

Article

Study of Plasma Interaction with Liquid Lithium Multichannel Capillary Porous Systems in SCU-PSI

Jianxing Liu ¹, Wenna Jing ¹, Hengxin Guo ¹, Yingwei Gao ¹, Sishu Wang ², Bo Chen ¹, Jianjun Chen ¹, Hongbin Wang ¹, Jianjun Wei ², Zongbiao Ye ^{1,*} and Fujun Gou ^{1,*}

¹ Key Laboratory of Radiation Physics and Technology of the Ministry of Education, Institute of Nuclear Science and Technology, Sichuan University, Chengdu 610064, China

² Institute of Atomic and Molecular Physics, Sichuan University, Chengdu 610064, China

* Correspondence: zbye@scu.edu.cn (Z.Y.); gfujun@scu.edu.cn (F.G.); Tel.: +86-18581510349 (F.G.)

Abstract: In this paper, an embedded multichannel capillary porous system (EM-CPS) was designed and fabricated with 304 stainless steel using the laser ablation method. The EM-CPS revealed its excellent ability to wick liquid lithium to its surface effectively. The interaction between Li-prefilled EM-CPS and plasma was studied, and the results showed that the surface temperature decreased by ~140 °C compared with the results of the experiment of EM-CPS without lithium filling. Additionally, EM-CPS displayed a better heat transfer performance and stronger radiation loss of the vapor cloud than the traditional woven tungsten-based meshes. In addition, the drift of the lithium vapor cloud center was found during plasma irradiation and led to a decrease in the intensity of the Li 670.78 nm emission line detected by the spectrometer at the observation point. When the thermal load deposited on the sample surface is reinforced by increasing the magnetic field, the rise in surface temperature is restrained due to the enhanced heat dissipation capability of lithium. SEM images of irradiated samples showed that the 304 stainless steel-based EM-CPS has corrosion problems due to the interaction between liquid lithium and argon plasma, but it still showed good plasma-facing characteristics. These findings provide a reference for further studies of embedded multichannel CPSs with plasma-facing components (PFCs) in linear plasma devices and tokamaks in the future.

Keywords: liquid lithium divertor; embedded multichannel structure; lithium vapor cloud; evaporation; emission spectrum



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1. Introduction

As an important component of fusion devices, the divertor performs the function of particle and energy treatment [1–3]. Due to their properties of good compatibility with D/T fuel, self-healing under plasma/neutron damage, and vapor shielding under a heat load [4], the design and investigation of liquid lithium divertors have attracted attention for a long time. Many experiments on free-surface and flow-surface liquid metal divertors have been carried out in NSTX [5], CDX-U [6], HT-7 [7], and EAST [8,9]. Evaporation [10] and vapor shielding [11] are two important processes that reduce the liquid divertor energy deposition under a high heat load. Evaporation can directly take away the heat load deposited on a liquid divertor. Additionally, a research finding showed that the injection of lithium aerosol was beneficial at reproducible, steady-state, ELM-free H-mode discharges [12]. The vapor shielding effect causes the evaporated neutral lithium atoms to form vapor clouds in front of the divertor, interact with plasma, absorb part of the energy through excitation or ionization, and lose it through radiation. When working in the vapor shielding regime, any accidental exhaust power excursion leads to increased evaporation, which may mitigate the impact on the divertor armor by self-protection [11,13]. Therefore, the liquid lithium divertor has become a candidate that has great potential for PFCs [14].

However, the temperature gradient, plasma current, and induced current in liquid lithium would lead to the splashing phenomenon under intense magnetic fields [7,15–17].

To enhance the stability of flowing liquid Li, the capillary force produced by capillary porous systems (CPSs) was applied to offset the $J \times B$ force [18,19]. Over the last decades, traditional woven metal mesh CPSs have been extensively studied and applied in fusion devices [20,21] and linear plasma devices [22,23]. Lin et al. fabricated superficial grooves by using the laser ablation method. The entire structure showed excellent lithium wicking capacity and could spread lithium on the sample surfaces effectively [24]. In consideration of the deficiency of traditional woven metal mesh under the high-parameter operations of fusion reactors, Tabarés proposed the concept of embedded CPSs [25]. Then, Rindt et al. exploited this concept and manufactured embedded CPSs [26–28]. Their experimental results revealed that the integrally formed embedded CPS has great potential for plasma-facing applications in fusion devices on behalf of a popular scheme for advanced divertor design.

