



Calculation and experimental investigation of fusion reactor divertor plate and first wall protection by capillary-pore systems with lithium

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Abstract

Estimations and experimental studies on the possibility of capillary-pore systems with lithium as the first wall and divertor target plate plasma-facing material have been conducted in support of the lithium liquid metal fusion reactor concept. The possibility of the lithium-filled capillary-pore systems to withstand a high energy plasma flux has been demonstrated. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

The idea of using a liquid metal for fusion reactor first wall and divertor plate shielding has been considered in reactor designs with inertial plasma confinement and in tokamak reactors with filmy liquid metal shielding [1–4]. The development of a liquid metal stable film on a complex surface is the main issue for the realization of such ideas. The solution of this problem has been proposed in the Russian lithium liquid metal fusion reactor concept (LLFR) and is based on the use of capillary-pore materials filled with lithium [5,6]. The lithium confinement, distribution and supply on the surface are provided by capillary forces in a capillary-pore system (CPS). Such a system is thought to be self-regulated, since the distribution of the lithium pressure in CPS responds to the local change of heat load distribution on its surface. The possibilities of capillary-pore systems filled with lithium accepting high specific energy without structural failure have been investigated [7,8].

In the program of LLFR development, the investigation and realization of a lithium capillary-pore system application are carried out in the following directions:

(a) the rated-theoretical research and CPS design optimization; (b) experimental studies of lithium CPS availability under stationary operating regime of reactor and at plasma disruptions; (c) materials science and process investigations; (d) the studies of hydrodynamic and magnetohydrodynamic (MHD) effects of lithium flowing in CPS.

2. Calculations of CPS availability

The assessment of lithium-filled CPS to accept and remove the high specific heat loads without structural failure and estimation of its design optimal parameters can be based on a force balance on the CPS surface during plasma exposure.

The capillary pressure difference ΔP_c at the different points on the CPS surface and volume is believed to be a driving force for liquid lithium flowing process. The capillary pressure has been determined by the familiar expression:

$$P_c \sim 2\sigma/R(R_{\text{eff}}, Q), \quad (1)$$

where σ is the liquid metal surface tension coefficient; $R(R_{\text{eff}}, Q)$ the liquid metal surface meniscus radius in CPS pores, depending on CPS parameter R_{eff} (effective radius of pore) with direct proportionality and on en-

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ergy load Q with inverse proportionality. Thus the liquid metal flow rate and direction in CPS are preset by the value and distribution of the incoming plasma flow energy on the surface.

The calculations of capillary pressure in lithium-filled CPS have shown that for a realized R_{eff} (2–3 μm) it reaches $6\text{--}8 \times 10^5$ Pa and slightly depends on temperature.

Under a steady-state operating regime, the availability of CPS with lithium as a first wall and divertor target plate plasma-facing material is defined by the following inequality at any point on its surface

$$\Delta P_c \geq \Delta P_f + \Delta P_1 + \Delta P_m + \Delta P_g - P_0 + P_p, \quad (2)$$

where ΔP_f is the pressure drop at liquid-vapor phase transition; ΔP_1 the hydrodynamic pressure drop in CPS; ΔP_m the magnetohydrodynamic pressure drop in CPS in a magnetic field; ΔP_g the hydrostatic pressure drop in CPS; P_0 the pressure in the CPS supply system; P_p the pressure of plasma flow on the CPS surface. Failure to fulfill these requirements results in deterioration of the lithium supply on CPS surfaces and structural damage under the action of the plasma flow.

Let us consider the main items of the balance condition. Due to reaction during evaporation of lithium under the action of plasma flow, ΔP_f can be approximately defined by the following expression

$$\Delta P_f = Q^2 / (r^2(t) k^2 \varepsilon_p^2 R_{\text{eff}} \rho_v(T)), \quad (3)$$

where $r(T)$ is the lithium evaporation latent heat; k the vapor exhaust coefficient, taking account of the meniscus form and vapor exhaust mode; ε_p the CPS surface porosity; $\rho_v(T)$ the lithium vapor density at given Q . As ΔP_f estimations indicate, its value does not exceed 2×10^4 Pa at a lithium temperature of 1300°C (at which the removed power by evaporation may reach 700 MW/m²).

