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Static arrangement of a capillary porous system (CPS): Modelling

Nikos Pelekasis*, Lefteris Benos

Dpt. Mechanical Engineering University of Thessaly, Volos 38334, Greece

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ABSTRACT

The static arrangement is studied of a thin CPS wafer which is filled from below with a liquid metal. The CPS is modelled as a thin cylindrical disk that is resting on a flat wall. It is in contact with a reservoir that provides liquid lithium. Isothermal conditions are considered and a liquid metal layer is assumed to have been established on top of the CPS and reached an axisymmetric static arrangement. A numerical solution is obtained via the finite element methodology that solves the Young-Laplace equation which incorporates surface tension, gravitational, pressure and electrostatic forces. The layer thickness is predicted at static equilibrium as a function of the imposed pressure drop across the wafer, i.e. between the reservoir and the surrounding medium, and the wetting and dielectric properties of the liquid metal. It is seen that at large reservoir overpressure surface tension balances pressure forces and the liquid metal assumes the form of an almost hemispherical drop of small radius. Gravity is not important in this limit. As the pressure drop decreases the drop assumes an oblate shape and a thin film is gradually formed that entirely covers the CPS and extends onto the wetted rigid substrate. In this range, gravity balances pressure drop and surface tension and the film thickness is on the millimeter range, which is relatively large and has negative implications on the stability of the liquid metal layer as the electric field strength increases. Below a certain pressure drop the film in conjectured to become very thin, on the order of μm, and the disjoining pressure is expected to balance the imposed pressure drop across it. Such static arrangements have been reported in the literature and are favored in terms of stability of the CPS against $\vec{j} \times \vec{B}$ effects.

1. Introduction

Free surface plasma facing components (PFCs) constitute one of the most critical technological challenges of future fusion reactors since they should have the ability to withstand power densities of the order up to 100 MW/m^2 for off-normal events such as edge-localized modes (ELM's) and disruptions. Based on available data from fusion reactors that are in operation, e.g. JET, divertor walls made of tungsten can withstand heat loads up to 20 MW/m^2. Beyond this level the plasma-wall interaction that is generated by such events is seen to cause problems such as erosion, thermal stresses, thermal fatigue and plasma contamination which may irreversibly impair the operation of the reactor. In order to circumvent the above problems liquid metals are considered as alternative plasma facing components (PFCs) [1–3]. The self-cooling and self-annealing properties of flowing liquids increase their life cycle as they interact with the scrape-off-layer of the fusion reactor. The flow pattern of liquid metals employed for protection of the divertor region and the blanket first wall is characterized by the formation of a free surface that is subjected to the electromagnetic field and heat load generated by the plasma.

PFCs involving free flowing films of liquid metals are susceptible to shear instabilities as a result of the film speed and thickness, on the order of 1 cm, required to exhaust the incoming heat flux [4,5]. Recent experiments at the ISTTOK tokamak [6] and a first principle study [7] validate the deflection mechanism of a liquid metal jet or drop moving inside an electromagnetic field as a result of $\vec{j} \times \vec{B}$ effects. The deflection increased with increasing magnetic field intensity and drops were observed to hit the collector walls.

As an alternative concept, a porous system that acts as a capillary pump pushing liquid metal through a porous medium has been employed [8]. In this concept capillary action is of central importance for renewing the liquid metal, typically lithium, which is in contact with plasma. As an alternative to lithium, liquid tin is envisioned as PFC, due to its low reactivity and much wider liquid state temperature range, which provides much higher extracting power from fusion plasmas [9]. Capillarity and wetting on the porous substrate is expected to stabilize the liquid metal against $\vec{j} \times \vec{B}$ effects and drop ejection [11], and this is a key issue underpinning the reliability of liquid metals as PFCs. Nevertheless, drop ejection and

* Corresponding author.
E-mail address: pel@uth.gr (N. Pelekasis).

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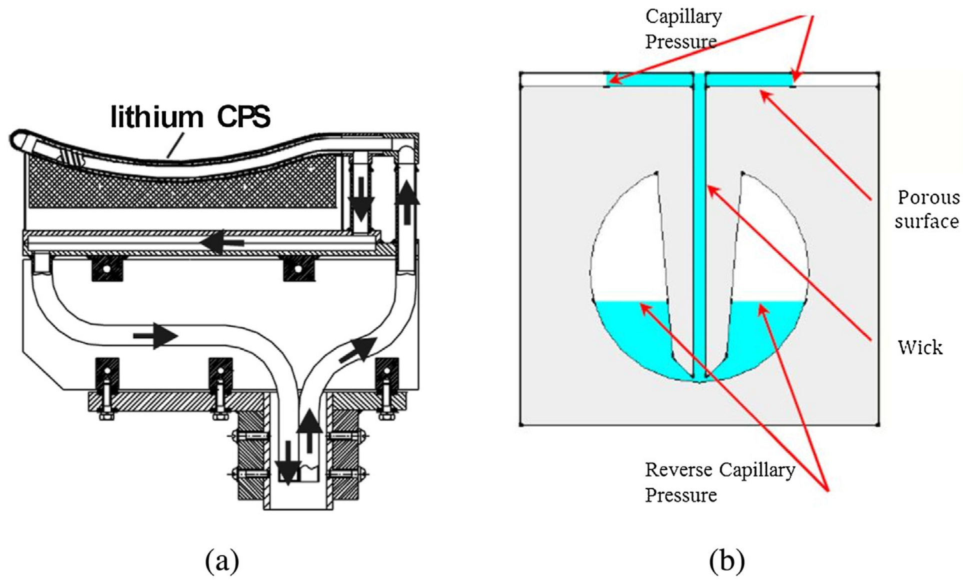

