Nuclear Materials and Energy 25 (2020) 100834

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Impact of liquid metal surface on plasma-surface interaction in experiments with lithium and tin capillary porous systems

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ARTICLE INFO

Keywords:
High heat flux test
Plasma-facing materials
Lithium
Tin
Capillary-porous systems
ITER
Fusion reactor

ABSTRACT

The lithium and tin capillary-porous systems (CPSs) were tested with steady-state plasma in the PLM plasma device which is the divertor simulator with plasma parameters relevant to divertor and SOL plasma of tokamaks. The CPS consists of tin/lithium tile fixed between two molybdenum meshs constructed in the module faced to plasma. Steady-state plasma load of 0.1 – 1 MW/m^2 on the CPS during more than 200 min was achieved in experiments on PLM which is a modeling far scrapeoff- layer and far zone of divertor plasma of a large tokamak. The heating of the CPS was controlled remotely including biasing technique which allows to regulate evaporated metal influx to plasma. After exposure, the materials of the tin and lithium CPSs were inspected and analyzed with optic and scanning electron micriscopy. Experiments have demonstrated sustainability of the tin and lithium CPSs to the high heat steady state plasma load expected in a large scale tokamak. The effect of evaporated lithium and tin on the plasma transport/radiation was studied with spectroscopy to evaluate changes of plasma properties and plasma-surface interaction.

1. Introduction

For a fusion tokamak reactor, liquid metal (lithium, tin) are attractive as components of the first wall. A liquid metal surface has a higher tolerance to neutron damage, it has reduced erosion and can 'self-heal' from damage during transients like disruptions and ELMs. Capillary porous systems (CPS) with liquid metals [1-4] are used as plasma-faced components of the first wall. The efficiency of the liquid lithium CPS has been demonstrated in experiments on tokamaks T-10 [5], T-11M [3], FTU [6], LTX [7], Magnum-PSI linear devices [8]. However, the reactivity of lithium leads to reactions with impurities (oxygen, nitrogen, etc.) in plasma and on the in-vessel components. It can lead to the solid deposits decreasing the advantageous effects of lithium CPS. Alternative components are liquid tin CPSs. Tin has low melting temperature and improved parameters to use the tin CPS as first wall component. Therefore, comparative tests of liquid lithium CPS and liquid tin CPS in experiments with steady-state thermal plasma should be carried out to predict their behavior in a fusion reactor. The condition of reactor relevant plasma load can not be fully achieved in modern tokamaks, at the same time some relevant tests can be carried out in linear plasma devices to estimate plasma-surface interaction. For such purposes, the PLM (Plasma Linear Multicusp) plasma device is used [9]. In this paper, results of plasma tests of liquid lithium and tin capillary porous systems with steady-state plasma in the PLM plasma device are presented.

2. The PLM device

The PLM device [9] was constructed at National Research University "Moscow Power Engineering Institute" (MPEI) for high-heat flux test of fusion materials including liquid metal components of the first wall. It is a linear plasma trap of an 8-pole multicusp magnetic field with stationary steady-state plasma discharge with parameters similar to the

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https://doi.org/10.1016/j.nme.2020.100834
Received 26 July 2020; Received in revised form 19 October 2020; Accepted 29 October 2020
Available online 4 November 2020

SOL (Scrape-off Layer) and divertor plasma in a tokamak: discharge chamber is of 16/80 cm in diameter/length, the diameter of hot plasma column is of 3.5 cm defined by scraper aperture of anode, magnetic field is of 0.01 Tesla on the trap axis and up to 0.1 Tesla in the cusps, discharge plasma current is of more than 15 A, plasma density is up to 5 $\times$ 10^{18} m^{-3}, electron temperature is up to 10 eV with a fraction of hot electrons of $\sim$ 50 eV, ion plasma flux onto the test materials up to 5 $\times$ 10^{21} $m^{-2}s^{-1}$, plasma heat load on test target samples 0.1–2 MW/m^2 and more, working gas is helium. The test samples are irradiated with plasma discharge of 200 min duration and more. Spectroscopy, Langmuir probes and pyrometers are used to estimate the thermal plasma load onto the exposed CPSs.

