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Energy removal and MHD performance of lithium capillary-pore systems for divertor target application

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Abstract

Experimental results of complex studies of lithium capillary-pore systems (CPS) for application as a plasma facing structure in divertor and on the first wall of a fusion reactor are reported. The ability of CPS to accept and to remove high heat fluxes (up to 30 MW m^{-2}) in steady-state conditions (tens of minutes) has been evaluated on target plate imitator mock-ups supplied with cooling and lithium feed systems under electron beam power load in a linear plasma facility. Experimental study of lithium flow up to 2.5 m s^{-1} in CPS made of material with final conductivity for various mesh sizes and of the effect of cross magnetic field up to 1.6 T on its parameters has been made. The results of successful experiments on the T-11M tokamak helium and hydrogen plasma interaction with a CPS-based lithium limiter and lithium puff influence on the plasma performances are presented and analysed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Energy removal; MHD performance; Lithium capillary-pore systems

1. Introduction

The idea to use a capillary-pore systems (CPS) providing a liquid lithium free surface for protection of divertor target plates and of other plasma facing high heat flux components has been taken as a principal solution in a lithium fusion reactor concept [1]. Preliminary calculations and experimental evaluations of lithium CPS-based tokamak plasma facing components under different conditions have shown the proposed solutions to be practically attractive [2,3].

Experimental facilities designed for comprehensive study of lithium CPS for fusion application have been made and investigations of MHD-effects of lithium flow in CPS and of their ability to accept and to remove high energy fluxes under steady-state conditions have been performed. A series of experiments with lithium limiter in the T-11M tokamak has been carried out as the first step of the studies of lithium CPS compatibility

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with tokamak plasma and of their resistance to plasma impact. The results of these investigations are given and analysed in the present work.

2. Lithium capillary-pore target under steady-state power load

The first quantitative characteristics of lithium filled CPS operating under high power loads have been obtained in the SPRUT-4 linear plasma facility [2,3]. Fig. 1 shows the present status of experimental set-up that was used in the cited references including improvements that have been introduced afterwards. The power load was provided by an electron beam at 9 keV. The beam came to a lithium filled CPS-based target receiving surface. The heated spot diameter was about 2 cm. Duration of tests for several targets varied from 30 s to 10 min. Lithium evaporation rate from the CPS surface was evaluated by mass and heat balance of the target, condenser and shield (Fig. 1). It was shown to range from 10^{-2} to 0.8 kg m^{-2} s^{-1} for 1–25 MW m^{-2} of power load. Surface temperature in the hot spot was also evaluated (it did not exceed 1000°C) as well as plasma characteristics of lithium plasma that was formed near the target during irradiation (10^{20} m^{-3} plasma density at maximum at the plasma boundary). These quantities were measured as functions of energy flux on the target [2,3]. The obtained results provided the first data for the assessment of a divertor based on a lithium filled CPS and gave the primary data for evaluation of lithium influx into the divertor volume. Further development of the experiment consisted in devel-

