouds.[16] The sputtering yields of lithium bombarded by charged particles H^+, D^+, T^+ and He^{++} are calculated by application of sputtering theory based on bipartition model of ion transport. The sputtering yield of α particle is the largest.[17] Our results have only in comparison 20%–50% differences in comparison with the experimental data given by Allain and Ruzic[18] at the incident He^+ particle energies between 200 and 1000eV of the He^+ particle.

There are two particular issues involving particle-induced erosion of liquid lithium and its transport in fusion plasma that must be discussed. The sputtering of liquid lithium as a function of temperature has been extensively studied both in linear plasma devices and particle-beam facilities.[8,10] Typically liquid Li surfaces used as PFCs are saturated with fuel particles, namely hydrogen isotopes. This is due to the high hydrogen retention properties of lithium. This results in diluted Li emission into the fusion plasma.[19] In addition, of the sputtered Li particles almost 2/3 is emitted as ions and with the presence of a plasma sheath in the vicinity region of the fusion reactor wall, they're immediately accelerated back to the surface. Those Li atoms which are removed as neutrals are readily ionized as has been demonstrated in several papers.[12,20,21] Therefore a significant contribution of particle-induced sputtered atoms into the core fusion plasma should be likely small and thus can be neglected, with the only exception that plasma edge conditions remain somewhat similar to the studies presented in the literature. For substantially different plasma edge conditions (i.e. magnetic field strength at PFCs, edge temperature, etc $\cdots$) further assessment of lithium sputtering and its implications on studies here must be investigated. However, MHD effects and

emission of lithium material due to off-normal events (i.e., Giant ELMs, ELMs and disruptions) cannot be neglected and must be accounted. Its inclusion is challenging, and these effects are not well understood yet and warrant further study.[7,12] Therefore, in the analysis presented in this paper, particle removal effects due to MHD forces or off-normal events (those events not constitute normal operation of a fusion reactor device) are beyond the scope of the paper and thus let us leave it behind for future work.

If the particle removal effects due to MHD forces and erosion are not considered, then the relation of the saturated vapour pressure and surface temperature $T_{\rm Li}$ of a liquid lithium curtain can be deduced by the fitting formula given by Douglas:[22]

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

where the pressure $P_{\rm Li}$ is in unit of torr (= 133.3Pa) and $T_{\rm Li}$ in K. By combining Eqs.(4) and (5), one obtains:

$$\lg\Big[\frac{(Z_{\rm eff}-1.2)n_{\rm e}kT_{\rm i}}{Z_{\rm Li}(Z_{\rm Li}-1)}\Big] = 12.9992 - \frac{8442.53}{T_{\rm Li}} - 1.64098 \lg T_{\rm Li} + 2.5968 \times 10^{-4} T_{\rm Li}. \quad (6)$$

For convenience, we convert the unit of plasma pressure $n_{\rm e}kT_{\rm i}$ to 10^{20} keV/m^3, and give 1 torr = 133.3 Pa = 8.3×10^{19} keV/m^3, thereby, we get the identity 1×10^{20} keV/m^3 = 120 torr. Then Eq.(6) takes the following form:

$$T_{\rm Li} \lg\Big[\frac{120(Z_{\rm eff}-1.2)n_{\rm e}kT_{\rm i}}{Z_{\rm Li}(Z_{\rm Li}-1)}\Big] - 12.9992 T_{\rm Li} + 1.64098 T_{\rm Li} \lg T_{\rm Li} - 2.5968 \times 10^{-4} T_{\rm Li}^2 + 8442.53 = 0, \quad (7)$$

where the pressure $n_{\rm e}kT_{\rm i}$ is in units of 10^{20} keV/m^3 and $T_{\rm Li}$ in K.