3. Experiments with liquid lithium CPS

The lithium CPS made of lithium tile 10x10x1 mm in size fixed between two molybdenum meshs. The module of the CPS is constructed in the cylindrical molybdenum module of 40 mm in a diameter and faced to plasma column in the PLM device, Fig. 1a. The lithium CPS was made similar to that of used in experiments on the T-10, T-11M tokamaks [3-5]. Such CPS construction is proposed to protect plasma-facing components and to provide improved characteristics of the plasma-surface interaction. Steady state plasma load of 0.1 – 1 MW/m^2 on the CPS during more than 200 min was achieved in experiments on PLM which is a modeling condition proposed for a fusion reactor. PLM plasma parameters were as followed: plasma density is of $1\cdot10^{12}$ cm^{-3}, electron temperature 2 eV with a fraction of hot electrons up to 50 eV. The

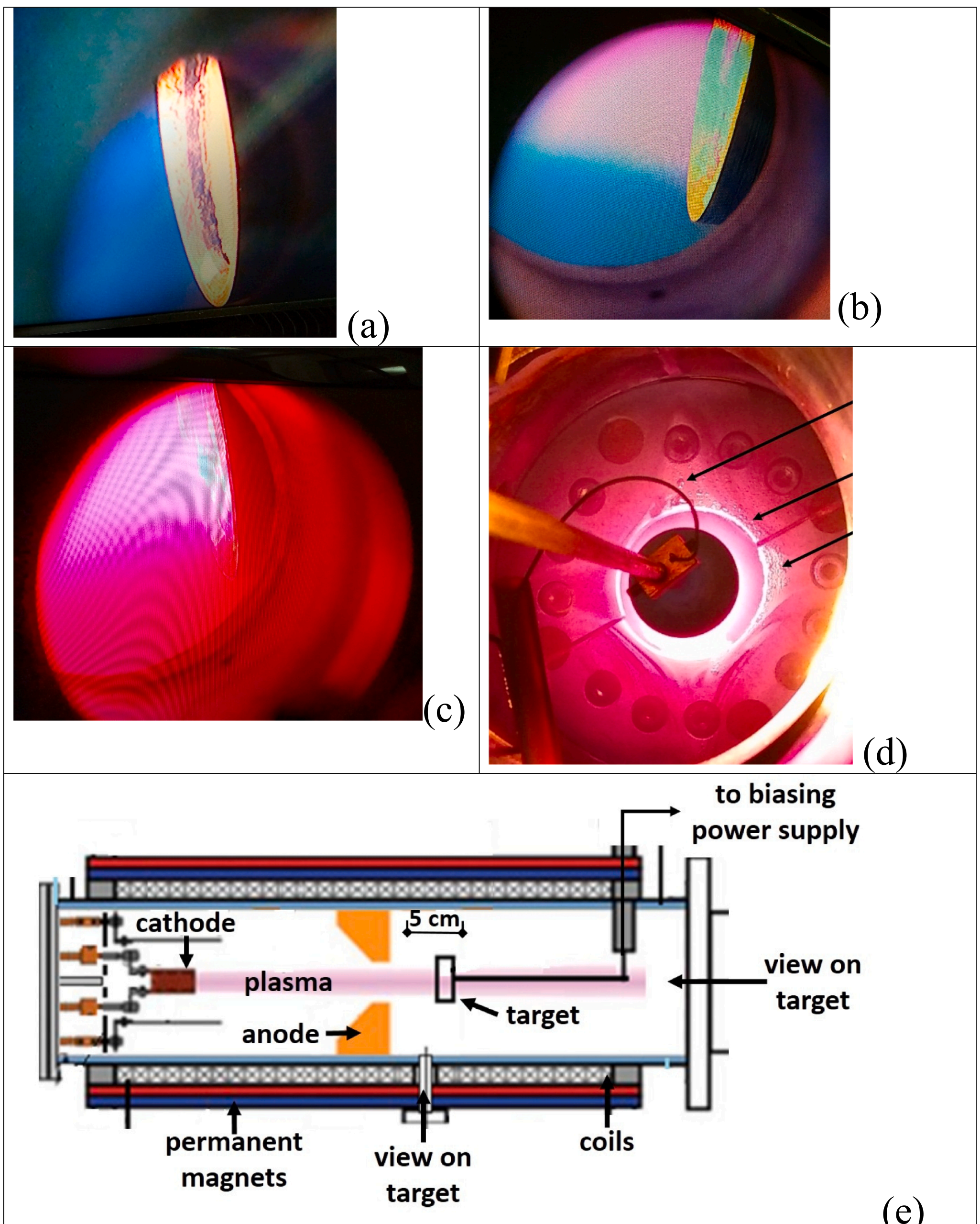

Fig. 1. The lithium CPS tests in helium plasma of PLM device: visible radiation of plasma: (a) CPS temperature 100 °C; (b) CPS temperature 190 °C; (c) CPS temperature 580 °C; (d) lithium drops deposited on the anode, arrow labels indicate the Li droplets; (e) overview scheme of the PLM, the position of the target and views on the target are shown.

module was installed in a plasma discharge near the anode. The heating of the CPS was controlled remotely including biasing technique which allows to regulate evaporated metal influx to plasma. The CPS was ohmically heated by ion and electron current from plasma to the surface due to biasing the CPS module relative to the vessel from −40 Volts to + 10 Volts. During the exposure, optical and pyrometric diagnostics have recorded the heating of the CPS in the range from 100° C to 580° C. The effect of evaporated lithium on the plasma radiation was studied with Langmuir probe and spectroscopy to evaluate changes of plasma properties and plasma-surface interaction. Optical emission of plasma near the surface of the lithium CPS changed in the color from blue to red, Fig. 1, indicating an intense flow of lithium from the surface of the CPS into the plasma. During the tests of the lithium CPS, the optical emission spectra of the lithium from plasma consisted of primarily of the red lines neutral lithium atoms Li I 670.78 nm, Fig. 1c. The intensity of singly ionized Li ions that are present in optical spectra is small and cannot affect in the red color of plasma near the surface of the lithium CPS observed in the experiment.