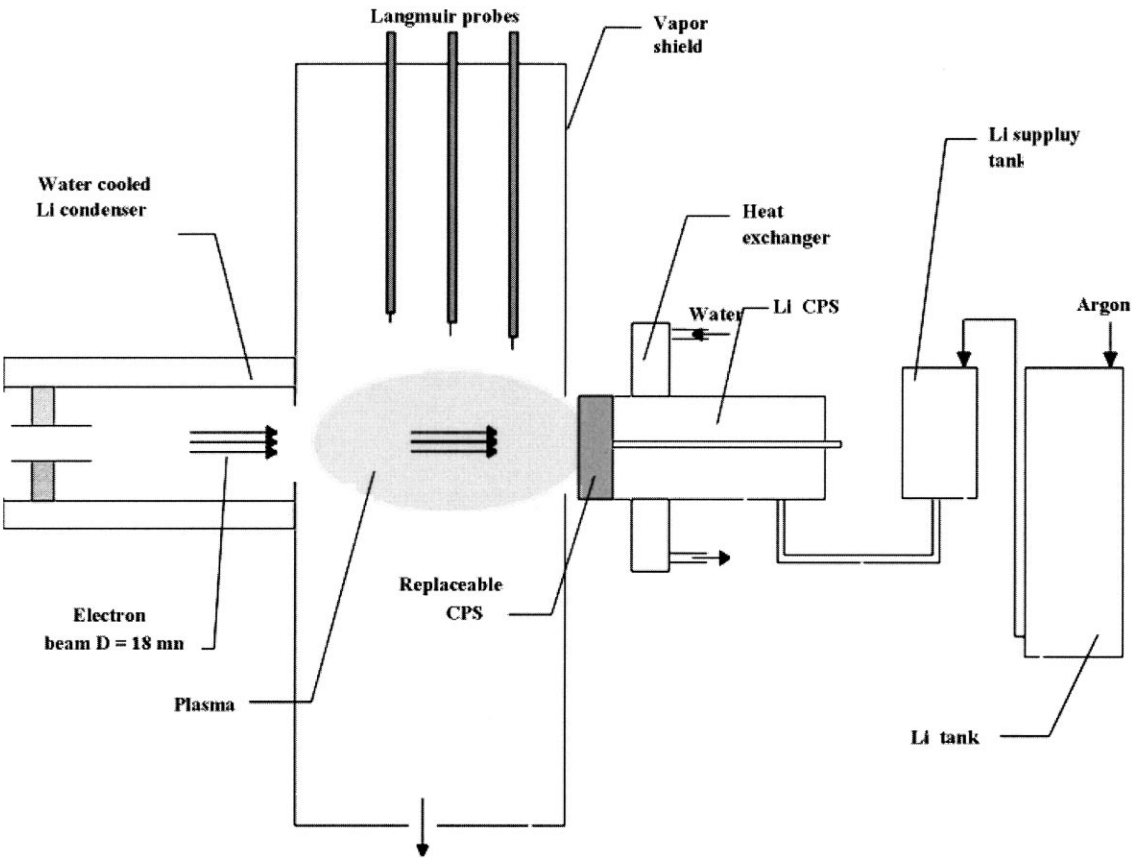

Fig. 1. SPRUT-4 device with lithium loop for CPS supply, scheme.

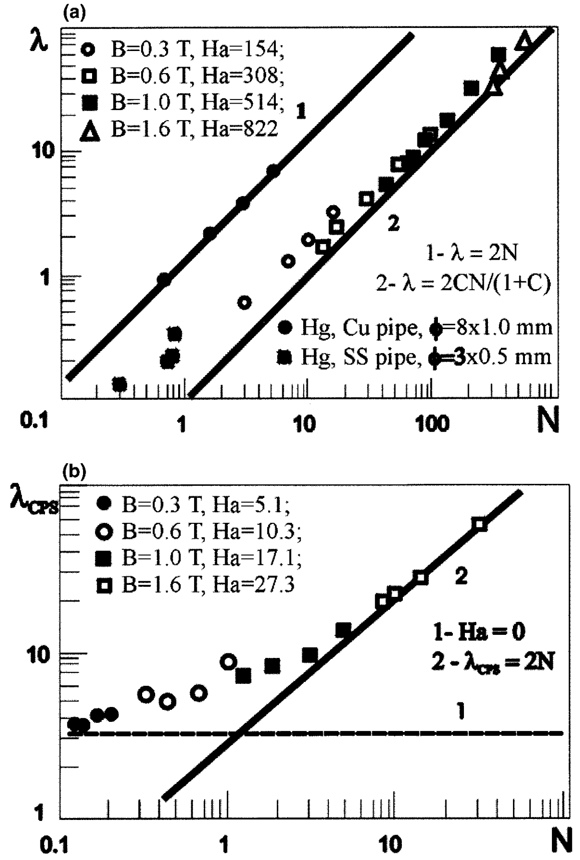

Fig. 2. Lithium flow hydraulic coefficient λ versus interaction parameter N: (a) cylindrical channel; (b) channel with CPS.

opment of a special liquid lithium feeding and heat removal systems (Fig. 1) to enlarge the scope of tests to higher durations, higher mass flow rates and to stabilise the target heat regimes. Now CPS targets may be studied in the SPRUT-4 device in steady-state heat conditions under electron beam irradiation during needed time interval (hours). It is now possible to measure energy and mass balance, electron beam characteristics, target and vapour shield temperature, removed heat in the target and condenser, plasma parameters (Langmuir probes and optical emission spectroscopy). Analysis of lithium radiation will give information on the relevance of the experimental simulation to the scheme of a radiating divertor. The importance of radiation in energy balance in the above experiments had not been established and one doesn't expect the formation of a shielding layer at rather low power fluxes that have been studied.

3. Lithium flow trough capillary-pore system in cross magnetic field

While a large amount of information is available on liquid metal flows in magnetic fields [4] MHD effects in CPS seem not to have been investigated for divertor application yet. It is known that performance of CPS-based heat pipes placed in magnetic field decrease substantially [5]. Experiments were undertaken to cover this problem in a specially designed facility allowing to study lithium flows in channels and CPS specimens of different structure.