For instance, we have studied the design option II of FEB-E.[13,14] The designed reactor parameters are: $P_{\rm f}$ = 741 MW, $T_{\rm i}$ = 13 keV, $n_{\rm e} = 2.178 \times 10^{20}$/m^3. For different $Z_{\rm eff}$, Eq.(7) can be written as:

$$a_{\rm i} T_{\rm Li} + b T_{\rm Li}^2 - c T_{\rm Li} \lg T_{\rm Li} - d = 0, \quad (8)$$

where

$$a_{\rm i} = 12.9992 - \lg\Big[\frac{120(Z_{\rm eff}-1.2)n_{\rm e}kT_{\rm i}}{Z_{\rm Li}(Z_{\rm Li}-1)}\Big],$$

i.e. $a_{\rm i}$ is dependent on $Z_{\rm eff}$, and the other coefficients are given as: $b = 2.5968 \times 10^{-4}$, $c = 1.64098$, and $d = 8442.53$. After solving Eq.(8), the variation relation of $Z_{\rm eff}$ with respect to $T_{\rm Li}$ can be shown in Fig.1 along with $a_{\rm i}$ coefficients.

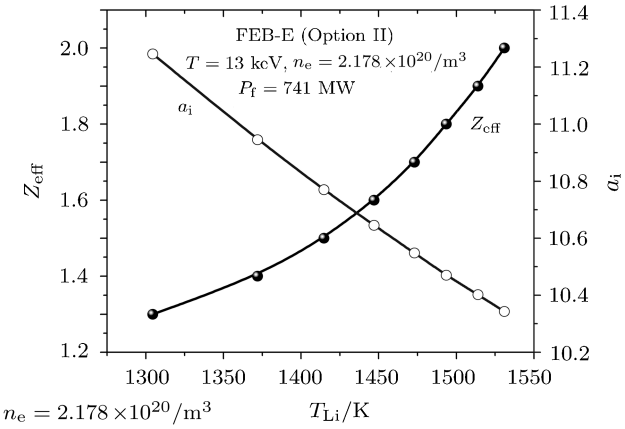


Fig.1. The variation relation between $Z_{\rm eff}$ and $T_{\rm Li}$.

Results show that to guarantee the effective plasma charge $Z_{\rm eff} \le 1.5$, it is necessary to keep the lithium curtain temperature $T_{\rm eff} \le 1415$ K. This result does not account for particle-induced sputtering, temperature-dependent erosion[10,23–28] or particle removal effects due to MHD forces and/or off-normal events in a fusion reactor device. However, as stated earlier the former assumption is viable due to lithium's high redeposition fraction.

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

As usual, the fusion power can be expressed as

$$p_{\rm f} = (n_{\rm DT}/2)^2 < \sigma V > E_{\rm DT}. \quad (9)$$

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

$$n = 2n_{\rm DT} + 3n_{\alpha} + 4n_{\rm Li}. \quad (10)$$

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

$$f_{\alpha} = \frac{n_{\alpha}}{n_{\rm DT}}, \quad f_{\rm Li} = \frac{n_{\rm Li}}{n_{\rm DT}}, \quad (11)$$

then

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

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

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

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

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

In Section 2, $n_{\rm Li}$ is given by:

$$n_{\rm Li} = \frac{(Z_{\rm eff} - 1.2)n_{\rm e}}{Z_{\rm Li}(Z_{\rm Li} - 1)}, \qquad (15)$$

and from the charge neutrality requirement

$$n_{\rm e} = n_{\rm DT} + 2n_\alpha + 3n_{\rm Li}. \qquad (16)$$

Then $Z_{\rm eff}$ can be described as

$$Z_{\rm eff} = 1.2 + \Big(\frac{6f_{\rm Li}}{1 + 2f_\alpha + 3f_{\rm Li}}\Big). \qquad (17)$$

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

$$\frac{P_{\rm f}}{P_{\rm f}^0} = \Big(\frac{4}{(4 + 6f_\alpha + 8f_{\rm Li})}\Big)^2. \qquad (18)$$

Figure 2 shows the fusion power reduction with respect to $f_{\rm Li}$, with f_α=0.1 fixed. The effective plasma charge $Z_{\rm eff}$ varies with $T_{\rm Li}$ and is shown in Fig.3 with $f_\alpha = 0.1$ fixed. The effects of the temperature $T_{\rm Li}$ of liquid lithium curtain on $Z_{\rm eff}$, fuel dilution factor $f_{\rm Li}$ resulted from liquid lithium atoms, and the reduction factor of fusion power density $P_{\rm f}/P_{\rm f}^0$ are shown in Fig.4 more clearly.