In this work, an embedded multichannel structure (EM-CPS), created using the laser ablation method, was designed and employed as a CPS to confine liquid lithium. The experiments on argon plasma irradiation with a Li-prefilled sample were carried out utilizing the Sichuan University plasma-surface interaction device (SCU-PSI). The emission spectrum of the lithium vapor cloud was analyzed in the experiment on multichannel array structures. The morphology and characteristics of lithium vapor clouds were studied. The morphology of the EM-CPS surface after irradiation was observed by using a scanning electron microscope (SEM).

2. Experimental Procedure

2.1. Sample Preparation

The EM-CPS shown in Figure 1 was made of 304 stainless steel via laser etching technology. The EM-CPS surface has a series of trench structures with uniform spacing and through-holes. The holes with a diameter of $120 \pm 20 \mu\text{m}$ are used as the supplemental channels of liquid Li. The grooves with a depth of $80 \pm 20 \mu\text{m}$ and width of $120 \pm 20 \mu\text{m}$ are the flowing channels of liquid lithium. The sample installation procedure is as follows. First, put the pure lithium sheet into the precleaned molybdenum crucible (about 1.3 g) in the glove box filled with Ar. Then, melt it at about 300°C in an argon atmosphere and with natural cooling. Finally, fix the sample above the crucible through the molybdenum cover.

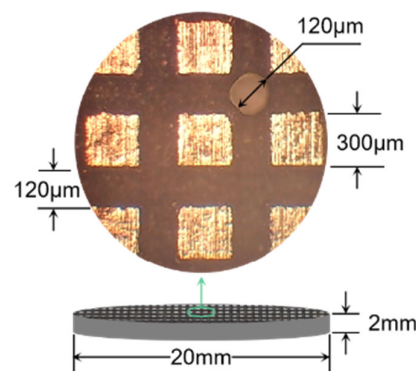


Figure 1. Surface morphology and size of EM-CPS.

2.2. Plasma Irradiation

The irradiation experiments of the lithium-prefilled EM-CPS were carried out in the SCU-PSI. The device can provide argon plasma with an electron density up to 10^{20} m^{-3} along the axial direction under a magnetic field [29]. The SCU-PSI device and the structure of the sample at the target are shown in Figure 2. The EM-CPS and the crucible are fixed at the target of the plasma through the stainless steel bottom plate and molybdenum cover, and the rest bases are insulated by using ceramic sheets. In this experiment, the device generates an irradiation area with a diameter of about 4 cm at the target 40 cm away from the source port. There is no additional bias voltage or heat source. For the diagnostic system, a Langmuir double probe (Keithley SourceMeter 2401) is utilized to diagnose the electron

density and the electron temperature of the plasma. An optical emission spectrometer (Avantes oes, AvaSpec-2048) with a wavelength range from 320 nm to 880 nm monitors the emission spectrum of the lithium vapor cloud area through the observation window. The temperature at the edge of the sample surface is obtained by the thermocouple.

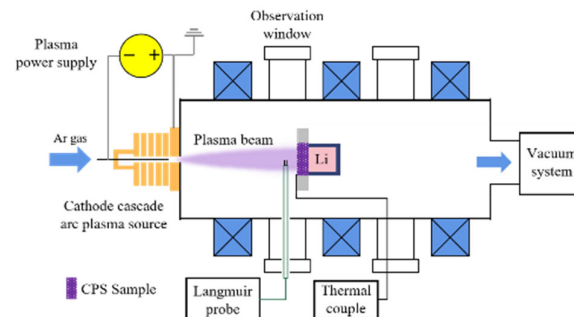


Figure 2. Schematic diagram of linear plasma device and sample irradiation.

3. Results and Discussion

To determine the experimental condition at the target, the plasma characteristics were measured, as shown in Figure 3. Electron temperature and density were measured by using the Langmuir probe, as shown in Figure 3a,b. The incident particle flux is calculated via Equation (1), as shown in Figure 3c. The thermal load is measured via calorimetry, as shown in Figure 3d. The experimental conditions are changed mainly by changing the discharge current and magnetic field. The gas flow is constant at 2000 sccm. The plasma electron temperature, density, and heat load at the target increase with the increase in the discharge current and magnetic field.

