

## Recent progress in the development of liquid metal plasma facing components for magnetic fusion devices

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### ABSTRACT

One of the most critical challenges for future fusion reactors is to develop longevity plasma-facing components (PFCs) exposed to extremely high heat and neutron loads. As opposed to those employing solid metals, PFCs with flowing liquid metals (LM) have shown self-healing, heat removal and good impurity control capabilities, all essential to fusion devices. Recently, significant progress in LM-PFC development has been reported globally, with data from several magnetic fusion devices. These studies reveal that LM-PFCs can endure extreme heat fluxes while maintaining plasma compatibility. New design concepts have been proposed and numerically analyzed, advancing models for liquid PFCs in future reactors. Despite existing technical challenges, these developments suggest that LM-PFCs hold promise for future fusion applications.

### 1. Introduction

The plasma boundary behavior is the most critical element, affecting the core plasma confinement performance as well as the survival of plasma-facing components. In future fusion reactors to produce electricity in an economical way as possible, a major challenge is how to exhaust high heat flux and control impurities for quasi or true steady state operation [1,2]. The solid high-Z metal divertor designs such as those employing tungsten (W) or molybdenum (Mo) will not meet the requirements for PFCs to be used in DEMO reactors [2–4]. Off-normal events, including vertical displacement events, disruptions, and an unmitigated edge localized mode (ELM) would produce energy fluxes up to 10 MJ/m<sup>2</sup> onto divertor targets in ITER [1]. Such a high heat load would cause wall erosion and thus significantly decrease the PFCs lifetime. Furthermore, long-term irradiation with 14.1 MeV neutrons would deteriorate the structural strength and also thermal conductivity [5]. All these requirements seem to be too difficult to be achieved by the

conventional divertor designs [6].

One of the possible solutions is to use liquid metal (LM), replacing tungsten. [6–8]. LM can be a long lifetime PFCs, due to its less sensitivity to neutron damage, heat flux handling capability, superior resilience to transient events such as ELMs, and removal of impurities, and control of particles recycling. The damaged surface material can self-heal and self-replenish via liquid convection. Moreover, flowing LM not only can remove the high heat and particle fluxes, but also protect the solid substrates [9,10]. By circulating LM, the heat flux and generated impurities on the PFCs surface can be transported to an ex-situ system for regeneration [11].

Currently, low melting point metals and their alloys such as lithium (Li), tin (Sn), and Li-Sn alloys are being considered for LM PFCs. However, potential technical issues include LM compatibility with the solid substrate, flow homogeneity and stability under MHD force. Also, cautions are required for the operational safety and handling, water coolant safety related to particularly true with Li, possible core plasma

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contamination, re-use of 'frozen Li/Sn', liquid droplet formation and avoidance, LM purification, tritium extraction, high power handling, LM lifetime in order to evaluate the application of LM-PFCs in future fusion DEMO reactors.

Focusing on these issues, over the past few years, the basic physical properties, including its corrosion and wettability on substrate materials, and hydrogen isotope extraction in LM, have systematically been investigated. Various static or flowing LM walls, including free surface and capillary porous system (CPS), 3D printed structures, and trench structural designs have been developed and examined in many laboratories and various fusion devices, such as CDX-U [12,13], NSTX [14], FTU [15,16], T-11M [17,18], TJ-II [19,20], COMPASS [21], ASDEX upgrade [22], HYDRA [23], HT-7 [24,25], EAST [26,27], and many laboratories. In addition, LM divertors with various conceptions are being designed for COMPASS-U, DTT, ST40, FNSF, and EU-DEMO. These evaluations are crucial for the development of long-lasting and compatible LM-PFCs for fusion reactors. And, some of the most important results related to LM-PFCs investigations are reviewed in this paper. This review at this moment would be important for designers to realize the status of LM-PFCs development, and then to find a suitable way to design a LM-PFCs for fusion research.

## 2. Investigations on metal materials for LM-PFCs

To choose the suitable materials for LM PFCs, one is required to comprehensively consider their physical and chemical properties, including melting and evaporation rate, the viscosity and mobility, the thermal conductivity, the compatibility with solid substrate materials, and plasma confinement performance. Based on these criteria, Li, Sn, and Li-Sn alloys with low melting points have been selected and investigated in some fusion devices.

Lithium (Li) is the most attractive LM that has a relatively low melting temperature and have a relatively high concentration allowed in the core plasma due to its low atomic number ( $Z = 3$ ). It offers low radiation in the core plasma which can be as high as 15%. Liquid Li PFCs have been actively conducted in several devices, including HT-7 [24,25], EAST [28,29], T-11 M [17,18], FTU [15,30], and NSTX [31]. In all these experiments, high core plasma performance have been observed. It has also been found that Li could also be used for an improved MHD stability, ELMs mitigation, and reduction in the H-mode power threshold. However, liquid Li also has several disadvantages, including its limited operation temperature window (200-500°C), high H isotopes retention, relatively high vapor pressure, strong reactivity with water and air, and possibly with the substrate metals.

Tin (Sn) has a milder chemical reactivity and relatively low vapor pressures, and a wider operation temperature window (350–800 °C) [32]. Therefore, it allows us to increase in the surface heat load on the liquid Sn surface up to substantially higher than Li. In FTU, the Sn limiter has successfully been exposed to the plasma with resultant heat loads of up to 17.2 MW/m<sup>2</sup> [32]. In ISTTOK [33,34], it shows a very low H retention with liquid Sn operation. However, due to the relatively high atomic number ( $Z = 50$ ), plasma contamination by Sn needs to be minimized. Related to the induced radioactivity issue, its activation/decay heat drops only ~ 10% after 1 year is another problem.

Lithium tin (Li-Sn) alloys have several desirable properties including lower evaporation vapor pressures, lower H retention and better plasma compatibility. It is expected to reduce the high-Z Sn to enter the plasma and would act as a low recycling wall duo to Li. The vapor pressure of Li-Sn alloy is typically ~10<sup>3</sup> lower than pure Li, and its sputtering yields are lower than pure Sn [35]. Nevertheless, the H isotopes retention is confirmed to be very low, similar to Sn in the ISTTOK [33,34] and TJ-II [19].

## 3. Investigations of LMs compatibilities with substrate materials

It is important to investigate the compatibilities of LMs, including

corrosion and wettability with materials in designing LM-PFCs. The corrosion of the components in contact with LMs is a critical issue, affecting the safety operation of LM-PFCs over the fusion reactor lifetime. The wettability of LMs on substrates would directly influence on the LM flow stability and uniformity.

The corrosion behavior of liquid Li on different materials has been investigated at elevated temperatures for a long time of > 100 h by the EAST team. The main results are listed in Table 1. It has been found that the protection of most tested materials in LMs, calculated from weight loss, decreases if the liquid Li temperature increases.