Hydraulic resistance coefficient λ and λ_{CPS} for lithium flow in a circular tube and in a CPS is determent by the known relation [6]:

$$\lambda = \Delta P[(l/d_{\mathrm{H}}) \times (\rho V^2/2)]^{-1} \tag{1}$$

where ΔP is the pressure drop in the experimental section, l and d_{H} in case of circular tube are the length and hydraulic diameter of experimental section, and in the case of CPS, the length and diameter of the CPS mesh wire, ρ and V is the lithium density and average flow rate. The MHD interaction parameter N was taken from the following relations:

$$N = Ha^2/Re \tag{2}$$

where Ha is Hartmann number, Re is Reynolds number.

For circular tube the hydraulic diameter was equal to the inner diameter of the tube, for CPS, to the wire diameter δ [6].

Lithium flow rate for CPS is determent by the relation $V_{\mathrm{CPS}} = V(1 + h_{\mathrm{c}})^2/h_{\mathrm{c}}^2$, where h_{c} is h/δ and h is the size of CPS pore (in this experiment $h = 0.5$ mm, $\delta = 0.2$ mm).

Experimentally determined hydraulic resistance of lithium flow in the circular pipe and in CPS is shown in Fig. 2a as a function of MHD parameter N. For circular pipe with conducting wall our results confirm well known behaviour of lithium flow for different N. The results for CPS placed in the channel as a grid package in transversal magnetic field are also quite clear on the basis of

MHD laws if we consider the CPS as a activator of flow turbulent pulsations. The presence of a CPS in the tube causes suppression of large-scale pulsations. Therefore below $N\sim 1$ this suppression effect is stronger than Hartmann effect and the growth of λ_{CPS} is not important. The Hartmann effect becomes stronger with rising N and at $N>10$ the dependence of λ_{CPS} on N becomes linear. It should be noted that determination of laminar and turbulent flows for CPS would be rather conditional. Though all experimental points fall in the $Re<250$ area, the flow cannot be considered as laminar in a pure sense because lithium overflows the obstacles located chaotically in the package (mesh wires). However, as it is evident from the Fig. 2, the linear dependence of loss factor in the circular pipe occurs at $N\sim 10^2$ and CPS at $N\sim 10$, respectively. This is due to the fact that $Re_{\mathrm{pipe}}>Re_{\mathrm{CPS}}$ and the flow pulsations in the pipe are suppressed at rather high values of magnetic induction. It should be noted that up to $N\sim 1$ the λ_{CPS} increase is not important, and at $N>10$ the experimental data correspond practically to theoretical dependence of λ_{CPS} on N for the pipes with high wall conductivity and it does not depend on the mesh parameters. This may be explained by the values $Ha\gg 1$, $C\gg 1$ for CPS. Hence, for the majority of practical cases if $N>10$ one may take well known relation $\lambda_{\mathrm{CPS}}=2N$ for calculation of hydraulic resistance of CPS in the strong magnetic fields. When $N<1$ the dependence of λ_{CPS} versus N is weakly expressed and exceeds by approximately 1.5–2 times λ_{CPS} at the absence of magnetic field.

The experimental pattern of lithium flow in CPS that have been obtained here are in good correlation with well known MHD laws for flows in pipes and channels. On this basis taking into account the above mentioned features of CPS one can make estimations of MHD effects in protection systems of the tokamak-reactor divertor and first wall in the first approximation.

4. Compatibility of lithium limiter with tokamak plasma

The most representative experiments of the lithium CPS serviceability should be those under tokamak conditions. Experiment in the T-11M tokamak became the first stage of such tests ($I\leq 100$ kA, $\tau\leq 0.1$ s, $B_{\mathrm{T}}=1$ T, $R=0.7$ m, $a=0.19$–0.23 m, $n_{\mathrm{e}}\leq(1.5$–$2)\ 10^{13}$ cm^{-3}, $T_{\mathrm{e}}(0)=0.5$–0.8 keV). The subject of the study was the compatibility of periphery plasma with CPS-based lithium filled limiter.

Lithium CPS limiter represented an oval structure made of multi-layer molybdenum mesh filled with lithium (wire diameter $d=0.1$ mm, mesh size 0.15 mm), and it was introduced into the discharge thus forming a horizontal rail diaphragm similar in geometry to ordinary graphite diaphragm placed besides in an adjacent section (90° in toroidal direction). The experiments with helium as well as with hydrogen discharges have not shown any anomalous lithium erosion channels in its interaction with T-11M tokamak plasma that would exceed greatly its thermal emission from the heated diaphragm.