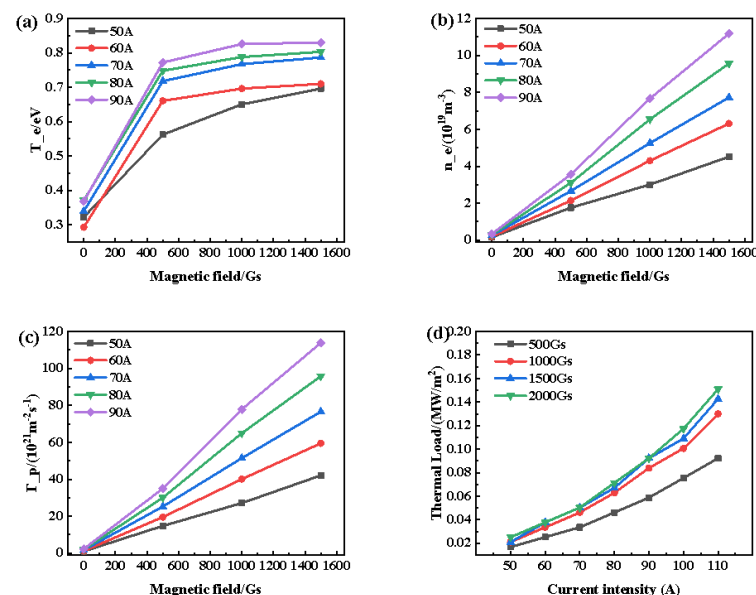


Figure 3. Ar plasma (a) electron temperature, (b) electron density, (c) incident particle flux, and (d) heat load on the target under the different experimental parameters.

The incident particle flux is given by the following formula [30]:

$$\Gamma_p = 0.5 \times 10^4 \times n_e \times \sqrt{2T_e/A_i}, \quad (1)$$

where n_e and T_e are the electron density and electron temperature, respectively, and A_i is the mass number of the Ar atom. Under the existing experimental conditions, the ion kinetic energy is about 3~5 T_e , which is far less than 10 eV. It does not reach the sputtering

threshold of lithium, which is usually greater than 20 eV [30]. When equilibrium is reached, it can be considered that most lithium losses are caused by thermal evaporation.

In this experiment, we mainly selected the current of 90 A and the magnetic field of 0.10 T as experimental conditions. Under these conditions, the SCU-PSI device can discharge argon plasma reliably. The surface temperature of the EM-CPS and the spectrum in front of the lithium vapor cloud were recorded, as shown in Figure 4. The heat load is $\sim 0.08 \text{ MW/m}^2$ at the target, and the corresponding surface temperature was measured to be around 670°C . Additionally, the evaporation flux of lithium is up to $\sim 2 \times 10^{23} \text{ m}^{-2}\text{s}^{-1}$ under this condition. The plasma parameters in front of the sample surface during plasma irradiation cannot be obtained after a high-density lithium vapor cloud appears because of the distortion of the voltammetry curve caused by the break-over of the Langmuir double probe.

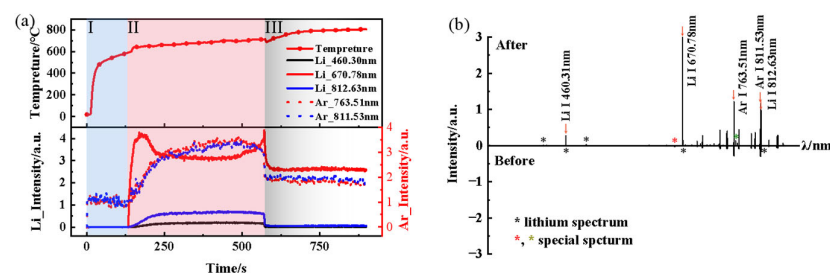


Figure 4. (a) The surface temperature (upper) and the emission spectrum of vapor cloud (bottom) during the experiment; (b) the spectral lines after (upper) and before (bottom) lithium evaporation in the experiment.

As can be observed in Figure 4a, the whole process could be divided into three phases: phase I is the stage where lithium is evaporated slowly, phase II is the period of intense evaporation of lithium, and phase III is the lithium evaporation attenuation stage. In phase I, the Li-prefilled EM-CPS was irradiated by argon plasma and heated up. Phase II is a noteworthy process, which reveals the interaction between plasma and lithium. Liquid lithium is nearly depleted as it enters the third stage, and the rest of the lithium cannot be replenished to the sample surface by capillarity (there will be 0.1–0.2 g of lithium left in the crucible). Figure 4b shows the emission spectrum of the lithium vapor cloud before and after lithium evaporation. The black asterisks represent lithium atomic emission lines that are detected. The red asterisk represents the H_α emission line, which indicates the presence of water vapor in the device. Additionally, the two emission lines at the green asterisk have yet to be analyzed. The rest of the emission lines are the argon atomic emission lines, which are not marked. Most of the emission lines were enhanced as the lithium began to evaporate. This is due to the increase in the electron density after the formation of the lithium vapor cloud, which results in the enhancement of the atomic emission spectra of lithium and argon. The Li 670.78 nm emission line and the Ar 763.51 nm emission line will be mainly analyzed later due to representativeness. However, the intensity of the ion emission line was found to be insufficient in this range of detection.