The weight loss rate ( $V_{\text{change}}$  in g·m<sup>-2</sup>·h<sup>-1</sup>) and corrosion depth rate ( $V_{\text{depth}}$  in μm·a<sup>-1</sup>) are also an important basis for evaluating the corrosion resistance of materials [36]. According to the reference [37], there are 10 grades of corrosion protection, from 1 to 10, where the smaller the value, the stronger the corrosion resistance of the material. Hence, according to the results of Table 1, it has also been found that the protection grade of materials in liquid Li at 600 K has a descend sequences of W [38], Mo [38], TZM [38], CLF-1 [39], F82H [40,41], 316L stainless steel(SS) [40,42], 304 SS [36,41], Cu [43]. Those experimental results indicated W, Mo, TZM and some reduced activation ferric steel could be used for liquid Li loop and PFCs substrate.

Specific Li-wetting experiments have been carried out. It was found that at a low temperature, for example, at 200 °C, Li is not good for wetting on W, SS, Mo. With the increase in temperature to 350°C, the wetting contact angle has been found to decrease to less than 80 degrees [45–47]. The results show that baking, glow discharge cleaning, and evaporating a thin layer of liquid Li on the target surface can reduce the wetting temperature and improve the wettability [45–47]. Li wettability could be enhanced by percolation through the porous W architecture [45,48]. Results indicate complete wetting of liquid Li at 250 °C on the porous W surface, which is a 100 °C lower temperatures than what has been observed on blocky W surfaces. It has also been found that liquid Li has better wettability on Mo than on SS [49]. Experiments have also shown the horizontal capillary structure helps increase the wettability of Li on SS [24].

Corrosion and wetting processes of W and Mo with tin have also been studied. It has been observed that that chemical reactions between 316 SS and Sn occurs at  $T \geq 400$  °C. Mo and W alloys were resistant to Sn up to  $T \leq 1400$  °C and demonstrated no signs of corrosion effect on the surface of these materials [50]. It has been shown that the removal of the contaminated layer from the Mo material surface was the key to improving the Sn wetting. The experimental observation also indicates the capillary can be used to improve Sn wetting. For Mo and W, the minimal temperatures for obtaining high-quality wetting has been found to be, respectively, 950°C and 1050°C.

**Table 1**

Corrosion protection grade of materials after exposure to liquid Li.

materials	Temperature. (K)	Time (hours)	$V_{\text{change}}$ (g·m <sup>-2</sup> ·h <sup>-1</sup> )	$V_{\text{depth}}$ (μm·a <sup>-1</sup> )	Protection grade
304 SS [44]	600	1320	$5.2 \times 10^{-3}$	0.58	1
	640	1320	$2 \times 10^{-3}$	2.2	2
	700	1320	$4.1 \times 10^{-2}$	15.7	3
316L SS [40,42]	600	1320	$6.4 \times 10^{-4}$	0.71	1
	820	256	$2.2 \times 10^{-3}$	2.5	2
CLF-1 [39]	620	528	$5.6 \times 10^{-4}$	0.63	1
	820	528	$-1.7 \times 10^{-3}$	-1.2	1
F82H [40,41]	623	250	$1.5 \times 10^{-3}$	1.7	1
	723	250	$2.3 \times 10^{-3}$	2.6	2
	823	250	$1.4 \times 10^{-2}$	15.8	3
Mo [38]	603	1320	$6.9 \times 10^{-4}$	0.65	1
	623	1320	$4.0 \times 10^{-4}$	0.34	1
TZM [38]	623	1320	$7.8 \times 10^{-4}$	0.67	2
W [38]	603	1320	$8.1 \times 10^{-4}$	0.37	1
Cu [43]	620	15	466.1	4.59*106	10

#### 4. Design concepts of LM-PFCs

LM-PFCs may be divided into several categories by functional parameters, such as LM flowing speed, substrate structure, and coolant. Up until recently, very few investigations have been done, related to static or fast-speed LM-PFCs. A static LM surface has a short lifetime, which requires refreshment frequently, such as the liquid Li divertor in NSTX [49]. Liquid jets with a flow speed of several m/s, would encounter strong MHD instability, leading to the ejection of droplets, which limits LM jets use in future fusion reactors [51 52] 72]. LM-PFC concepts on the CPS confined structure or concepts free surface concepts with modest flow speeds have been further developed or upgraded depending on the experimental and modelling results.

##### 4.1. Development of confined surface LM-PFCs using CPS

To prevent LM splashing induced by the  $J \times B$  force, the so-called capillary porous system (CPS) utilizes the surface tension forces to suppress LM splashing into plasma. Traditional CPS employing metal meshes in 15–100  $\mu\text{m}$  are used in T-11M [53], FTU [15], CAMPASS [21]. In this kind of system, a porous construction with a capillary-pore “pumping” system could drive LM to the CPS surface and form self-sustaining and self-regulating LM PFCs. High thermal loads could be decreased by LM evaporation and non-coronal radiation, which would then lower the edge plasma temperature and protect the structure from high power loads.

Recently, the application of 3D printing technology to CPS has been proposed to increase the structural strength and thermal conductivity through flexible structure designs, which is becoming more like the new research direction. Four main 3D printed CPS structural designs, such as tree structure, vertical type deflector structure, finger-type diverter, and IO type CPS, have been proposed and evaluated, as shown in Fig. 1 [54–57]. The finite element analysis shows that the thermal stress of the tree structure is two orders of magnitude lower than that of the tungsten monoblocks employed in the ITER divertor under the identical conditions [65]. Under the thermal load of  $10 \text{ MW/m}^2$ , the thermal stress in the finger target plate structure is far lower than the yield ultimate strength [67].

At PPPL, the capillary porous systems with flow (CPSF) concept leverage recent advancements in the 3D printing technology to create a new generation of divertor components [58,59]. The internal channels of the CPSF deliver a continuous flow of liquid Li directly to the plasma-facing surface. If the surface experiences localized damage due to high heat flux events, the LM can readily replenish the affected area, ensuring continued LM divertor functionality.

##### 4.2. Development of free surface flowing LM-PFCs

Flowing LM-PFCs with a free surface seems an attractive solution, because heat fluxes and impurities could flow out from the inner vessel to the outside to form a circulated loop, which allows to purify LM outside of fusion reactor vessel. Mainly, four kinds of flowing LM-PFCs