Fig. 1. Schematic diagram of the CPS arrangement in (a) ENEA Frascati [8] and (b) NSTX-U [12].

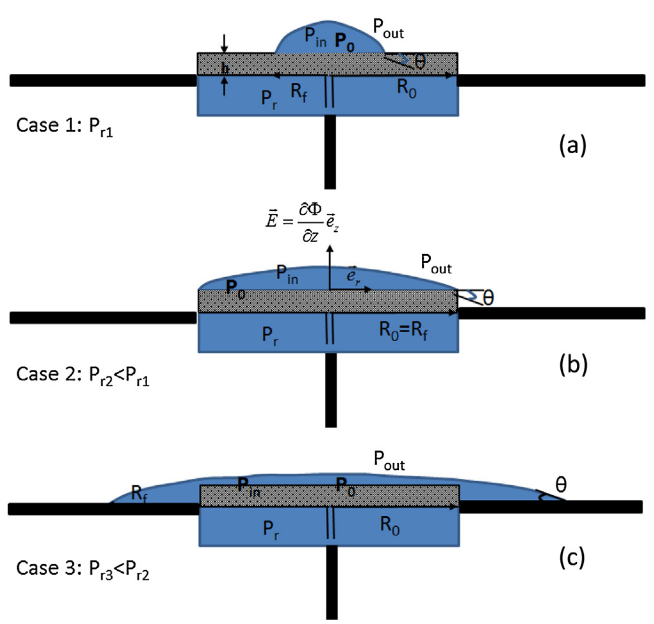

Fig. 2. Schematic of the geometry studied in the present study and the resulting static configurations.

splashing has been reported during operation of CPS systems in the literature [11,18], especially when $\vec{j}\times\vec{B}$ forces are present.

In the present study, the static arrangement of a CPS system is investigated in order to assess the thickness of the liquid metal film that rests on top of it protecting it from surrounding plasma. Fig. 1a shows the CPS system employed at ENEA Frascati. Owing to its complex curved geometry, a simplified static arrangement is investigated, Fig. 1b, which provides a simplified schematic diagram, that resembles the wicking process envisioned for NSTX [12]. In the absence of reliable experimental measurements of the static film thickness we examine the simplified arrangement depicted in Fig. 2a,b,c where filling from below is envisioned, with the pressure drop between the liquid metal reservoir and the surrounding medium treated as a parameter that determines the film thickness, given the liquid metal properties and the topography of the CPS system. The film thickness is of central importance in the stability and viability of the CPS system, as protective coating of the divertor against electromagnetic and thermal disturbances during plasma operation. To this end, the effect of an external electric field is included as a means to address the impact of field forces on the static arrangement and investigate the possibility for dynamic instabilities to appear that will destroy the cohesion of the protective film by enhancing drop ejection.

In Section 2 the problem formulation is presented along with the major simplifying assumptions for the case of an axisymmetric porous wafer. In Section 3 the numerical methodology is presented via the finite element method that is most suitable for free surface problems. Next, in Section 4.1 a parametric study is presented highlighting the relative importance of capillarity, gravity and pressure drop as the reservoir overpressure decreases. The importance of electric stresses in the static arrangement is addressed in Section 4.2 and the ensuing dynamic stability of the liquid metal layer is discussed [13]. Finally, in Section 4.3 the importance of the disjoining pressure is stressed [14], in maintaining a very thin film of liquid metal coating on top of the porous structure for negligible reservoir overpressures -filling of the porous structure will be performed under vacuum conditions [12] – conclusions are drawn and directions for future research are proposed.

2. Problem formulation

We are interested in the static arrangement of a CPS system as a function of the overpressure, P_r-P_{out}, between the reservoir and the surrounding medium and the physical properties of the employed liquid metal. Fig. 2 illustrates the anticipated static configuration as the above overpressure decreases, to be verified in the results and discussion Section 4. We consider a porous system shaped as a circular disk of small thickness h on the order of 1 mm.

The characteristic pore radius, R_p, is on the order of tenths of μm's in which case a static arrangement cannot be obtained with the liquid metal partially filling the porous wafer. The porous system is in contact with a reservoir that provides the liquid metal via a thin wick. Static arrangements are obtained with partial or full coverage of the top surface of the porous structure, depending on the reservoir overpressure, Fig. 2a,b,c, for fixed radius R_0 of the porous wafer.

We are interested in, (a) investigating the possibility for a static arrangement to be established with the liquid metal covering the