Lines Li I and Li II were registered by the emission spectrum, Fig. 2, demonstrating lithium flow into plasma column. No molybdenum lines are found in the spectrum. Under the plasma load for ~200 min, significant amount of lithium evaporated from the CPS surface toward the plasma and than deposited on the anode surface and vessel surface. No catastrophic change has been registered in plasma parameters and no disruption of plasma discharge was detected.

The redeposition of lithium vaporized from the CPS surface on the vessel surface of the PLM as droplets was observed, Fig. 1d. The mean free path of Li atoms is ≈10 m and of Li ions is ≈16 cm within plasma are estimated for experimental plasma parameters in the PLM; ionization probability of lithium atoms is 0.1 when crossing the plasma column of 0.35 cm in a diameter. These properties provide lithium re-deposition on the walls and in-vessel components.

After exposure, the construction of the lithium CPSs were inspected and analyzed with optical and scanning electron microscopy. Inspection of CPS modules after testing did not reveal serious damage of molybdenum mesh, Fig. 3. It confirmed the stability of the materials and likely the effect of screening the surface of the CPS with a layer of lithium vaporized into near surface plasma. Experiments have demonstrated sustainability of the lithium CPS to the high heat steady-state plasma load expected in a large-scale tokamak.

4. Experiments with liquid tin CPS

The tin CPS was manufactured as a tin tile of 15x15x1 mm in size, located between two molybdenum meshs, Fig. 4a. Such tin CPS construction is proposed as a plasma-facing component of the first wall under the plasma load, see, e.g., [2,18]. The CPS was fixed in stainless steel (of grade AISI 321) cylindrical module with a diameter of 20 mm and a height of 2 mm, Fig. 4a. A reference tin test plate of $3 \times 3 \times 3$ mm^3 was fixed under the module.