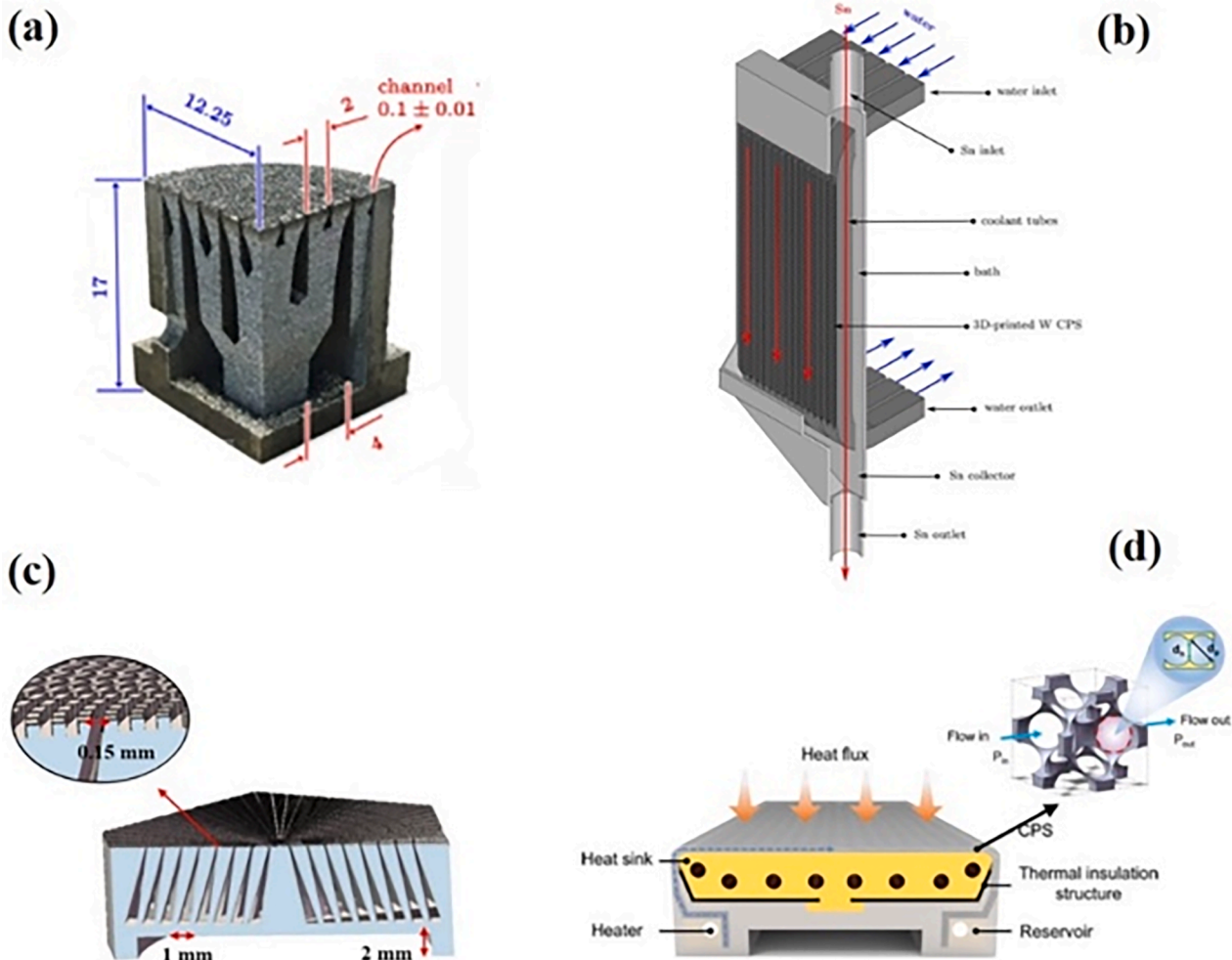


Fig. 1. 3D printing CPS structure design: (a) tree structure, (b) vertical type deflector structure, (c) finger-type structure diverter, and (d) IO type CPS, respectively [54–57].

with free surface have been proposed and two of them have been tested in EAST tokamak.

In the concept of a flowing liquid Li limiter using a thin film at the free surface, with a thickness of less than 0.1 mm is considered to increase the surface tension to suppress droplet ejection [60]. And a low flowing rate could be achieved for particle flux control. Flowing Li limiters using this kind of concept, named “FLiLi”, have successfully been tested in EAST [26,27,61–63]. In EAST, FLiLi was positioned at a vertical angle to use the gravity to help Li flow down the substrate and a specially designed an in-vessel direct current (DC) electromagnetic (EM) pump to drive Li to distributor at top from a reservoir at bottom, shown in Fig. 2. The Li flow rate could be controlled by changing DC current and toroidal magnetic field of EAST. Experiments have demonstrated a continuously recirculating loop could easily be formed by the system itself.

The Liquid-Metal Infused Trenches (LiMIT) with a free surface was proposed to use thermoelectric magnetohydrodynamic (TEMHD) force to drive Li flow along with a trenched front face [45]. Experiments at UIUC and Magnum PSI have shown that the liquid Li could withstand  $10 \text{ MW m}^{-2}$  and the liquid Li flow velocity could be accelerated to  $60 \text{ cm/s}$  [64–66]. Based on the technologies developed for FLiLi, experiments of the LiMIT style limiter using a TZM alloy plate in EAST [65] have confirmed that the liquid Li could be driven by the  $J \times B$  force. Recently, structured large-pore foams have been developed to improve the thermal performance of LiMIT-style liquid Li PFC. No indications of dry-out or impending damage have been observed during the high heat flux electron beam test with  $6.8 \text{ M}\cdot\text{m}^{-2}$  [66].

The Actively Convected LM Divertor (ACLMD) [2] is another concept of flowing LM PFCs with the free surface. Heat convection of LM due to rotating motion driven by the  $J \times B$  force. Recently, based on the ACLMD concept, a magnetically-guided LM divertor and first wall have been proposed [67,68]. It is thought those magnetically-guided LM PFCs would serve as an automatic disruption mitigation system. Recent experiments using plasma bombardment and IR spot-heating have shown that  $J \times B$ -forced convection would significantly enhance the transport of particles and heat as well in LMs [47]. A duct for reducing grad-B MHD drag has also been proposed by expanding the duct along B and shrinking the duct in a perpendicular direction to make electromotive force approximately constant along the duct [69].

The “divertorlet” concept utilizes an array of narrow, closely spaced channels with alternating vertical velocities [70,71]. Toroidally oriented slats with alternating polarity are designed to drive electrical currents for the achievement of high flow rates of the LM. Experimental “divertorlet” prototypes have shown good agreement with analytical models and MHD simulations.

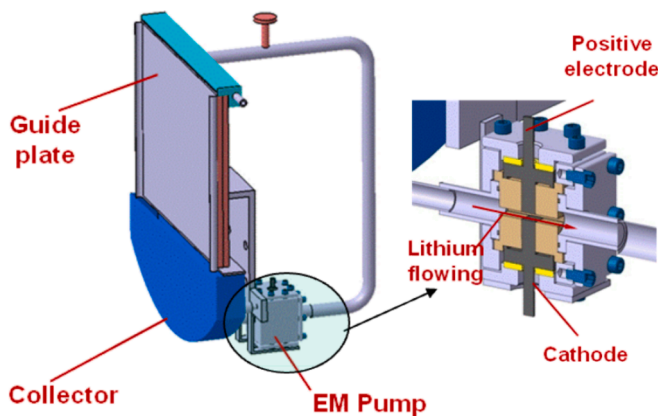


Fig. 2. Structure of flowing liquid Li limiter for EAST.

