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Modeling the lithium loop in a liquid metal pool-type divertor

G.F. Nallo [a], S. Carli [a], G. Caruso [b], F. Crisanti [c], G. Mazzitelli [c], L. Savoldi [a], F. Subba [a], R. Zanino [a,*]

[a] NEMO Group, Dipartimento Energia, Politecnico di Torino, Torino, Italy
[b] Università degli Studi di Roma "La Sapienza", Roma, Italy
[c] ENEA Frascati, Italy

HIGHLIGHTS

- A preliminary design of liquid Li pool-type divertor for DTT is presented.
- The design includes an evaporation chamber (EC) and a differential chamber (DC).
- The Li loop is analyzed with a self-consistent thermodynamic model.
- The Li vapor shield is shown to be effective for plasma heat flux redistribution.
- Low Li vapor flux to the main plasma is achieved thanks to the DC pumping action.

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ABSTRACT

Considering that solutions for the steady-state power exhaust problem in future fusion reactors (e.g. DEMO) are not provided by present experiments and it is uncertain if they will be provided by ITER, because the expected heat fluxes, as well as the level of neutron irradiation, will be much higher, dedicated work packages are being devoted to this problem within EUROfusion and even a dedicated facility (the Divertor Tokamak Test – DTT) is being proposed in Italy. Among the possible options, a liquid metal (LM) divertor is being considered. The present work aims at developing a simple model of the LM loop in the case of a pool-type divertor, including the most important physical phenomena and allowing to roughly determine the operating range of the system, in terms of surface temperatures and vapor pressures. This work therefore sets a preliminary basis for the conceptual design of a LM divertor for the DTT facility. The model includes the incoming plasma heat load and a basic treatment of the interactions of the Li vapor with the plasma. The reduction of the Li vapor efflux due to ionization by the plasma is also taken into account. The model includes two chambers: a first divertor box, the evaporation chamber (EC), is open towards a second divertor box, the differential chamber (DC), which is in turn connected to the main plasma chamber (MC). The model is used to study the effectiveness of the LM vapor in radiating isotropically the parallel heat flux incoming in the divertor. The results indicate that the presence of the DC allows a significant reduction of the Li vapor efflux towards the MC, which in turn would imply a lower contamination of the core plasma.

1. Introduction

Safe power exhaust, even in steady state, is one of the major issues in fusion reactors and a potential show-stopper towards the production of the first kWh from the fusion energy source, which the EU roadmap [1] has set as the major target for its DEMO reactor in 2050. The power produced by deuterium-tritium reactions in the alpha particles channel may be partly – more or less isotropically – radiated, but the rest reaches the plasma-facing components (PFCs) in the strongly anisotropic channel of plasma advection-conduction. This leads to high particle and heat fluxes, because of the relatively small wetted areas associated with the thin scrape-off layer (SOL) predicted in future machines, affecting not only the PFCs lifetime but also the core plasma purity (measured by the Z_{eff} parameter), because of sputtering.

In ITER, the control of the steady-state peak heat load q_{peak} below 10 MW/m^2 on the PFCs, as well as of the Z_{eff}, relies on a single-null divertor with W target and on the Be first wall (FW),

* Corresponding author.
E-mail address: roberto.zanino@polito.it (R. Zanino).

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combined with detached plasma operation and seed impurity puffing [2,3]. Even if this complex combination of conditions should be confirmed experimentally in ITER, extrapolation to DEMO is not automatically guaranteed. Furthermore, as the increase in size from ITER to DEMO is much smaller than the increase in the design thermal power to be produced by the two machines, in DEMO it will be even more difficult to meet the technological constraints on q_{peak} related to the use of a solid divertor.

Among the risk-mitigation strategies currently foreseen, the one especially relevant for the present work is the liquid metal (LM) divertor [4]: the high latent heat of evaporation of the LM, together with the liquid nature of the wall, which can be constantly replenished, and the plasma cooling by interactions with the LM vapor, could in principle guarantee the exhaust of hundreds of MW/m^2, with much more limited, if any, damage to the target than the solid target option and consequent increase of the divertor lifetime.

Possible LM choices include in the first place Li [4], which will be considered here, but also others, e.g. Sn. As to the nature of the LM target, different options are being considered, ranging in complexity from a simple pool to a moving liquid film, to the use of a so-called capillary porous structure (CPS) [4], recently tested on the liquid Li limiter (LLL) in FTU [5]. While the CPS should guarantee, better than other solutions, the avoidance of splashing phenomena with generation of LM droplets, which could easily compromise the plasma purity, we will refer in the present work to the simpler case of a LM pool without CPS and without external (pumped) circulation of the LM.

In the EU, significant attention is being given to these problems within the EUROfusion Work Packages DTT1 and DTT2. DTT is also the name of an Italian proposal for a machine entirely devoted to the issues of power exhaust and Z_{eff} in DEMO perspective [6].