The tin CPS was tested in helium plasma of the PLM for 3 h with plasma parameters: density is of $1 \cdot 10^{12}$ cm^{-3}, electron temperature is of 2–5 eV. During the exposure, pyrometers registered the CPS's heating temperature of ~ 600 °C [10] significantly higher than the melting point of tin (231.9 °C). The melting of the reference tin module fixed under the bath was visually observed, Fig. 5a. Plasma load ~ 1 MW / m^2 was estimated from the melting of the stainless steel module, Fig. 4b, using typical heat load estimations, see [11-14].

To estimate an impact of tin CPS on plasma optical spectra were measured from the location over liquid tin surface of the CPS. Atoms and ions of tin in plasma were registered by spectra measured from a zone 3 mm above the tin CPS, Fig. 5b, Sn II spectral lines (362.05 nm and 371.5 nm). Atoms and ions of tin in plasma were registered by spectra. Spectra and optical radiation of plasma column, Fig. 5b, support a view that upon evaporation from the CPS, tin is localized near the surface.

Molybdenum mesh and stainless module of the tin CPS were inspected after exposure. The melting of the stainless steel module under thermal plasma load (zone of several square millimeters) was detected, Fig. 4b. At the same time, the molybdenum mesh and construction of the tin CPS was not damaged. No significant losses of tin from the CPS mesh was detected. The observations of spectra and post-mortem analysis of CPS materials open the issue if the vaporized tin atoms / ions create a shielding effect over the CPS's surface. Considering this issue, it should be taken into account that there are no dominant lines of chemical components of stainless steel in the optical spectra. Plasma tests has demonstrated the sustainability of the tin CPS under steady-state plasma load. The relevancy of liquid tin CPS for protection of plasma-facing components should be tested in divertor tokamak as well. The mean

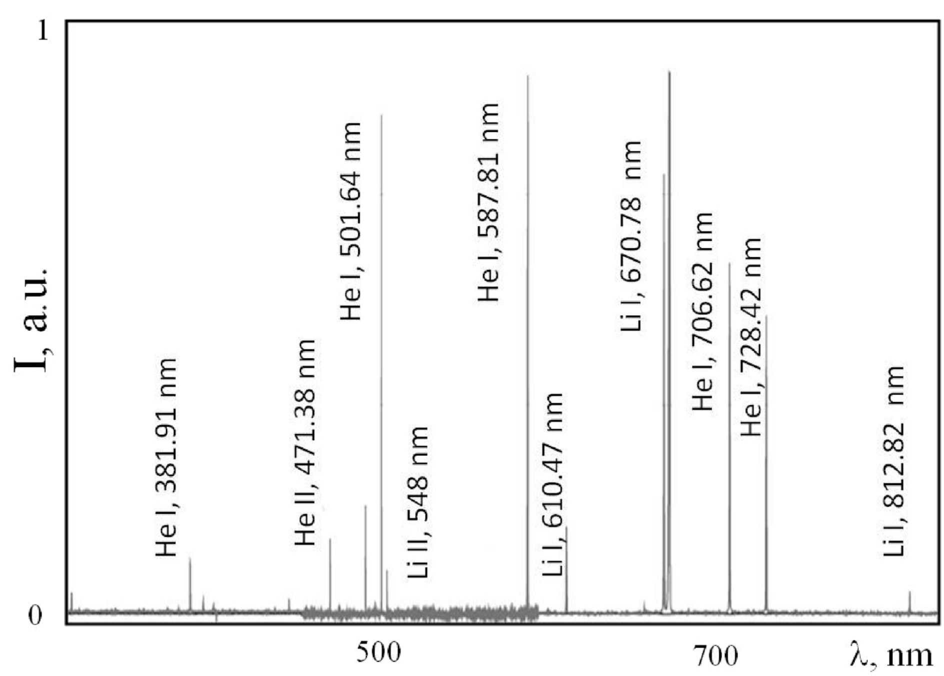

Fig. 2. Plasma test of lithium CPS in PLM device: emission spectrum of plasma radiation.