#### 4.3. LM divertor concepts based on radiation/detachment

The Li vapor box concept presents a conceptually different approach for handling divertor heat flux. This design envisions a chamber positioned near the divertor region filled with high-density Li vapor [72,73]. The intense heat and momentum from the plasma are transferred to the Li vapor through volumetric processes, essentially spreading the heat load throughout the vapor volume. Multi-stage differential pumping systems are employed to isolate the Li vapor from the main plasma, reducing contamination and maintaining plasma purity.

The radiative liquid Li divertor concepts (RLLD) focuses on the use of the strong radiative properties of non-coronal radiation to manage divertor heat flux [74,75]. During operation, a thin layer of liquid Li coating is put down on the plasma-facing surface of the divertor. The intense divertor heat flux from the plasma induces the evaporation of the Li, creating a cloud of Li vapor near the divertor plate. Due to its low ionization energy, Li will readily be ionized in the plasma environment. These ionized Li ions are highly efficient radiators, emitting non-coronal electromagnetic radiation and hence significantly reducing the heat flux directly on the divertor surface. Recently, active Li injection in such a system (ARLLD) has been proposed to protect the divertor surface material from transient heat loads with an active Li injection. By injection Li into the path of transient heat loads, it could prevent surface temperature rise through a rapid radiative cooling, and even with a partial success, it could prevent damages to divertor PFCs.

### 5. Main experimental results on LM-PFCs

#### 5.1. Investigations of the flowing stability of LM-PFCs

The stability of LM is important for the performance of LM-PFCs. The flow velocity and wettability of LMs are two important factors affecting the stability. There has not been much research on the flow properties through a metal mesh structure because in such structure the LM flow is quite slow. However, in a metal mesh CPS structure the wetting and intermolecular forces on the porous substrate are effective in stabilizing the LMs against electromagnetic and thermal forces and avoiding droplet ejection, as observed in T-11 M [76], FTU [77], and other devices.

From the observations in HT-7 and EAST, a stable liquid Li limiter without droplet ejection was observed to be beneficial for the improvement of plasma performance [25–27,61,63,78]. The Li limiter with a CPS-confined defined surface or a thin-flowing film surface could reduce liquid Li droplet ejection into the edge plasma, possibly preventing plasma disruptions. It was found that the effect of the liquid Li on plasma performance was generally like that of Li coatings, i.e. reduced impurity radiation, reduced wall recycling, and improved plasma confinement. In addition, the mitigation of plasma-materials interactions via passive Li injection from the surface of a flowing liquid lithium limiter was observed in EAST as shown in Fig. 3 [63].

A slow flowing rate (1–60 cm/s) of LMs in a narrow trench structure could be used to avoid the MHD instability, as confirmed by LiMIT at UIUC [64], Magnum PSI [46] and FLiLi in EAST [79]. A thin LM film and a large-wetted area of the substrate were used to increase surface tension which suppress droplet ejection. However, achieving uniformly flowing lithium on a large surface and reducing substrate erosion due to the drying out of the Li coating are very important challenges for the stable operation of FLiLi and LiMIT. At the beginning test in HT-7 and EAST of both FLiLi and LiMIT, Li flow is not stable due to nonuniform wetting, which leads to Li dry-out and substrate damage. With new technologies, i.e. a horizontal capillary structure for better wetting, Hot Isostatic Press (HIP) technology to improve the thermal contact, using a TZM substrate instead of SS, building a more homogeneous distributor, and a large EM pump were all used in the upgraded limiters. This resulted in a uniform Li flow on the TZM substrate with a surface coverage of about 87% (the ratio of Li covered area to the entire surface) and no damage on the

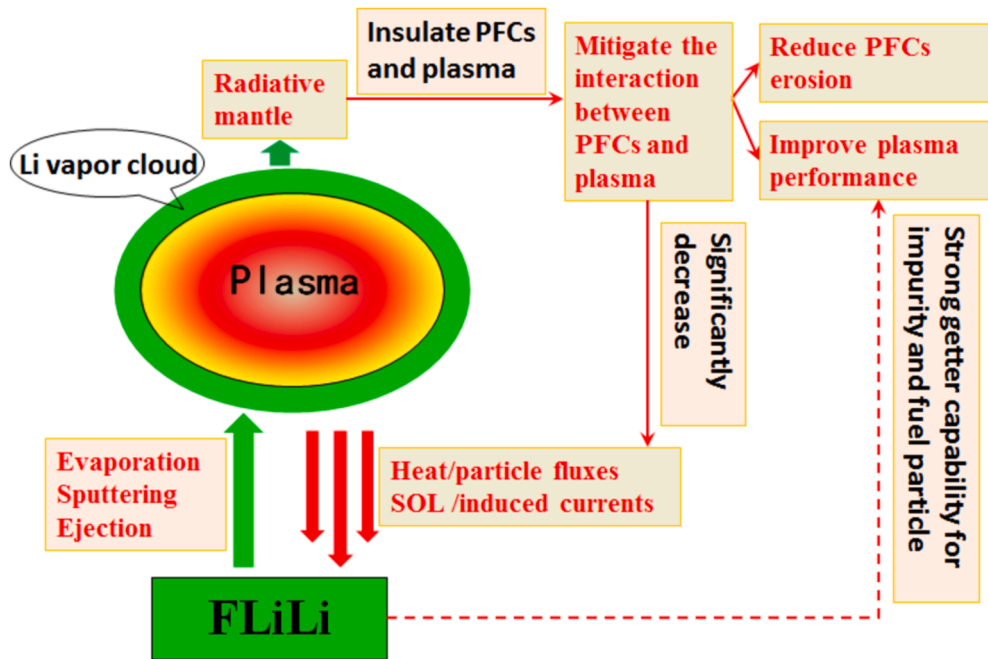


Fig. 3. Basic FLiLi and plasma interaction mode [63].

substrate was found, as shown in Fig. 4 [80].

A great deal of effort to study the MHD instabilities has also been done in a number of laboratories. For example, the experimental results at the University of Chinese Academy of Sciences have shown that the magnetic field strongly inhibits the free surface wave along the spread direction, making the surface waves propagate along the flow direction, and the thickness of the LM film increases with the increase of magnetic field intensity [81,82]. When the magnetic field is strong enough, the liquid Li becomes trapped, and eventually, no LM film flowed due to the MHD effect [83]. It has also been found that the film thickness increases with an increasing flow rate, whereas it decreases with an increasing inclination angle at a constant value of the magnetic field [84,85]. It was also observed that the Li splashes from the surface of the liquid Li flow surface with a large flow rate, leading to the ejection of droplets [86].

### 5.2. Investigations on heat removal using LM-PFCs

Under a plasma condition, high heat fluxes can be handled by LM-PFCs not only via heat conduction as solid PFCs, but also via evaporation, convection and radiation. A high-density vapor formed near the surface of LM would dissipate the heat flux and decrease the incoming heat flux due to boundary plasma cooling by non-coronal radiation.