According to previous studies, the evaporation rate of lithium caused by the thermal effect can be expressed as [30]:

$$Y = 3.09 \times 10^{26} \times \frac{10^{8-8143/T}}{\sqrt{T} \cdot M_{Li}}. \quad (2)$$

Here, T is the temperature of liquid lithium and M_{Li} is the molar mass of lithium. The evaporation heat of a lithium atom can be expressed as the Trouton law: $\Delta H = 1.576 - 1.095 \times 10^{-4}T$. Hence, the heat energy taken away by liquid lithium evaporation per unit of time can be calculated as:

$$q_{ep} = Y \times \Delta H. \quad (3)$$

If it is considered that lithium atoms are excited during the collision with plasma, the energy absorbed by the lithium atoms is expressed by:

$$q_{ec} = Y \times \Delta E_1, \quad (4)$$

where ΔE_1 is the energy of the Li 670.78 nm light wave. The heat load taken away by both the thermal evaporation of lithium and the excitation of lithium atoms can be superimposed as $q = A(q_{ep} + q_{ec})$ in the experiment. A is a constant ($A = \frac{1}{22} = \frac{1}{4}$) related to the lithium vapor cloud radius (~2 cm) and the radius (~1 cm) covered by liquid lithium on the sample surface. The heat taken away by the evaporation of the liquid lithium and the heat taken away by the excitation of the lithium atoms is shown in the evaporation and excitation (non-ionization) curves in Figure 5. Considering that lithium atoms are only partly excited during the interaction with plasma, our experimental conditions should be between the evaporation curve and the excitation curve.

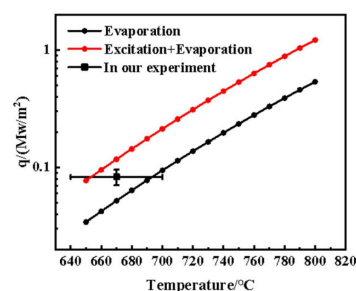


Figure 5. Heat loss due to thermal evaporation and excitation of lithium atoms.

The phenomenon of redeposition during the experiment is also worth considering. Firstly, lithium in the experiment is only prefilled to about 1.3 g. However, according to the surface temperature in phase II, Equation (2) is used for the integral calculation of lithium evaporation, which requires about 1.58 g during this period. This value is larger than the prefilled mass of lithium. It indicates that the redeposition of lithium exists during the experiment. Furthermore, there is clear evidence of redeposition as a large amount of lithium was found at 1 cm directly below the sample after the experiment.

The damage to the substrate will be very serious when the plasma bombards the substrate directly [31]. Therefore, the liquid lithium renewal rate of the sample surface is noteworthy in the process of irradiation. According to the calculation formula of capillary force [14]:

$$P_r = 2\sigma \cos \Theta / r. \quad (5)$$

Here, σ is the surface tension coefficient, Θ is the wetting angle, and r is the capillary radius. The capillary force of the EM-CPS can reach 10^4 N when the sample is fully wetted. In the study of [25], it is considered that the driving force of liquid metal is provided by the capillary force $\Delta P \approx P_r$, regardless of $\mathbf{J} \times \mathbf{B}$ forces. The ideal maximum lithium flow rate of a single through-hole is expressed as follows:

$$Q = \rho \pi r^4 \times \Delta P / (8\eta l), \quad (6)$$

where ρ is the density of liquid lithium, η is the viscosity coefficient, and l is the through-hole length. The ideal maximum lithium flow rate of a single hole is 3.2 mg/s. For the lithium consumed by evaporation (700 °C), each hole needs at least 0.05 mg/s to meet the demand (according to Equation (2)). Even taking into account the action of $\cos \Theta < 1$ and $\mathbf{J} \times \mathbf{B}$ forces [32], the lithium flow is reduced by an order of magnitude and still meets demand.

Two additional groups of experiments were set up with the same irradiation condition; one is an EM-CPS without lithium prefilled (blank), and the other is a lithium prefilled

tungsten mesh structure (W-CPS). Data were recorded throughout the three experiments, as shown in Figure 6.