Analysis of the CPS surface after a series of experiments ($\sim 10^3$ discharges) have shown the absence of signs of the molybdenum mesh (basis of the CPS) degradation (Fig. 4). The CPS-based lithium diaphragm has demonstrated its advantage over the solid one and this was the constant self-healing of diaphragm material surface during operation, namely, lithium film in this case. There are no marked traces of effect of plasma electrons and ions on the CPS basis material. This could indicate the absence of such possible erosion mechanisms of diaphragm as the excessive heating, sputtering by ions and energetic atoms, unipolar arcs and others. Efficient cooling of the CPS basis material by lithium evaporation prevents the surface temperature from achieving melting point value for molybdenum. Besides, the evaporative cooling seems to inhibit initiating of the unipolar arcs and even quench them when initiated. Lithium protective film on the CPS material surface impedes its spraying and prevents molybdenum atoms to be puffed into the tokamak plasma.

The effect of MHD forces on liquid lithium in the CPS that was seen during experiments and manifested in lithium drops loss (see Fig. 3) corresponds completely to plasma confinement conditions and experimental parameters (current through diaphragm — 600 A, $B_T = 1.3$ T) and to the CPS characteristics ($R_{eff} = 75$ μm).

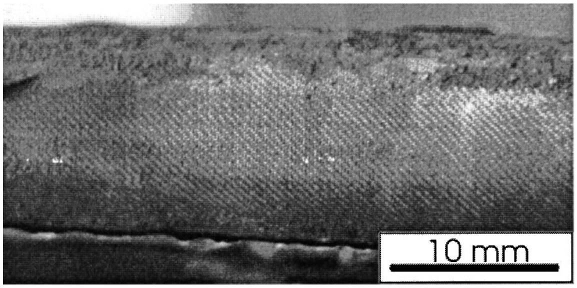

Fig. 3. Lithium limiter surface view after tests (~ 1000 discharges) in T-11M tokamak.

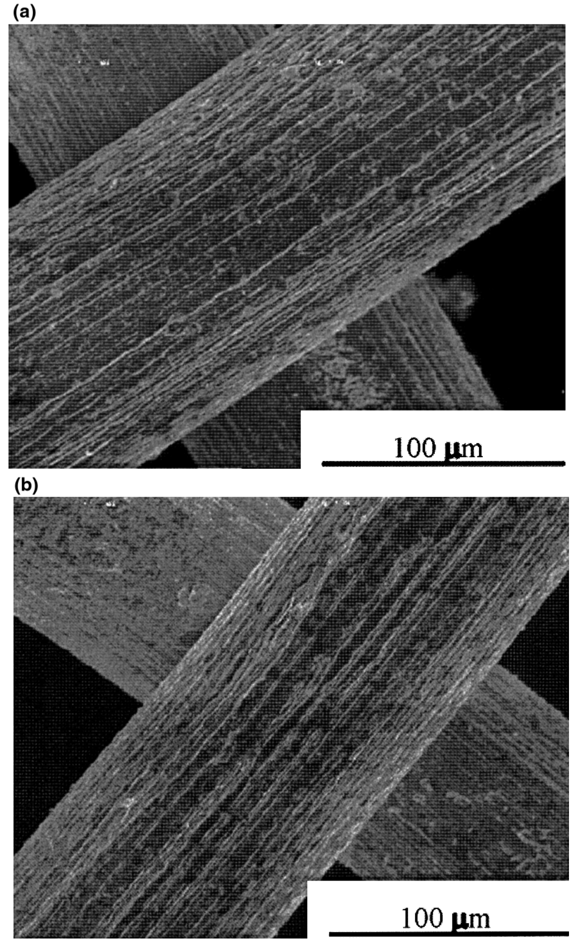

Fig. 4. External layer surface of molybdenum mesh samples from lithium limiter after tests in T-11M tokamak (~ 1000 discharges): (a) outside of plasma interaction zone; (b) ion side of plasma interaction zone.

5. Conclusions

The experimental data obtained here on lithium flows through CPS in transverse magnetic field and on serviceability of lithium CPS under high steady-state heat loads make it possible to arrive close to the development of a lithium divertor target plate models and to conduct experimental simulation of its operation (evaporation, condensation, re-radiation in the lithium plasma, forced cooling, magnetic field).

Experiments in the T-11M have shown, that lithium CPS are compatible with plasma of a tokamak facility and their application will offer solutions for a number of principal issues. So, it gives an approach to the problem of heat removal from the bulk plasma to the first wall of the tokamak chamber as well as to the divertor.

The following stage of lithium CPS study should be their tests as a diaphragm structure and divertor plate models under durable discharge conditions (1 s and more), that is possible in the T-10, TEXTOR and in other tokamaks.

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