Concerning heat conduction, W is regarded as an excellent plasma-

facing material because of its outstanding heat conductivity of 174 W/mK at room temperature. In a liquid phase, the heat conductivity of Li and Sn are 47 W/mK and 27 W/mK, respectively, at a temperature of 700 K. Therefore, it would appear that liquid Li or Sn would remove a lower heat load than using solid W. However, an encouraging result was found that during FLiLi operation in EAST, the plasma wetted all the surfaces that had Li flow, which is much larger than the plasma-wetted area on a solid PFC, which is only a narrow line at the middle of the solid substrate [26]. This indicates that LM would reduce peak heat flux from the plasma and the heat load would be uniformly removed by heat sink via heat conduction.

As to evaporation, atoms would escape from the liquid state of metals to form a vapor cloud above the LM-PFCs. Meanwhile, the incoming heat flux would be dissipated by interacting with the vapor, known as the vapor shielding effect. Subsequently, the vapor cloud phenomenon is considered to be a favorable heat shielding effect, in addition to the reduction of recycling/impurities and improvement of plasma stored energy [87]. Further investigation in EAST has shown that approximately 42 % of the parallel heat flux is dissipated via Li vapor interactions and their associated radiation [88]. In FTU, the liquid Li limiter with CPS structure can withstand thermal loads of up to 2 MW/m<sup>2</sup>, due to the Li vapor shielding effect [89]. In the liquid targets experiments using CPS structure in Magnum-PSI, it has been found that a

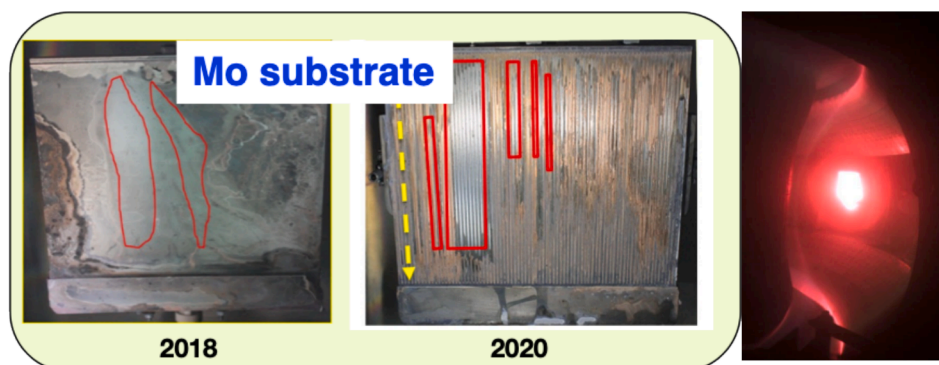


Fig. 4. A uniform Li flow on the TZM substrate with a surface coverage of 87% and no damage on the substrate using FLiLi [80].

surface temperature limit of the Li-based target was reached if the deposited power flux was at least  $\sim 10 \text{ MW/m}^2$ . This illustrates the benefits of vapor shielding effect, which is also expected to be extremely robust against the power deposited during short transient events [90]. For the liquid Sn target, there is a  $\sim 30\%$  reduction in conducted power and lower electron temperature in front of the liquid surface compared to the solid Mo reference. The plasma exhaust was remarkably reduced by the enhancement of the vapor effect and induced a dynamic equilibrium between the plasma and liquid target ruled by re-combinatory processes observed in Pilot-PSI [91]. High incident heat flux mitigation in steady state and ELM-like pulse were respectively obtained in SCU-P SI [92] and Magnum-PSI [93].

A flowing LM with a free surface has shown to be an efficient heat removal capability via heat convection [67]. Using a linearly magnetized steady-state plasma facility and an IR spot-heating device, it was confirmed that  $J \times B$ -forced convection significantly enhanced the transport of heat in LMs [47]. High-speed LM flow would increase heat removal via heat convection. For example, in the International Fusion Materials Irradiation Facility (IFMIF), it can be inferred that flowing liquid Li at a high velocity of 10–20 m/s can carry away heat fluxes of the order of  $1 \text{ GW m}^{-2}$  [94].

The radiative loss of LM could greatly alleviate its evaporation through the ionization and non-coronal radiation of lithium and significantly reduce the required LM supply under heat flux irradiation. An RLLD concept has been proposed at PPPL to demonstrate the capacity of heat load handling [74]. Their theoretical results showed heat fluxes could be notably reduced by the radiation. Experiments also confirmed the radiation would induce heat flux reduction to the LM targets in EAST [95] and Magnum-PSI [96].

Recently, LM components using 3D printing CPS have been widely investigated. Magnum-PSI experiments have shown that no damage to the target plate was observed under a thermal flux of  $16 \text{ MW/m}^2$  [54,96,97,98]. In the Pilot-PSI experiment with a sustained heating for 20 s under a plasma heat flux of  $22 \text{ MW/m}^2$ , a reduction of the heat flux on the CPS LM target was found to be approximately 30%, compared to traditional solid Mo targets [99]. In SCU-PSI, experiments have shown that the surface temperature of the pre-filled Li CPS target is lower than that of the CPS target without Li pre-filling by approximately  $140^\circ\text{C}$  [100]. Sn-filled irradiation experiments on different structures have also been carried out under a high transient heat load ( $58 \pm 14 \text{ MW/m}^2$ ) in OLMAT facility and have shown that the 3D-printed tungsten target has very good heat load handling capacity [101,102].

Experiments investigating the interaction between a tin CPS and plasma under simulated disruption and ELM loads have also been conducted. Using a quasi-stationary plasma accelerator (QSPA), the absorbed heat flux on the target surface was about  $1.1 \text{ MJ/m}^2$  for an incident plasma energy density of  $2.4 \text{ MJ/m}^2$ . This means LM PFCs have superior resilience to a transient heat flux [93]. Magnum-PSI experiments have shown that ELM-like plasma pulses with 0.3 to  $1 \text{ GW/m}^2$  could impact a Li 3D printed CPS target without damage [103]. In those experiments, the effect of vapor shielding of LM PFCs was thought to be important to reduce the extremely high transient heat flux.

### 5.3. Investigation on fuel recycling/retention, impurity suppression using LM PFCs

It is well known that Li can capture fuel particles, including H, D, T, and other impurities, including O, C, and N due to its very strong chemical properties. It has widely been observed the important consequence of lithiation and liquid Li experiments is to suppress fuel recycling and impurities. For example, the recycling coefficient R was dropped from 1 to 0.3 in T-11 M by the application of Li CPS limiter [53] and  $\sim 90\%$  of the total radiation losses were distributed in a relatively thin (5 cm) boundary layer, which resulted in heat load mitigation on the first wall due to Li radiation [18]. Experiments in EAST have shown that the fuel particle recycling was reduced by a factor of approximately

50% and the value of  $Z_{\text{eff}}$  was decreased from 2.3 to 1.6 with low radiation of both high-Z and low-Z impurities using FLiLi and LiMIT limiter [27]. Recently, besides H pumping by liquid Li, a He pumping effect during the liquid Li experiment was observed, which seems to occur when  $\text{Li}^+$  ions were present in HIDRA device [104].