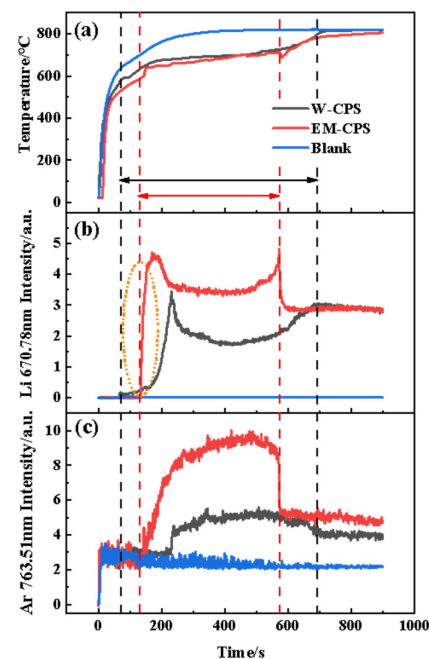


Figure 6. The changes in (a) the surface temperature, (b) the Li 670.78 nm emission line, and (c) the Ar 763.51 nm emission line under plasma irradiation with heat load $\sim 0.08 \text{ MW/m}^2$ (phase II is marked with dashed lines).

As shown in Figure 6a, the surface temperature of the sample began to rise when the irradiation started. Additionally, the surface temperature, from high to low at 160 s, is in the order of the blank group, the W-CPS, and the EM-CPS. Part of the energy was used to heat the lithium in the Li-prefilled groups; thus, the temperature of the Li-prefilled groups rose relatively slowly compared with the blank group. For the W-CPS and the EM-CPS, it is known that the thermal conductivity of tungsten is $174 \text{ W/(m}\cdot\text{K)}$, and that of 304 stainless steel is $20\sim 30 \text{ W/(m}\cdot\text{K)}$. The thermal conductivity of tungsten is stronger than 304 stainless steel. However, the temperature of the W-CPS rose faster in phase I than that of the EM-CPS. The increase in porosity reduces the heat transfer coefficient [23] and causes heat accumulation. Additionally, this could cause an accumulation of heat and damage the base when liquid lithium is not replenished. The surface temperature of the Li-prefilled sample decreased by about 18% compared with the blank group due to the evaporation and vapor shielding effect of lithium during phase II. In phase III, when the lithium cannot be replenished to the sample surface by capillarity, the surface temperatures rose to the same level for the three groups eventually. At this stage, the evaporation and vapor shielding effect of lithium gradually attenuated.

The lithium emission lines indicate that the interaction between lithium atoms and plasma happened [33,34]. It was found that the Li 670.78 nm emission line increased at first, and then decreased for both the EM-CPS and the W-CPS in the experiment, as shown in Figure 6b. It can be observed that the Li 670.78 nm emission line appeared earlier in the experiment of the W-CPS than that of the EM-CPS, and this phenomenon could be attributed to the local high temperature in the W-CPS. The heat accumulated in the central area due to the weak thermal conductivity of the W-CPS. The center area of the W-CPS reached the wetting temperature of lithium faster than other regions. Furthermore, it has been found that the lithium emission line rose steeply at the moment the lithium emission line appeared in the experiment of the EM-CPS (in the dotted box in Figure 6b). Additionally, the decrease in the Li 670.78 nm emission line had never been observed before. These phenomena will be discussed later.

With the intensification of liquid lithium evaporation, the argon emission line was enhanced, just as the Ar 763.51 nm emission line was enhanced, as shown in Figure 6c. When the Ar plasma flow into the cloud of lithium vapor, some of the energy carried by the plasma was transferred into the lithium vapor cloud, which was lost in the form of radiation [22,35]. During the interaction between the lithium vapor cloud and the plasma, both the argon emission line and the lithium emission line appear to rise, as shown in Figure 6b,c. However, compared with the W-CPS, the EM-CPS rises to a higher degree and its radiation loss is larger. This indicates that the interaction between the lithium vapor cloud and the plasma is more intense compared with the W-CPS during the EM-CPS irradiation experiment.

The embedded multichannel structure presented a similar performance as the traditional woven mesh CPS, and was even more advantageous. However, the embedded multichannel structure also exhibited some different characteristics. These results provide an experimental basis for our subsequent design of a better embedded multichannel structure.

The evolution of the vapor cloud was observed, and the images of the Li-prefilled EM-CPS under plasma irradiation were recorded. A typical irradiation image is shown in Figure 7a. The contours of the upper part of the vapor cloud at different times were extracted, as shown in Figure 7b. It can be seen that the size of the vapor cloud increased as the irradiation progressed and disappeared rapidly at the end of phase II. Along the central axis, the outline first expands and then decreases. In addition, the central area is marked by a dotted box, and the line intensity along the central axis in this area was calculated at different times, as shown in Figure 7c (the brightest points along the central axis are marked with black dots). The central bright spot of the vapor cloud brightened and drifted outwards with the irradiation process, and finally reached stability. Along the center line, the line intensity showed the phenomenon of strengthening at first, and then weakening.

