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Investigations on interactions between the flowing liquid lithium limiter and plasmas

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ABSTRACT

Two different designs of flowing liquid lithium limiter were first tested for power exhaust and particle removal in HT-7 in 2012 autumn campaign. During the experiments, the reliability and compatibility of the limiters within Tokamak were experimentally demonstrated, and some positive results were achieved. It was found that the flowing liquid lithium limiter was effective for suppressing H concentration and led to a low ratio of H/(H + D). O impurity was slightly decreased by using limiters as well as when using a Li coating. A significant increase of the wall retention ratio was also observed which resulted from the outstanding D particles pumping ability of flowing liquid lithium limiters. The strong interaction between plasma and lithium surface could cause lithium ejection into plasma and lead to disruptions. The stable plasmas produced by uniform Li flow were in favor of lithium control. While the limiters were applied with a uniform Li flow, the normal plasma was easy to be obtained, and the energy confinement time increased from ~0.025 s to 0.04 s. Furthermore, it was encouraging to note that the application of flowing liquid lithium limiters could further improve the confinement of plasma by ~10% on the basis of Li coating. These remarkable results will help for the following design of flowing liquid lithium limiter in EAST to improve the plasma operation.

1. Introduction

With exceptional particle pumping properties and low Z, application of Li in fusion reactors has been tested in Tokomaks and other magnetic confinement devices for many years [1–4]. Li coating has been regarded as an effective method to reduce impurities and edge particle recycling in TFTR, NSTX, TJ-II and EAST [5–8]. The main results from Li coating are summarized as follows: first, the outstanding ability of pumping particles of Li results in very low impurity and recycling level in plasma; second, most of Li atoms are ionized and radiate at the plasma edge due to the low Z and low ionization energy to avoid the contamination on core plasma; third, ICRF heating efficiency improves according to the minority ions heating mode due to the low H/(H + D) by Li coating; fourth, Li coating can suppress MHD and ELMs in plasma; finally, it also can reduce the H-mode power threshold and improve the plasma confinement. However, a future fusion device still faces several issues related to materials, such as stringent power exhaust capabilities and material lifetime. Applying liquid Li as plasma facing components (PFC) is a potential solution for future fusion device and has been tested in many Tokamak devices. Using a toroidal liquid Li pool limiter on CDX-U, plasma discharges with a lower loop voltage, wall recycling and impurities level were achieved [9]. In T-11M, a lithium limiter with capillary-pore system (CPS) has been demonstrated for its ability in confining the liquid Li in the CPS during disruption and protecting PFC from high power bombarding during quasi steady state and disruptions regimes due to Li non-coronal radiation, which resulted in clean (Z_{eff} = 1) deuterium plasma discharges and the radiation losses concentrating in a relatively thin boundary layer [10]. In FTU, a liquid Li limiter system composed by three similar units could withstand 5 MW/m^2 heat load, Greenwald limit and higher electron temperature were obtained [11].

Liquid Li limiters have been tested on HT-7 since 2009 [12–14]. Using a movable liquid Li limiter with free surface, increased plasma confinement, suppressed impurities and reduced recycling during ohmic plasma discharges were observed as well as Li coating. Confined surface and suppressed Li splashing during the disruption regimes was achieved by application of a Li limiter with CPS. Furthermore, a re-filling liquid Li limiter experiments on HT-7 confirmed the possibility of driving the Li flow by Ar pressure. In

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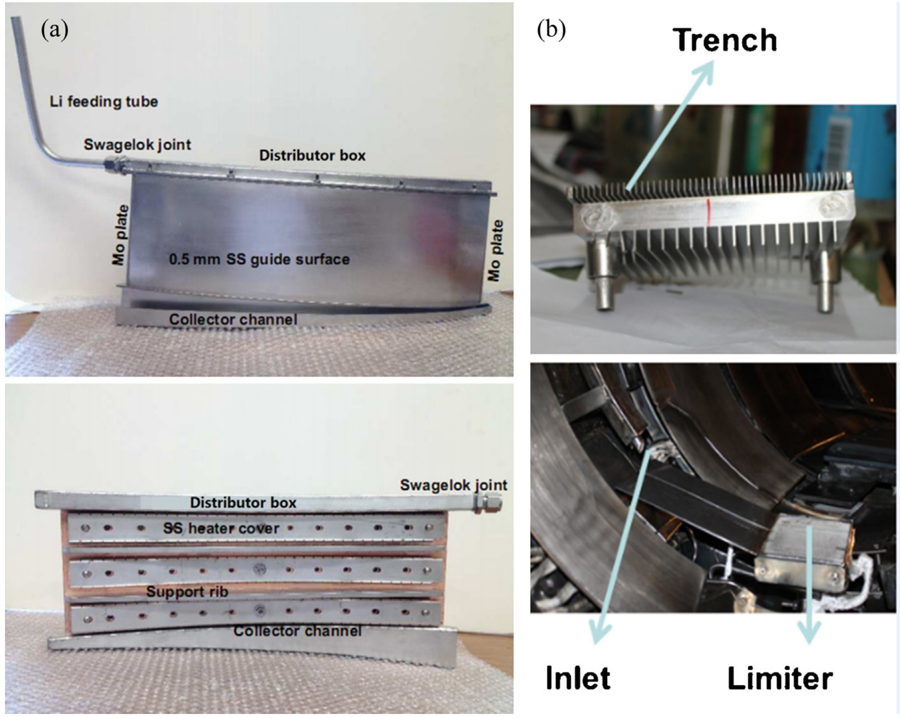