The effect of liquid Sn, LiSn, and GaInSn on the fuel retention and the plasma contamination have been investigated recently. It was observed the fuel retention was very low and impurity radiation was kept at a very low level when liquid Sn and Li-Sn limiters were used in TJ-II [19,20]. During the LiSn experiment in COMPASS, it was observed there was no clear contamination of the core and SOL plasmas due to Sn [21]. In liquid tin limiter experiments in FTU, it has found a Sn concentration with a electron density of about  $5 \times 10^{-4}$ , deduced from the variation of the  $Z_{\text{eff}}$  value [105]. However, in Asdex-Upgrade (AUG), the problem of the bubble formation due to hydrogen super-saturation occurred. This has been observed in several experiments for the case of Sn and SnLi [106]. Employing liquid GaInSn, laboratory experimental results have indicated that both hydrogen and helium recycling could be noticeably reduced when  $J \times B$ -forced convection occurs [107].

### 5.4. Effect of LM PFCs on plasma performances

In tokamaks, liquid Li PFCs application would effectively decrease H recycling, impurities and MARFE edge instabilities. These effects would profoundly modify the plasma edge conditions to reduce the particle outward transport, resulting in a remarkably peaked density profile [108]. And plasma density was close to the Greenwald density limit, even though no central particle fueling tool was applied [109].

Recently, a flat electron temperature profile with a hot edge ( $>200 \text{ eV}$ ) has been observed in LTX, due to Li pumping reducing wall recycling and edge neutral density, avoiding the low edge temperature boundary condition imposed by the influx of cold neutrals from the wall [110]. Meanwhile, the resulting flat temperature profile should decrease turbulences driven by the temperature gradients in the plasma. Reduced turbulence which is attributed to the anomalous transport would lead to higher particle and energy confinement [111].

In the experiments of FLiLi, it has been found liquid Li would decrease L-H transition threshold and gradual mitigation of edge local modes (ELMs) [26]. By applying the FLiLi, ELM-free phases have been observed with increasing the plasma confinement time. FLiLi is also effective on the mitigation of type-I ELMs in low  $q_{95}$  H-mode plasmas.

Recently, experiments have shown that liquid Sn or Li-Sn have different results on the plasma confinement. In FTU, it has been found if the liquid Sn surface temperature is below the evaporation onset, the plasma performances would be unaffected [112]. In COMPASS, by applying Li-Sn PFCs, no degradation of the energy confinement time was observed [21]. Test of a liquid Sn divertor target using 3D printing CPS during ASDEX-upgrade L-mode and H-mode operation has shown that it has no adverse influence on plasmas in L-mode, but has unacceptable radiation by Sn in the plasma core in H-mode [113]. It was found that droplet formation and subsequent ejection into plasma would cause unacceptable radiation and that it remains one of the major issues for developing liquid Sn PFCs.

### 5.5. Investigation for co-deposited Li-D films and D absorption by liquid Li

Li emitted from liquid Li PFCs would co-deposit with deuterium plasma to form Li-D films. Experiments showed that the Li-D films during water vapor exposure would cause transformation into LiOH and release deuterium [114]. Analysis of the T-10 ring limiter has shown all surfaces were completely covered by deposits and droplets of Li, SS, and Mo [115]. Other analyses have shown that the D concentration is dependent on the deposition temperature, with a maximum of 30% at 350–500 K. In addition, Li deposition rate on the substrate would decrease rapidly at deposition temperatures above 570 K [116]. It also has been found the D content in co-deposited Li-D films could be fully

replaced by the hydrogen isotope via isotope substitution at H<sub>2</sub> environment with a pressure of 10<sup>5</sup> Pa and temperature of 400 K for 1 day [117]. Those experiments have indicated that under a high-temperature (above 570 K) environment, water vapor and high-pressure H<sub>2</sub> isotope exchange, are effective in the releasing of D from Li-D films and give a good reference to release tritium in Li-T films in the case of liquid Li PFCs in future magnetic fusion devices.

D absorption by liquid Li in high temperature has also been investigated [118,119]. It has been found that the D release mostly happens around 485 °C and many release peaks were observed at a high temperature between 600–650 °C, as shown in Fig. 5. The presence of a small number of impurities such as N<sub>2</sub> and H<sub>2</sub>O can react with hydrogen isotopes in liquid Li to form new compounds, leading to an increase in the desorption temperature of hydrogen isotopes. This effect was related to the proportion of impurities to hydrogen isotopes and was more sensitive to H<sub>2</sub>O than N<sub>2</sub>. It has also been demonstrated that the ratio of contaminants to D<sub>2</sub> plays a vital role in the desorption performance of D<sub>2</sub>, which reveals that a high ratio might restrain the desorption D<sub>2</sub>-H<sub>2</sub>O therefore is much more important in comparison to that of N<sub>2</sub> and O<sub>2</sub> for the D<sub>2</sub> release temperature.

## 6. Investigation on circulated LM flow loop for future fusion reactors

A circulated flow loop is a basic requirement for LM-PFCs application for future magnetic fusion reactor. The loop should be robust for safety in long operation. The loops not only need a stable flow in the inner vessel of the magnetic fusion reactor, but also need a good purification system to reuse the LM and plasma fuel. In the loop, by the continuous and recyclable Li flowing cycle, D/T and other impurities would be captured in the LM divertor, and they would be taken out along the LM pipes and then be released outside the devices by thermal desorption and other filter systems.

Present investigations on the development of the circulated LM flow loop mostly focus on liquid Li loop. The circulating liquid Li on the first wall continuously remove plasma impurities including tritium from the vacuum chamber while carrying a significant amount of heat flux from the plasma. A basic idea of the liquid Li loop, similar to a tritium fuel cycle system, has been proposed [120]. By operating liquid Li at lower temperatures ≤ 450 °C than the first wall, the liquid Li-covered divertor chamber wall surfaces can serve as an effective particle pump, as impurities generally migrate toward lower temperature LL divertor surfaces. Running the Li loop continuously could carry the dust particles and impurities generated in the vacuum vessel outside, where the dust/impurities would be removed by dust filters and trap systems.

To reliably operate a circulated liquid Li flow loop on a long time scale to year level, high purity and reuse of Li in future magnetic fusion

reactors are the most important issues to be investigated [121]. The hydrogen isotopes dissolved and retained in Li are relatively high, and they can be extracted from liquid Li through appropriate techniques for processing and extraction, thus reusing it as a new fuel. In principle, liquid Li purification could be carried out by application of various methods, such as chemical [122], electrochemical [123], physical [124], distillation [125], vacuum degassing [126], crystallization [127].