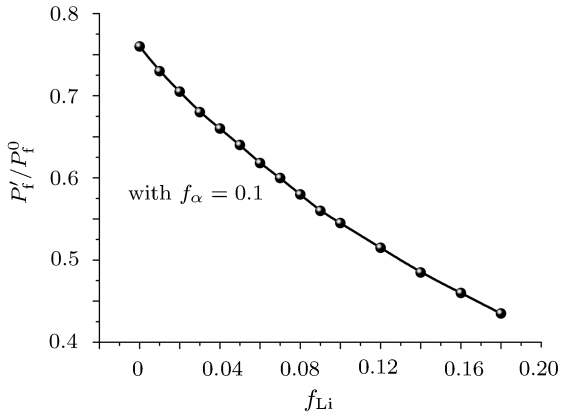


Fig.2. Fusion power reduction due to fuel dilution.

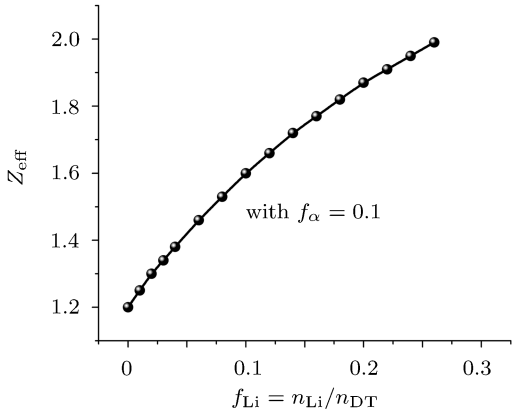


Fig.3. $Z_{\rm eff}$ variation with $f_{\rm Li}$ for FEB-E reactor, with $f_\alpha = 0.1$ fixed.

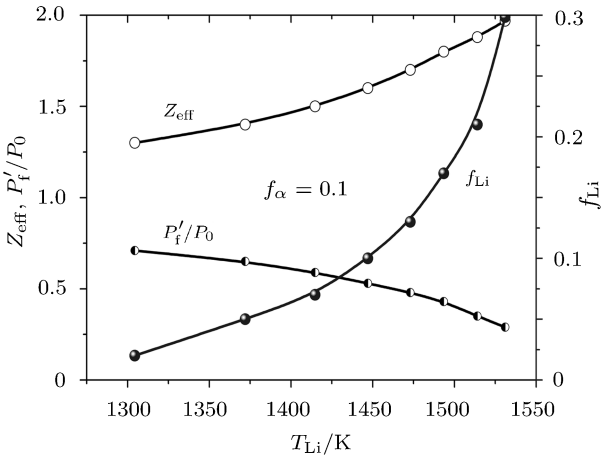


Fig.4. The effects of $T_{\rm Li}$ on $Z_{\rm eff}$, $P'_{\rm f}/P_0$ and $f_{\rm Li}$.

4. 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. For instance, we consider the FEB-E design option II: with fusion power $P_{\rm f}$ = 741 MW, auxiliary heating power $P_{\rm aux}$ = 37 MW, plasma major radius R = 4 m and minor radius a = 0.845 m, elongation κ = 1.8. Assuming that the fraction of plasma exhaust power to the divertor is $f_{\rm div}$ = 0.55 and the peaking factor of heat flux on the first wall is $\hat{f}_{\rm fw}$ = 1.5, we can regard the divertor target area as a fraction $\varepsilon_{\rm div}$ = 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:

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

Assume that one can keep the liquid curtain flowing with constant speed by making use of MHD effects [J. P. Allain note: however, we do not account for MHD effects self-consistently in this analysis, so this assumption is very limited]. Because of the continuity requirement, the liquid curtain should follow $({\rm d}/{\rm d}z)(v\delta)=0$ 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 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

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

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

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

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

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

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

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

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

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

Let $\chi=k/\rho c_{\rm p}$ and make Laplace transform, then

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

From Eq.(23), we get

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

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

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

and the solution of Eq.(26) is

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

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

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

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

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

The solution of Eq.(29) is

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

Inverting Eq.(31), we obtain

$$T'_{\rm Li}(r,t)=\frac{1}{k}(q_{\rm fw})\sqrt{\chi}\Big[2\sqrt{\frac{t}{\pi}}\exp\Big(\frac{-r^2}{4\chi t}-\frac{r}{\sqrt{\chi}}\Big)\times{\rm erfc}\Big(\frac{r}{2\sqrt{\chi t}}\Big)\Big]. \quad (32)$$

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

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

we find that erfc(ξ) is related with the common error function erf(ξ) by

$${\rm erfc}(\xi)+{\rm erf}(\xi)=1. \quad (34)$$

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

$$(T'_{\rm Li})_{\rm max}=q_{\rm fw}\sqrt{\frac{4\tau}{\pi\rho k c_{\rm p}}}\,. \quad (35)$$

The maximum temperature rise $(T'_{\rm Li})s_{\rm max}$ of an element of the liquid curtain varies with the flowing speed of the curtain for FEB-E design and is shown in Fig.5. 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.

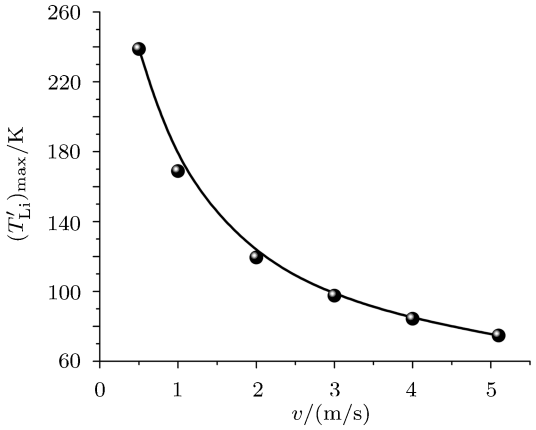


Fig.5. $(T'_{\rm Li})_{\rm max}$ varies with flowing speed of the curtain for FEB-E design.

5. Discussion and conclusions

Studies indicate that application of a flowing liquid lithium curtain in the front of the solid first wall would not seriously jeopardize the core plasma performance for FEB-E design with higher power density. For example, the inlet liquid lithium temperature is 500 K, even though the flow speed is as low as 0.5 m/s, the outlet temperature only rises to 740K. Under such low temperature the evaporation rate of liquid lithium is not high.[14] Since the evaporation heat of a liquid lithium atom is 10 times that of a water atom. Our conclusion is 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 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.[11] If we consider the removal effects of evaporated lithium atoms due to the divertor, then a much higher lithium temperature can be allowed, this fact results in a lower flow speed required, or lower pumping power. All this being said, however, 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 vapour is generated. However the vapour is fully ionized near the edge and provides power shielding protecting PFCs. Additional benefits of using liquid lithium are found on resulting low-recycling regimes that can be achieved[6,11,12] and lead to steep temperature profiles at the edge.

Moreover MHD-induced effects leading to unusually large influx of lithium into the fusion plasma can be mitigated with novel advanced systems in future fusion reactors such as the lithium capillary-pore system.[12] Off-normal events present in pulsed and quasi steady-state fusion devices could also present a challenge for application of flowing liquid lithium curtain. This topic has important implications on the calculated effective plasma charge and fuel dilution calculated in this study. Additional studies include liquid lithium sputtering and lithium atom transport in SOL region. Divertor-pumping effects and their effect on parameters studied in this paper are in progress.

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