The hydrodynamic pressure drop in CPS is determined by the following equation:

$$\Delta P_1 = (\mu GL) / (\rho(T) S k_0), \quad (4)$$

where μ is the lithium dynamic viscosity; $G = \rho(T) (dV/dt)$ the lithium mass flow; L the distance from supply point to CPS evaporation surface; $\rho(T)$ the lithium density; S the CPS sectional area; k_0 the CPS permeability coefficient determined experimentally; dV/dt the lithium volume flow. The lithium mass flow is related to specific energy flow by the relation $G = QS_e/r(T)$, where S_e the evaporation surface area.

At present, the MHD pressure drop in a CPS in a magnetic field is not possible to be determined in analytical form. However, when it is considered that the CPS permeability coefficient is a function of the perpendicular component to lithium flow under a magnetic field intensity H and lithium flow velocity, the lithium

flowing characteristics in CPS can be estimated from the expression similar to Eq. (4)

$$\Delta P_m = (\mu GL) / (\rho(T) S k_m(v, B)), \quad (5)$$

where $k_m(v, B)$ is the CPS permeability coefficient in a magnetic field, which is determined experimentally and lies in the range of $k_0 \geq k_m(v, B) \geq 0$ at magnetic field from 0 to ∞ .

It is seen from the (Eqs. (1)–(5)) that the CPS availability is determined by its characteristics (ε_p , ε_v , k_0 , $k_m(v, B)$, R_{eff}) and chosen design parameters (L , S , S_e). By analyzing the expression (2), the allowable specific heat flow on the receiving surface and the optimal characteristics of a CPS can be in principle defined. For example, the maximal value Q , at which the lithium-filled CPS can withstand without structural damage, is provided for the achievable minimum value R_{eff} . However, this is inconsistent with the high value k_0 and $k_m(v, B)$ requirements that fits the high values of R_{eff} , for the homogeneous CPS with low pressure drop, which limits the permissible values of Q . To eliminate such a contradiction there are a lot of procedures, i.e. the use of complex CPS with differential porosity, arterial structure with low hydraulic resistance and so on, which make it possible to obtain the acceptable hydraulic and magnetohydrodynamic losses.

The estimation of a lithium-filled CPS availability at plasma disruption condition may be fulfilled on the basis of the determination of possible plasma interaction mechanisms. It has been shown that about 97–98% of plasma energy is reradiated in a vapor cloud near the surface and only a power flux of 300–500 kW/cm² falls on the surface [9]. CPS availability is determined by its structural melting and splashing processes under these flux and plasma pressures. The CPS erosion estimation method is being developed now.

3. Experimental results

The investigation of structural material parameters on CPS resistance to failure by the action of hydrogen plasma flow with specific energy density of 5 MJ/m² and duration of 0.5 ms was carried out on the targets impregnated with lithium, which represent a multilayer rectangular matrix 2 mm thick, 3 × 3.5 cm in size. A mesh of molybdenum wire with pore size R_{eff} of 200–15 μm served as a base of their structure. The target temperature before the test was 20°C, which allowed to determine the mass losses and lithium layer depth removed during plasma exposure.

As the microscopic study of target surface indicated, there is a lithium layer removal to a certain depth, depending on the CPS pore size and lithium redistribution through the center of the target to the periphery (Fig. 1). The CPS structure in the absence of lithium was



Fig. 1. Lithium-filled CPS surface view after one plasma pulse.

ruptured on one plasma pulse exposure (Fig. 2(a) and (b)) and lithium-filled CPS were free from any structural failure at plasma exposure (Fig. 2(c)–(f)).

The measured results of lithium layer depth removed during one plasma pulse exposure are presented in Fig. 3. The data on lithium mass losses determined by weighing (the lower curve) and by estimation of removed layer depth with regard to the CPS surface porosity (higher curve) are given in Fig. 4.

Formation of a lithium dense plasma layer of 10–20 mm thick with $n_e \geq 5 \times 10^{16} \text{ cm}^{-3}$ on the lithium target surface as a result of magnetized hydrogen plasma exposure has been observed by laser interferometry.

Since the data on the hydraulic resistance of CPS with a complex structure and the MHD resistance to liquid metal flowing in CPS are unknown, experiments to obtain these data have been incorporated in test program. The experimental lithium facility for CPS tests in lithium flow with a velocity up to 2.5 m/s in magnetic field at the induction up to 1.6 T has been constructed [10]. At present, the properties of different types of CPS are being measured.