The commonly used method for the solid impurities removal in a circulated LM loop is the “cold trap method [125]”, which involves lowering the temperature of the liquid Li to 200 °C and then filtering out the oversaturated solid compounds. Since the saturation solubility of oxygen and carbon in liquid Li at 200 °C is only 7 ppm and 2 ppm, respectively, it is believed that the cold trap method can effectively control these two types of impurities [128]. However, nitrogen has a much higher saturation solubility in liquid Li, reaching 1460 ppm, necessitating additional means to remove nitrogen dissolved in liquid Li after the cold trap method. However, there is currently no mature technology available for this purpose. Currently, one of the methods considered to have promising development prospects is using iron–titanium alloys to adsorb nitrogen from liquid Li [129].

A possible solution for hydrogen isotope extraction is to decrease the temperature of liquid Li from 400 °C to 200 °C, so that the hydrogen isotopes can be saturated and precipitated as much as possible in the form of Li hydrides. Since the densities of Li hydrides are higher than that of Li, centrifugation can be also used to separate the solidified phase, which will be heated to decomposition temperature to extract hydrogen isotopes [118]. In future magnetic fusion reactors, sufficient hydrogen gas needs to be added to high-temperature liquid Li to achieve a high hydrogen atom concentration, then dropped liquid Li temperature to precipitate tritium from the liquid Li [130]. Another extraction method is to use solid metal adsorbent to trap hydrogen isotopes from liquid Li with very low content [131–134]. The most extensively studied adsorbent is yttrium (Y). However, it was found that the trap efficiency would decrease very quickly after adsorption saturation, and contaminations like O and N in Li were proved to have a negative effect on the hydrogen trapping rate when Y was used as an adsorbent [135].

A Li purification system, to remove and extract hydrogen from molten Li and to collect the evaporated Li, has been successfully demonstrated in UIUC, as shown in Fig. 6 [125]. In this system using the cold trap method, a tower system was utilized to remove impurities such as nitrogen, oxygen, carbon, and hydrogen from liquid Li, reducing their concentrations below their saturation solubility in liquid Li at 200 °C. Based on the saturation solubility of this compound, the cold trap method or centrifugal separation could be utilized to separate the Li-N, Li-O compound from the liquid Li. In such kind a system, experiments have shown that H extraction from LiH has a peak of about  $5.1 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$ , and the peak after H<sub>2</sub> exposure is about  $8 \times 10^{20} \text{ m}^{-2} \text{ s}^{-1}$ .

## 7. Modelling development for LM-PFCs

Modelling on the interaction between LM and plasma, MHD instability, and droplet ejection have been widely developed, not only for the understanding of experimental results but also for the prediction of the possibility of LM application on future fusion devices.

The SOLPS-ITER code has been used to simulate Li transport for designing the Li vapor box divertor on NSTX-U [73,136,137]. Further, the vapor shielding effects on LM erosion and transport have been studied using the SOLPS code [138,139 140–142]. Studies on the upstream density and divertor flux associated with the liquid Li divertor design for Fusion Nuclear Science Facility have been also carried out by the SOLPS-ITER code [143,144]. The 3D effects of the toroidally localized liquid Li limiter [145] and Li injection [146–148] on EAST have been studied by EMC3-EIRENE code to elucidate the relation between the Li emission belts and 3D magnetic configuration. WBC/UEDGE modellings have been studied for simulation on the erosion and redeposition characteristics of the Li coating to assess the divertor lifetime on

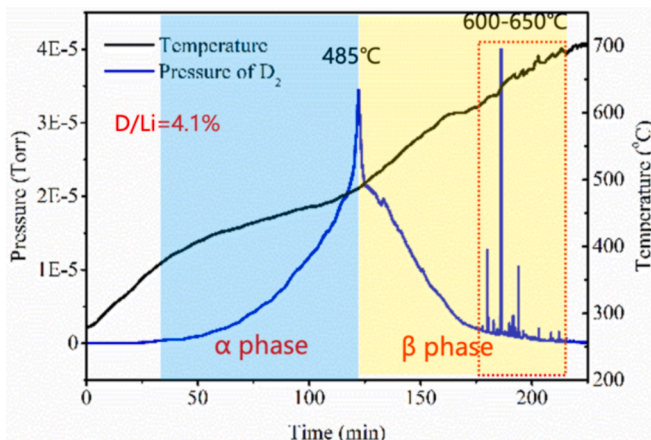


Fig. 5. Typical TDS spectrum of D release from liquid Li [118,119].

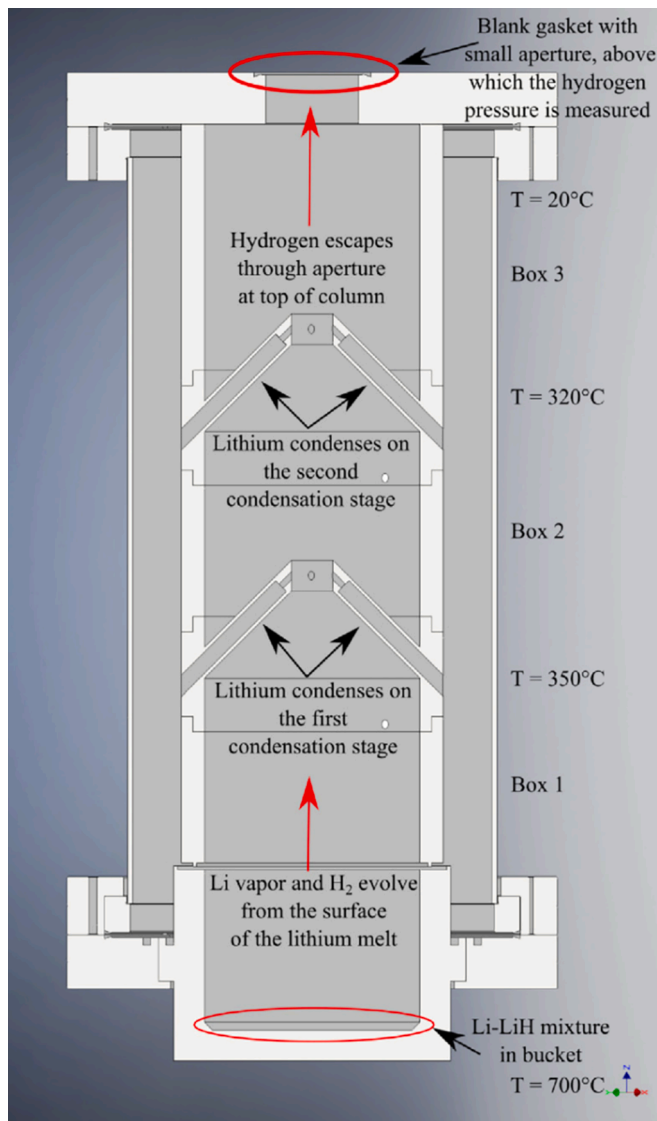


Fig. 6. Design of Li purification system to remove and extract hydrogen from molten Li and to collect the evaporated Li [125].

