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Active radiative liquid lithium divertor concept

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HIGHLIGHTS

- In this paper, we propose an active radiative liquid lithium divertor concept (ARLLD).
- We summarize a previously introduced radiative liquid lithium divertor (RLLD) concept.
- We also point out various roles liquid lithium can play in the divertor system with ARLLD complementing RLLD.
- We point out the ARLLD can play an effective first line of defense for protecting divertor PFCs.

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ABSTRACT

Developing a reactor compatible divertor has been identified as a particularly challenging technology problem for magnetic confinement fusion. Application of lithium (Li) in NSTX resulted in improved H-mode confinement, H-mode power threshold reduction, and reduction in the divertor peak heat flux while maintaining essentially Li-free core plasma operation even during H-modes. These promising Li results in NSTX and related modeling calculations motivated the radiative liquid lithium divertor (RLLD) concept [1]. In the RLLD, Li is evaporated from the liquid lithium (LL) coated divertor strike point surface due to the intense heat flux. The evaporated Li is readily ionized by the plasma due to its low ionization energy, and the poor Li particle confinement near the divertor plate enables ionized Li ions to radiate strongly, resulting in a significant reduction in the divertor heat flux. This radiative process has the desired effect of spreading the localized divertor heat load to the rest of the divertor chamber wall surfaces, facilitating divertor heat removal. The modeling results indicated that the Li radiation can be quite strong, so that only a small amount of Li (∼a few mol/s) is needed to significantly reduce the divertor peak heat flux for typical reactor parameters. In this paper, we examine an active version of the RLLD, which we term ARLLD, where LL is injected in the upstream region of divertor. We find that the ARLLD has similar effectiveness in reducing the divertor heat flux as the RLLD, again requiring only a few mol/s of LL to significantly reduce the divertor peak heat flux for a reactor. An advantage of the ARLLD is that one can inject LL proactively even in a feedback mode to insure the divertor peak heat flux remains below an acceptable level, providing the first line of defense against excessive divertor heat loads which could result in damage to divertor PFCs. Moreover, the low confinement property of the divertor (i.e., <1 ms for Li particle confinement time) makes the ARLLD response fast enough to mitigate the effects of possible transient events such as large ELMs.

1. Introduction

Developing a reactor-compatible divertor system is a particularly challenging physics and technology problem for magnetic confinement fusion [2,3]. While tungsten has been identified as the most attractive solid divertor material, many challenges including surface cracking and deleterious modification of the surfaces by the plasma must be overcome to develop robust plasma facing components (PFCs) [4]. In recent DEMO divertor design studies [5–7], the steady-state heat handling capability of a tungsten-based divertor design is only about 5–10 MW/m^2, which is nearly an order of magnitude lower than the anticipated unmitigated heat flux

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~40–60 MW/m^2 for the next generation ST-based Fusion Nuclear Science Facility (FNSF) [8], Pilot Plant [9], and a 1 GW-electric-class DEMO/Power Plant with the device size of ITER. In addition, there are serious concerns over potential damage to the PFCs by the very high transient heat fluxes accompanying ELMs and other uncontrolled events. Application of lithium (Li) in the NSTX spherical tokamak resulted in improved H-mode confinement, H-mode power threshold reduction, and ELM mitigation while maintaining essentially Li-free core plasma operation even during H-modes [10–21]. A particularly important and relevant observation from the NSTX liquid lithium divertor (LLD) experiment for the present paper is the divertor heat flux reduction accompanying the Li coating of divertor surfaces in NSTX [22]. The measurements showed a ~50% reduction in peak heat load on the divertor strike point surfaces with only a modest amount of Li (~300 mg) evaporation prior to the discharge compared to 150 mg evaporation. It is estimated that <10% of the evaporated Li is deposited over the LLD surfaces. The heat flux reduction is accompanied by an increase in the localized radiation measured by bolometers from the region above the inner and outer strike points. Motivated by this observation, a liquid lithium (LL) based radiative divertor concept termed RLLD (radiative liquid lithium divertor), has been proposed [1]. For those not familiar with the RLLD concept, it is reviewed briefly in Section 2. In Section 3, the motivation for the active Li radiation based divertor concept is described. In this paper, we examine the case of active Li injection upstream to the divertor plate, but within the divertor chamber near the divertor throat. The injected Li ionizes quickly and radiates as it flows toward the divertor plate. We term this active version of the radiative LL divertor the ARLLD. In Section 4, a model calculation for ARLLD is described. The model predicts significant reduction in the heat flux to the divertor by non-coronal equilibrium Li radiation with a modest amount of Li injection. Encouragingly, even for an ITER-sized 1 GW-electric fusion power plant, the calculated required Li evaporation rate is quite modest, i.e., ~a few mol/s. In Section 5, we discuss the ARLLD and RLLD concepts under reactor conditions. In Section 6, conclusions and discussion are given.