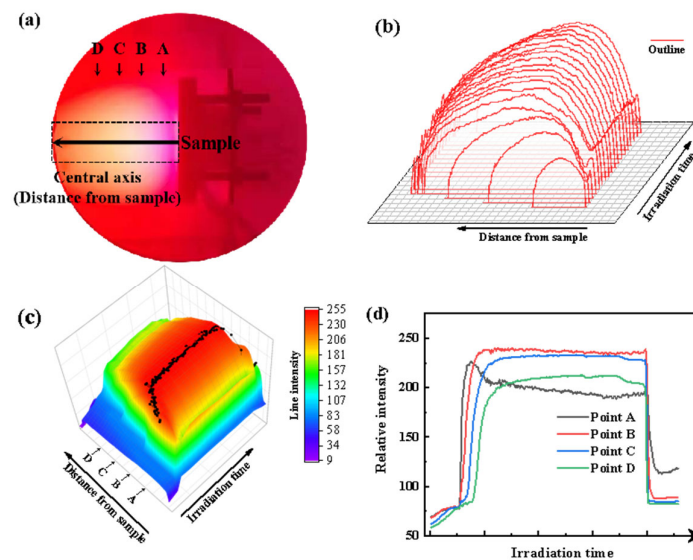


Figure 7. (a) Typical irradiated image of EM-CPS. (b) The shape of vapor cloud, (c) the line intensity of light on the central area, and (d) the intensity of light at different observation points vary with irradiation time.

To explain the decrease in the intensity of the Li 670.78 nm emission line, four inspection points (A, B, C, and D) were set at different positions perpendicular to the central axis, as shown in Figure 7a. The average intensities of the four sites at different times were recorded, as shown in Figure 7d. The variation trend of the intensity at point A could explain the decrease in the Li 670.78 nm emission line, as shown in Figure 6c. Point B represents the position with the highest intensity. It is the place where lithium atoms interact most strongly with plasma in the vapor cloud. The results suggest that a fixed-point

spectral diagnosis may not be suitable for the study of plasma interaction, and a multipoint spectral diagnosis should be considered in the future.

Plasma parameters [29], $J \times B$ forces [18], and the morphology of lithium vapor clouds are influenced by the magnetic field in the experiment. Therefore, after adjusting the magnetic field to 0.05 T and 0.15 T, two additional experiments were carried out to compare to the condition of 0.10 T, as shown in Figure 8. When the magnetic field is 0.05 T, $T_e \sim 0.77$ eV, $n_e \sim 3.6 \times 10^{19} \text{ m}^{-3}$, and the heat load decreases by $\sim 0.025 \text{ MW/m}^2$ compared with 0.10 T. When the magnetic field rises to 0.15 T, $T_e \sim 0.83$ eV, $n_e \sim 11.8 \times 10^{19} \text{ m}^{-3}$, and the heat load increases by $\sim 0.010 \text{ MW/m}^2$.

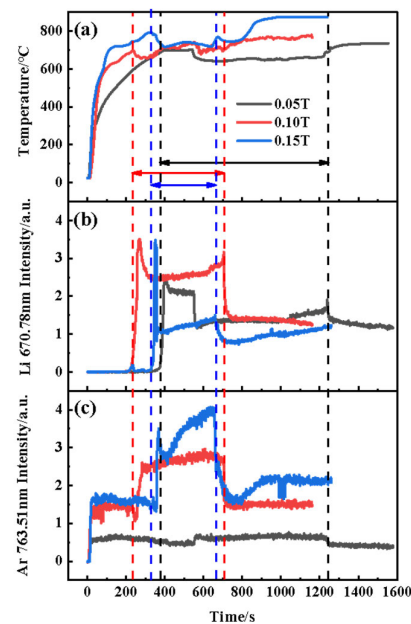


Figure 8. The changes in (a) the surface temperature, (b) the Li 670.78 nm emission line, (c) and the Ar 763.51 nm emission line under plasma irradiation with different magnetic fields.

According to the variation of temperature in Figure 8a, it can be seen that the temperature under the conditions of 0.10 T and 0.15 T is similar in the time range of 400–670 s. This is due to the temperature locking phenomenon caused by the vapor shielding effect [22]. On the one hand, this is because the heat taken away by lithium evaporation changes exponentially with temperature, as shown in Figure 3. An enormous increase in the heat load results in only a small increase in surface temperature. On the other hand, an increase in the magnetic field results in an enhanced intensity in the argon emission line, and thus, the loss of radiation was also enhanced. As seen in Figure 8c, the Ar emission line of 0.15 T is stronger than that of 0.10 T in the second stage. It is worth noting that, under the experimental condition of 0.15 T, the intensity of the Li 670.78 nm emission line is smaller than that line of 0.10 T, as shown in Figure 8b. This result was not expected. When the magnetic field is enhanced, the argon emission line satisfied the expected behavior. However, the sharp drop in the Li emission line is hard to explain. We consider this to be a special case, and the experiment needs further study.