4. Discussion

Strong erosion with mass losses considerably exceeding the losses due to surface vaporization is observed. In Fig. 3 the removed lithium layer depth is shown to be dependent on the CPS pore size. As it can be seen, erosion depth h is close to the pore size δ up to $\delta = 100 \mu\text{m}$, but $h \approx 100 \mu\text{m}$ at $\delta > 100 \mu\text{m}$. This can be explained by the use of the model ‘a splashing wave’ with velocity $V_s \approx 0.2 \mu\text{m}/\mu\text{s}$, therefore the erosion

depth $h = V_s \tau = 100 \mu\text{m}$ for time duration $\tau = 500 \mu\text{s}$. In Fig. 4 mass losses are shown. As it is seen, the mass losses determined by weighing (the lower curve) are less than determined by calculation on lithium erosion depth profile in the central area of the targets (upper curve) what is explained by redeposition of liquid lithium droplets. Mechanisms of splashing (the hydrodynamic Kelvin–Helmholtz and Rauleigh–Taylor instabilities and the volume vapor boiling) and corresponding splashing wave velocities are discussed in Ref. [9].

As follows from numerical calculations on a first approach, the observed lithium vapor plasma mass is not enough for shielding the target surface because of the small width of the lithium vapor $h\nu$ and low emissivity of lithium. The observed shielding efficiency may be explained by the presence of a small amount of molybdenum vapor. From the analysis of such a complicated heterogeneous system, it follows that the concentration of molybdenum atoms $\xi = 10^{-5}$ is enough for the shielding without melting of the molybdenum substrate and, therefore, failure of the CPS structure filled by lithium. Thus, the observed damage of a dry CPS can be explained by the absence of the molybdenum vapor under the target surface due to pushing of the molybdenum vapor into dry pores in the CPS body by the incoming plasma flow pressure.

The following conclusions can be made from corresponding calculations. The lithium vapor layer with a small amount of the high Z impurity atoms absorbs all incoming plasma flow energy S_0 and reradiates most of it (see Fig. 5). The necessary vapor concentration ξ for the molybdenum is governed by the ratio $\eta = R_{\text{eff}}/R_{\text{wire}}$ (R_{wire} – radius of wire) in dependence of the plasma action duration time τ for provision of good shielding without melting of the substrate. It follows from calculations for $\tau = (0.3–0.5) \text{ ms}$ that the optimal value of R_{wire} is about $80 \mu\text{m}$. It follows from this analysis that the use of another substrate material, for example, the vanadium, is also available because the emissivity of high- Z elements at the decisive range of the vapor temperature of tens of electron volt is practically the same. The lithium-filled CPS substrate is protected during reduced plasma energy flow S_{in} effect due to lithium evaporation and heat removal from the surface layer to CPS body.

The splashing rate due to the main possible mechanisms can be decreased by optimization of the CPS parameters.

5. Conclusions

The estimation confirms the feasibility of a lithium-filled CPS for fusion reactor high energy-loaded component shielding. The availability of CPS with lithium