2. A review of radiative liquid lithium divertor (RLLD)

To briefly review the concept, the RLLD is placed at the bottom of the reactor chamber for obvious reasons from the LL handling point of view, and also to capture any impurity particles including dust generated within the reactor chamber [23] as illustrated in Fig. 1. A simplified schematic of the RLLD is shown in Fig. 2, noting that the actual RLLD shape should follow the contour of an outer divertor leg. The LL is introduced at the upper part of the RLLD at multiple toroidal locations, and it gradually flows down the RLLD side wall as a thin film via gravity and capillary action. The thin LL film thus formed should provide very effective pumping (or entrapment) of the working gas, impurities, and dust generated within the reactor chamber. The RLLD chamber being of the lowest temperature in the reactor chamber together with the usual divertor action, should facilitate the pumping of the entire reactor chamber. The RLLD chamber wall temperature can be in the 250–450 °C range, which is significantly lower than that envisioned for the fusion reactor first wall. The LL flowing down the divertor side wall accumulates at the bottom of RLLD where the divertor strike point is placed. By placing the LL surface in the path of the divertor strike point, the LL is evaporated from the surface through sputtering, evaporation, and chemical processes [24]. The evaporated Li is quickly ionized by the plasma and the ionized Li ions can radiate strongly, reducing the heat flux to the divertor strike point surfaces and protecting the substrate material.

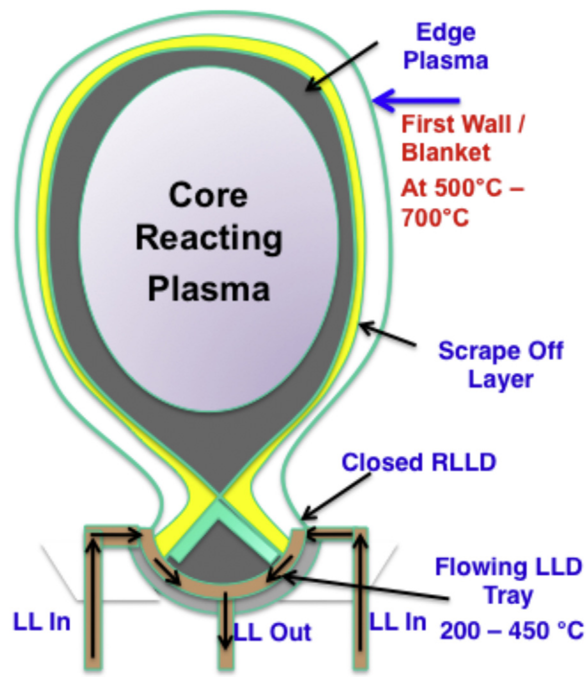

Fig. 1. A possible RLLD configuration in a fusion power plant. (a) RLLD is envisioned to be placed at the bottom of the reactor chamber to capture LL, dust, and other solid impurities.

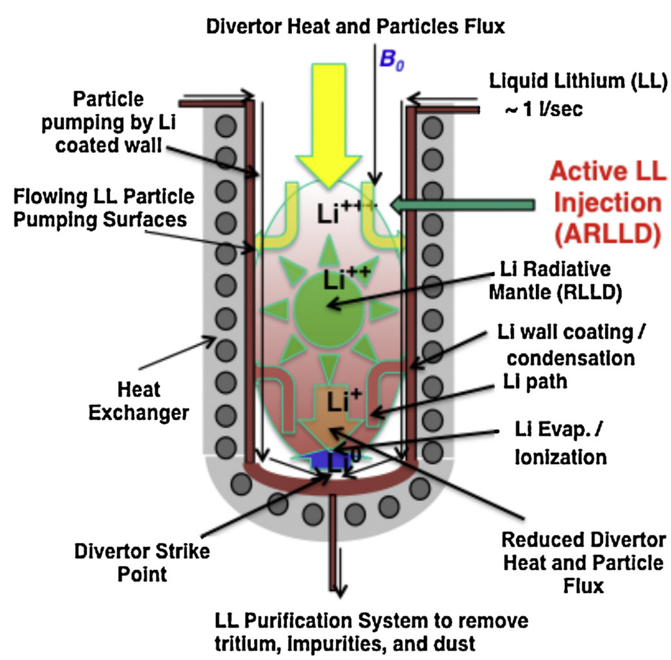

Fig. 2. A simplified schematic of RLLD chamber. The LL flows down along the side wall to provide pumping, and the thicker LL layer at the bottom provides radiative Li source for heat flux reduction and divertor substrate protection. A new feature is the active LL injection from the side wall.

3. Motivation for active radiative liquid lithium divertor (ARLLD)

The motivation for LL utilization for divetor heat flux mitigation can be seen in Fig. 3. The figure depicts various possible protective functions LL can perform for divertor PFCs. Perhaps the last line of defense is the LL evaporation from the LLD tray. Through evaporation, Li can carry some heat away from the material surfaces