The steep rise of the Li 670.78 nm emission line was observed in the above experiments at the moment the lithium emission line appears. This reflected that the lithium evaporation intensifies, and the surface temperature of liquid lithium was also rising rapidly. This could result in a huge temperature gradient in liquid lithium. Huge temperature gradients lead to an increase in the $J \times B$ force by a pyroelectric effect. This condition is likely to happen after an edge localized mode (ELM) event and has rarely been studied [36,37]. However, it has been found that droplets may be jetted using unwetted conventional tungsten screens as the CPS, such as in the previous study of [38]. Hence, some attempts were made to improve this situation.

The experiment of prewetting the EM-CPS was carried out. The emission lines and temperature during the experiment are shown in Figure 9. For the traditional prewetting method, the sample should be immersed in liquid lithium under vacuum conditions in advance and held for 4 h at a high temperature (~ 500 °C). Then, the sample surface will be coated with lithium completely. In the irradiation experiment, the surface temperature of the prewetting sample was lower than the sample without prewetting, as shown in Figure 9a. As a consequence, the lower surface temperature resulted in reduced lithium evaporation and a prolonged phase II of the prewetting sample compared to the sample without prewetting. Furthermore, the surface temperature of the prewetting sample was especially lower than that of the sample without prewetting at phase I. This is because the thermal conductivity of the sample covered with lithium increased [39]. Prewetting can also effectively improve the wettability of the sample surface so that the liquid lithium could wick to the sample surface easily in the irradiation process, as can be observed in Figure 9b. As for the prewetting sample, the Li 670.78 nm emission line appeared at low surface temperatures, about 350 °C. When the sample was not prewetted, the Li 670.78 nm emission line appeared at high surface temperatures, about 600 °C. Under the same irradiation conditions, the prewetted EM-CPS showed a better heat emission performance than the EM-CPS without prewetting. However, after prewetting, both argon and lithium spectra are weaker than those of the samples without prewetting. The intensity of the lithium vapor cloud interaction with the plasma is reduced.

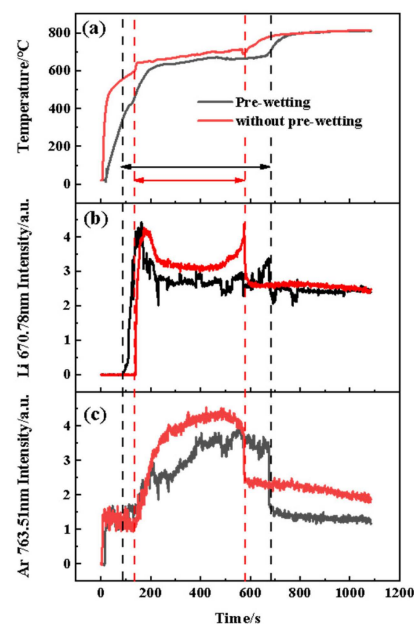


Figure 9. The changes in (a) the surface temperature, (b) the Li 670.78 nm emission line, and (c) the Ar 763.51 nm emission line under plasma irradiation of the EM-CPS with or without prewetting in advance.

The surface morphology of the EM-CPS after irradiation was observed via an SEM as shown in Figure 10. It can be observed in Figure 10c that the sample without prewetting appeared as a hole-like structure on the surface morphology after irradiation. Although the surface temperature of the prewetting sample was lower than that of the sample without prewetting during the experiment, larger and deeper holes appear on the surface of the prewetting sample, as shown in Figure 10d. In past studies, it was found that the corrosion of 304 stainless steel in static liquid lithium mainly results from the dissolution of Fe, Ni, Cr, and C and the formation of corrosion products on the surface of the sample [40]. Additionally, the corrosion of liquid lithium on the surface of 304 stainless steel is not uniform [41]. Furthermore, the phenomenon of Fe sputtering does not happen under the current experimental conditions (argon plasma energy is less than 20 eV) [42]. Therefore,

under the synergistic effect of lithium and plasma, the surface of the sample after irradiation appeared with holes due to the action of uneven lithium corrosion. The phenomenon of aggravating serious corrosion occurred after the experiment as compared to the sample without the prewetting treatment because the prewetting sample holds heat with lithium for 4 h in the environment of 500 °C. Despite the EM-CPS having some advantages, the corrosive effect is inevitable, and subsequent research on the multichannel structure of tungsten and other materials should be carried out.