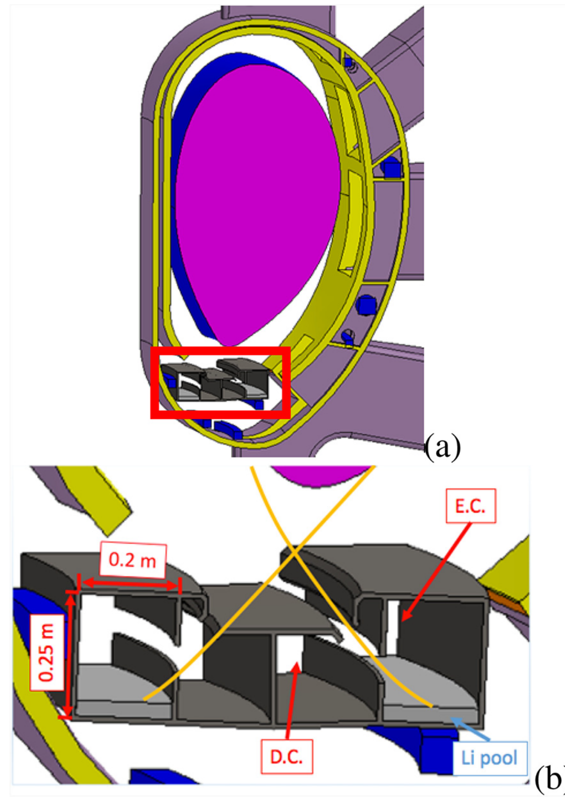

Fig. 1. (a) DTT main plasma chamber with the divertor highlighted and (b) preliminary sketch of the LM divertor.

2. System description

Starting from the current design of the DTT chamber [7], a first preliminary sketch of a possible liquid metal divertor geometry to fit in the available space has been prepared, see Fig. 1. This is based on the idea originally proposed by Nagayama [8] and eventually further developed in [9]: the SOL plasma flowing from the main plasma chamber in a reference Single Null (SN) DTT equilibrium enters first the Differential Chamber (DC, see Fig. 1) and finally the Evaporation Chamber (EC), where the LM pool is located.

The schematic representation of the EC used to write down the model equations is shown in Fig. 2. Even though the shape shown in the schematic is different with respect to the one in Fig. 1, this is not relevant for a 0D model, the only requirement being to conserve the surface areas and the chamber volumes. The sub-systems are:

- the liquid Li in the pool;
- the Li vapor in the remaining volume of the EC;
- the Li vapor in the DC;
- the solid walls in contact with liquid Li (identified in the following with the subscript *pool*);
- the solid walls in contact with the Li vapor in the EC (identified in the following with subscript *EC*).
- the solid walls in contact with the Li vapor in the DC (identified in the following with subscript *DC*).

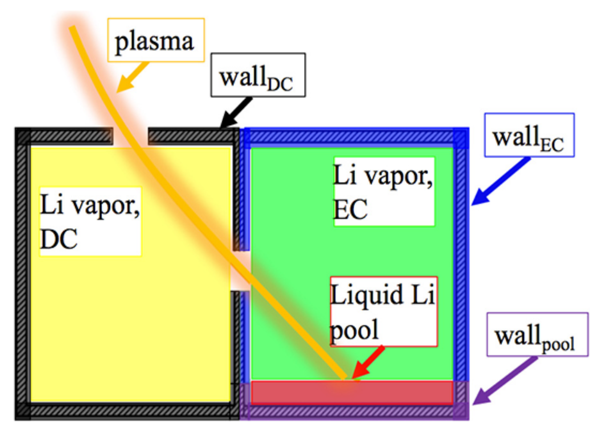

Fig. 2. Schematic of the computational domain.

3. Phenomenology

The Li evaporating from the pool flows upwards, then either condenses on the relatively colder surfaces of the EC or moves to the DC, where it either condenses or moves outside of the box-structure of the divertor towards the main plasma chamber. The condensed Li is assumed to flow back to the Li pool both from the EC (by gravity) and from the DC (by means of an external circuit, not included in this model for the time being).

The presence of a DC in the original Nagayama proposal is motivated by the necessity to reduce the core plasma contamination associated with the eroded (evaporated/sputtered) Li flowing out of the EC. The extra chamber allows for differential pumping, i.e. the connection of two chambers having different pressures by means of intermediate chambers, actively and/or passively pumped (see Fig. 3). In such a system, when a large pressure difference is involved, choked flow is likely to occur between successive chambers [10].

The intermediate chambers allow a progressive reduction in mass flow rate from the higher pressure boxes to the lower pressure boxes, thanks to the – active and/or passive – pumping of the vapor. In the concept considered here, this is achieved by means of net condensation of Li vapor on the walls of the EC and of the DC, i.e.