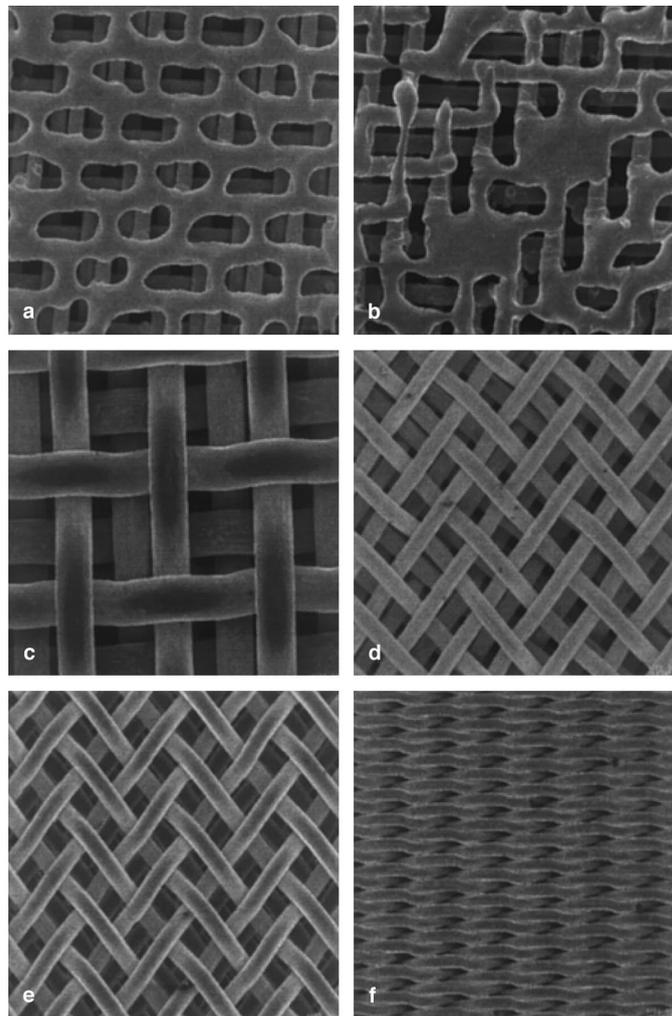


Fig. 2. CPS surface view after plasma irradiation. (a, b) Without lithium, (c) $R_{\text{eff}} = 100 \mu\text{m}$, (d) $R_{\text{eff}} = 75 \mu\text{m}$, (e) $R_{\text{eff}} = 35 \mu\text{m}$, (f) $R_{\text{eff}} = 15 \mu\text{m}$ – with lithium.

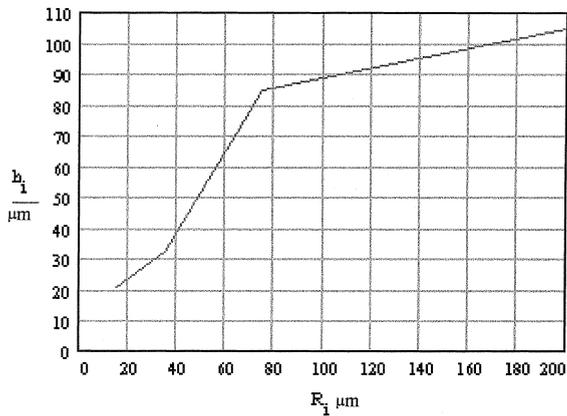


Fig. 3. Dependence of the removed lithium layer depth on CPS pore size.

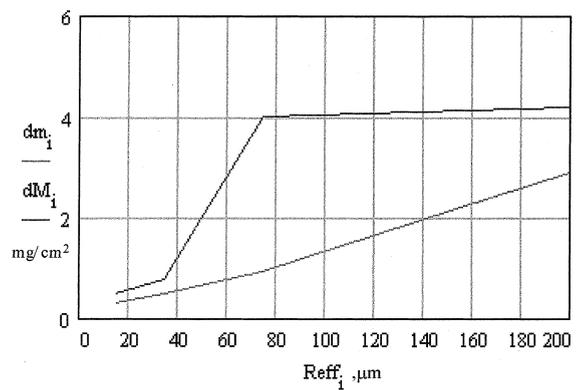


Fig. 4. Dependence of the lithium-specific mass losses dmi (experiment), dm_i (calculation) on the CPS pore size.

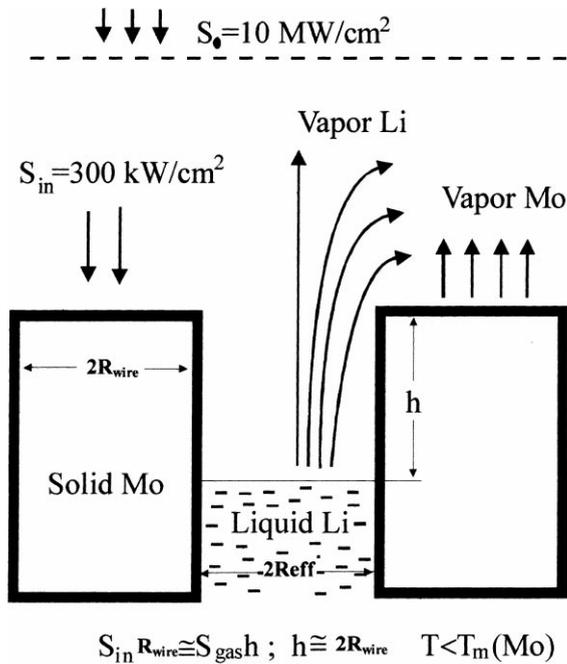


Fig. 5. Scheme of the plasma flow interaction processes with lithium- filled CPS under disruption condition.

under disruption condition and its high protective efficiency is supported by the experimental results.

The dependence of redistributed and removed lithium quantity on CPS pore parameter R_{eff} suggests a particular role of the capillary forces in the stability of the lithium film under the interaction between plasma flow and lithium target surface.

The appropriate choice of CPS design and assessment of optimal parameter relations of its structure will require complex experimental and technological studies.

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