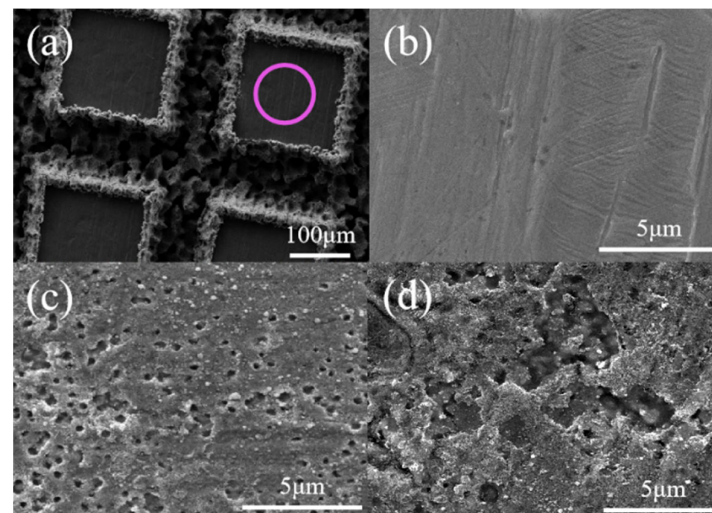


Figure 10. (a) SEM images of large scale on EM-CPS surface. SEM images of (b) EM-CPS before irradiation experiment, (c) EM-CPS without prewetting after irradiation experiment, and (d) prewetting EM-CPS after irradiation experiment (the circle in (a) is the shooting area).

The in situ wetting technology was developed in our research group [43]. The plasma used to preheat the EM-CPS could prevent the situation of violent lithium evaporation, as shown in Figure 11. First, stage I is EM-CPS irradiation by plasma with a heat load of $\sim 0.01 \text{ MW/m}^2$. The temperature of the EM-CPS reached about 350 °C, but the Li 670.78 nm emission line intensity was close to zero. It is concluded that the lithium did not wet the sample. Then, the heat load increased to $\sim 0.02 \text{ MW/m}^2$ at stage II. At this point, the emission line of Li 670.78 nm appeared, and it could be concluded that liquid lithium wetted the sample. Finally, the heat load was increased to the set value at phase III, and the sample entered the normal irradiation stage. This method of prewetting can help us avoid using the long-term, high-temperature treatment process compared to the traditional static method. A similar effect can be achieved by considering preheating (up to 400–500 °C) in fusion devices.

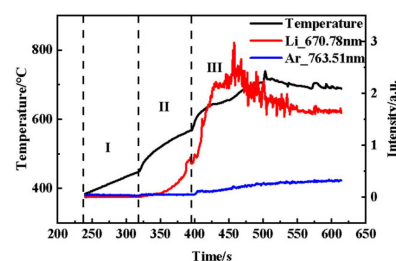


Figure 11. The surface temperature curve of EM-CPS, the Li 670.78 nm emission line curve, and the Ar 753.51 nm emission line curve of in situ plasma wetting experiment.

4. Conclusions

The interaction between the Li-prefilled EM-CPS and plasma was studied through the analysis of surface temperature, the optical emission spectrum of the vapor cloud, and surface morphology. We found that the surface temperature in the irradiation experiment

with lithium prefilling decreased by $\sim 140^\circ\text{C}$ compared with the blank experiment. Additionally, the EM-CPS displayed a better heat transfer performance and stronger radiation loss of the vapor cloud than the traditional woven tungsten-based meshes. Furthermore, it was found that the center of the lithium vapor cloud moved away from the sample surface during the experiment, and this result leads to a decrease in the intensity of the Li 670.78 nm emission line detected by the spectrometer at the observation point. When the thermal load deposited on the sample surface is increased by changing the magnetic field, the rise in surface temperature is limited due to the enhanced heat dissipation capability of lithium. This indicates that liquid lithium mitigates the impact on plasma heat flux deposition by self-regulating. The phenomenon of the lithium emission line rising sharply was observed when the lithium emission line appeared. This situation may cause droplets to spray. The prewetting treatment of the EM-CPS could reduce the occurrence of this situation. SEM images of irradiated samples showed that the 304 stainless steel-based EM-CPS has corrosion problems due to the interaction of liquid lithium and argon plasma, but it still showed good plasma-facing characteristics. A tungsten-based EM-CPS will be investigated in the follow-up work. These findings provide a reference for further studies of embedded multichannel CPSs with plasma-facing components (PFCs) in linear plasma devices and tokamaks in the future.

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