Fig. 1. Structures of the FLiLi limiter (a) and LIMIT limiter (b).

this paper, we investigate two different types of limiters which are termed as the FLiLi limiter and the LIMIT limiter respectively in order to study the compatibility with plasma and interaction between the flowing liquid Li limiter and plasma.

2. HT-7 experiment

HT-7 was a middle size Tokamak with major radius $R = 1.22$ m and minor radius $a = 0.27$ m. A toroidal limiter located at the bottom of the vacuum chamber and a belt limiter installed on the high-field side had a total surface area of $1.28\ m^2$. Both of them were Mo materials in the 2012 campaign.

During 2012 HT-7 campaign, more than 700 ohmic plasma discharges were demonstrated with a discharge flattop in the range of 0.5–2 s. Two different designs of flowing liquid Li limiters, FLiLi limiter and LIMIT limiter, were tested in this campaign (see Fig. 1) [15]. The operation temperatures of both of the two limiters were above 300 °C. FLiLi limiters using a thin flowing film concept were installed on the mid-plane of the high-field side. This kind of FLiLi limiters had a special distributor with multiple channels to guide the liquid lithium from the distributor to the SS guide plate surface according to the magnetohydrodynamic (MHD) effect of the pressure drop when the liquid Li was moving across the channels in a magnetic field. The pressure drop along the channels larger than that inside the distributor box guaranteed a uniform supply from the channels to the guide surface. The minimal magnetic Reynolds and Hartmann numbers due to the designed velocity of flow less than 1 cm/s and 0.1 mm flow thickness resulted in a negligible interaction of the free surface flow with the magnetic field. For HT-7, the typical particle flux to FLiLi limiter surface is 3.3×10^{20}/s approximately. Assuming Li absorbing capacity as 10% (atomic), removing the particle flux from limiter would require replenishment of 3.3×10^{21}/s atoms which is satisfied with the designed velocity. The heat flux from the plasma can be effectively removed using the heat sink with an actively cooling system. Furthermore, a self-sacrificial liquid lithium surface can protect PFC from the disruptions and ELMs due to its rapid evaporation. Such kind of FLiLi limiter was experimentally demonstrated in HT-7, in which a uniform liquid Li film slowly crept along the guide surface driven by Ar pressure.

The other flowing liquid Li limiter was using the thermoelectric magnetohydrodynamic (TEMHD) effect to drive the liquid Li flow in a stainless tile with Li-metal infuse trenches (LIMIT). This LIMIT was installed at the bottom of the vacuum chamber to face the heat flux (>100 kW/m^2) during the ohmic plasma discharges. A thermoelectric device creates voltage when there is a different temperature on liquid Li and SS tile. This thermoelectric voltage creates an electric current, which has a component perpendicular to the SS surface of limiter and drives the lithium flow by $J \times B$ force. The velocity of liquid Li in the trench can be assessed as: $\bar{u} = \left(P/B\right) \times \left(\mathrm{d}T/\mathrm{d}z\right) \times \left((H\alpha - \tan\mathrm{h}(H\alpha))/(H\alpha + C\tan\mathrm{h}(H\alpha))\right)$,, where P is the difference of the Seebeck coefficient between SS and Li, B is the magnetic field intensity, $\mathrm{d}T/\mathrm{d}z$ is the gradient of temperature and $H\alpha$ is the Hartmann number. Therefore, the average velocity of Li flow in HT-7 is about 4.2 cm/s [16]. During the application of LIMIT in HT-7, it was observed that the liquid Li flow near plasma touched area had a velocity about 3.7 ± 0.5 cm/s along the trenches driven by $J \times B$ force, which was approximately in accordance with the estimations.

3. Surface control related to plasma performance

It has been reported that too much Li influx into the plasma would radiate the power to the edge plasma from the core and induce the thermal instability at the edge [17]. Mostly disruptions follow the boundary MHD instability which happens simultaneously with an increased Li emission. This is the critical disruption point. The current from SOL and the induced current in liquid Li have two components, which are normal and parallel to the limiter surface. The $J_{\parallel} \times B_p$ force points to core plasma and induces the Li ejection from the limiter surface, when the thinner Li film is in favor of resisting electromagnetic forces. The current normal to the limiter combined with the plasma wind drives the Li droplet moving along the poloidal + I_p direction. Liquid droplets ejection and