NSTX tokamak [149]. Moreover, the detailed analysis of the impacts of the Larmor gyration, sheath acceleration, self-sputtering and reflection on Li transport and distribution has been investigated by ITCD/EMC3-EIRENE modelings [150].

A developing HeatLMD code is a time-evolving code for LM erosion modeling, including 3D heat conduction, LM erosion, prompt redeposition, and vapor cooling. It is also designed to take direct inputs from diagnostics and is used for transient events and short pulses, which have been applied for COMPASS [151], and AUG experimental predictions [152–153]. Modeling towards integrated target-SOL-core plasma simulations for liquid divertor has been proposed based on SOLPS-ITER and includes its coupling with a target erosion model written in FreeFem++ and a core plasma model (ASTRA/STRAHL) [154]. Coupling the SOLPS-ITER code with an LM MHD/heat transfer code to model a Li open-surface divertor design has also been carried out [155].

A Lagrange equation describing a viscous liquid surface deformation in a magnetized plasma could be derived using Rayleigh's method, and it has been found the combined effect of the sheath electric field and the magnetic field would play a crucial role in driving instability [156]. A new consistent and conservative scheme has been developed to accelerate MHD computations on complex flows in flowing LM PFCs [157,158]. It could integrate surface tension, electromagnetic fields,

heat, and mass transfer effects in MHD two-phase flow [159]. An MHD-Multiphysics numerical simulation platform has been developed to accurately and efficiently deal with liquid divertor MHD film flows over large areas with a strong magnetic field [160]. Simulations by OpenFOAM and ANSYS CFX Codes have been used to investigate the MHD drag effect to predict MHD drag on the flowing Li and optimize channel design to achieve a more uniform flow profile with the desired flow rate [85]. Three reduced-order mathematical models to access MHD flow development effects, velocity distribution, and surface waves have been reported [161]. To calculate the target temperature distribution for the case of evaporation from the divertor, analytical and numerical models for LM PFCs have been developed [162].

## 8. Summary and discussion

Over the past decade, significant advancements have been achieved in the investigation of LM PFCs, representing substantial progress and promising results.

The focus of materials for LM-PFCs has expanded beyond Li to include Sn and Li-Sn alloys. Li is continued to be confirmed as a promising material for the improvement of plasma performance. Sn and Li-Sn could be operated in a larger temperature window compared to Li. Promising results from experiments are that plasma performances have not been significantly degraded by Sn and Li-Sn PFCs applications in TJ-II and COMPASS. However, challenges such as bubble formation from hydrogen supersaturation and excessive radiation from droplet formation, as observed in the ASDEX-Upgrade, may limit their utilization for future reactors.

A series of corrosion experiments have shown that many important metals considered for magnetic fusion devices, such as W, Mo, TZM, and some low-activity ferric steels, could be used for liquid Li loops and PFCs substates. These experiments have also identified that wettability can be enhanced through methods such as increased temperatures, surface cleaning, or prior coating, with Mo and W alloys showing corrosion resistance to Sn up to 1400 °C.

Innovative LM PFC based on mesh CPS structure, including Sn and Li-Sn limiters, has been optimized and successfully tested in various tokamaks. Newly proposed CPS LM PFCs using 3D printed structures show high heat handling capability. Free surface LM limiters with modest flow, such as FLiLi and LiMIT have been upgraded and tested in EAST tokamaks, and good flowing uniformity and stability could be achieved with the help of new technologies. Newly proposed structured large-pore foams for LiMIT-style liquid Li PFC could improve flow stability to avoid dry-out and droplet ejection. Effective heat convection due to rotation pushed by  $J \times B$  force has been proved in experiments. Other four concept designs for LM divertor components: divertorlets, CPSF, Li vapor boxes, and RLLD/ARLLD, have been investigated by continual tests in laboratory and/or advanced simulations.

More information on the flowing stability of LM PFCs have been obtained recently and suggested that confined surface CPS structure or modest flow free surface LM PFCs are good way to reduce MHD instability and to avoid droplets ejection. Excellent heat load handling of LM PFCs have been confirmed in various aspects, such as heat conduction, evaporation, convection, and radiation. The vapor shielding to dissipate heat flux has been widely investigated and confirmed to be effectively in tokamaks and liner plasma devices.

Present experiments in tokamaks showed that liquid Li PFCs can effectively reduce recycling and impurities, suppress ELMs to improve plasma performance. It has been shown that most D can be release from Li-D film by heating or isotope exchange.

Investigation on circulating LM flow loops for future fusion reactor have been initiated. Many LM loops have been constructed in laboratories with key components development. A experimental Li purification system has been tested and some promising results related to hydrogen isotope extraction have been obtained.

Modelling codes on the LM-PFCs have been widely developed,

including not only on the model of SOL plasma, LM vapor/neutrals, core plasma self-consistency, but also on the interaction between LM and plasma, MHD instability, droplet ejection, which is being used for the design of LM PFCs for future devices.

Despite these advancements, further works are still needed to clarify the performance of various LM PFCs under fusion reactor conditions. Key issues, such as flowing stability, re-use of 'frozen Li/Sn', liquid droplet avoidance, tritium extraction, power handling and component lifetime, should be further investigated. The designs of the LM divertor should be optimized and to be tested in tokamak environments with a comparable long time for future reactors. LM purification and hydrogen isotope extraction need more experiments to find good solutions for a circulating LM loop. Neutron irradiation on LM should be investigated. Other challenges may include coupling among evaporation, power handling and plasma dilutions or contamination, tritium retention in LM deposits and its removal, and LM safety. Those will be accomplished by LM-PFCs experiments in present fusion devices, along with many dedicated LM loop development and integrated laboratory construction. Most important is that in the near future, large-scale and full-size LM divertors will be available in tokamaks, such as COMPASS-U [152], NSTX-U [161], and DTT [163]. EU DEMO has started modeling on the application of liquid Li divertor [164]. FNSF-USA considers using one type of liquid Li divertors which will be tested in NSTX-U [161].

In conclusion, while a considerable progress has been made in understanding and developing LM PFCs for future fusion reactors, ongoing research and optimization are essential to address the remaining technical challenges to fully harness the potential of these innovative systems.

#### CRediT authorship contribution statement

**J.S. Hu:** . **G.Z. Zuo:** Project administration, Methodology, Investigation. **L. Li:** Software. **D.H. Zhang:** Data curation. **H.L. Bi:** Formal analysis, Data curation. **Z.B. Ye:** Formal analysis, Data curation. **J.H. Pan:** Formal analysis, Data curation. **S.Y. Dai:** Formal analysis, Data curation. **X.C. Meng:** Formal analysis, Data curation. **Z. Sun:** Formal analysis, Data curation. **M. Ono:** Formal analysis, Data curation. **Y. Hirooka:** Formal analysis, Data curation. **D.N. Ruzic:** Formal analysis, Data curation.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Data availability

Data will be made available on request.

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