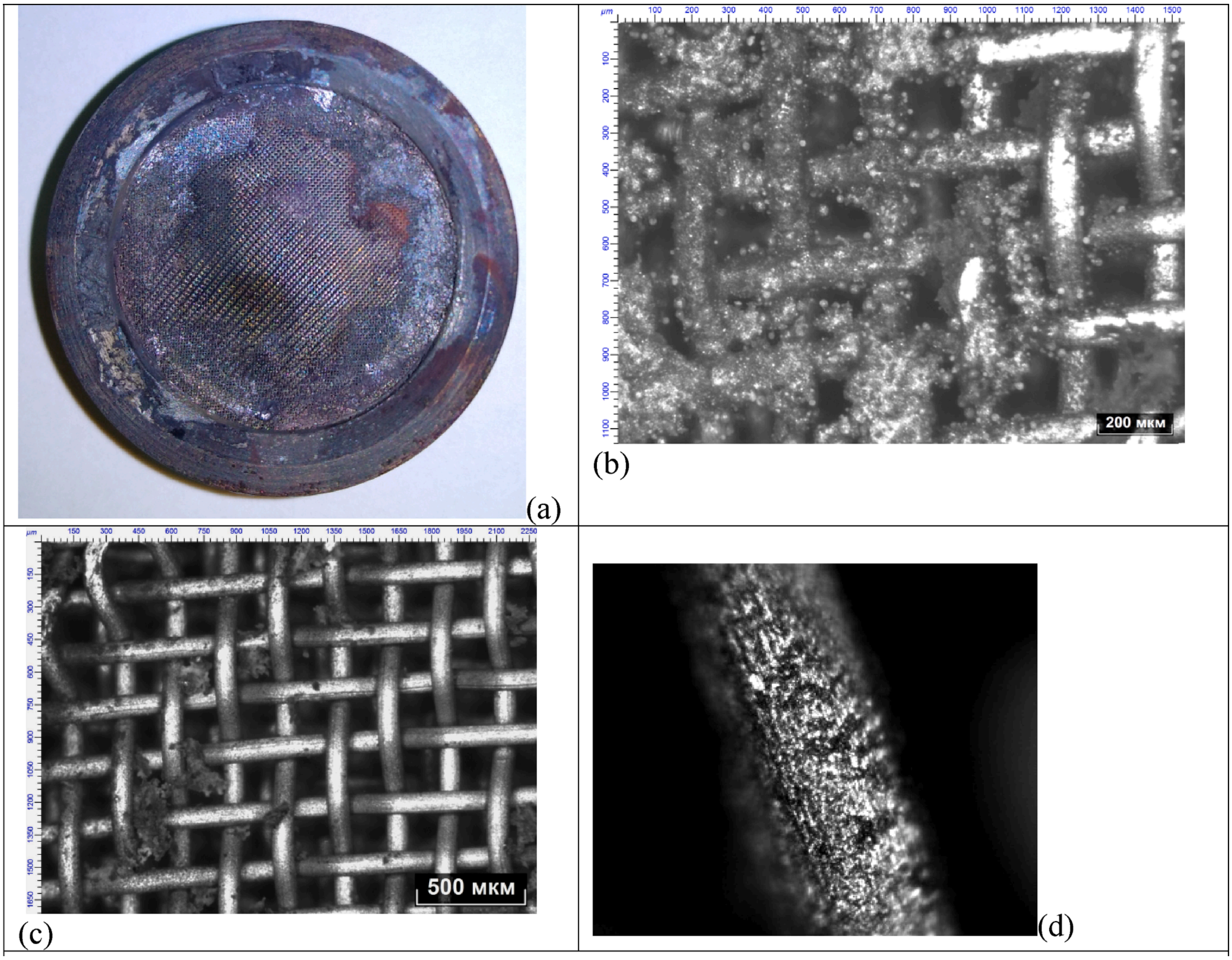

Fig. 3. The lithium CPS after irradiation with plasma for 200 min in PLM device: (a) - module overview; (b) molybdenum mesh with residues of lithium; (c) - molybdenum mesh after the evaporation of lithium; (d) - the molybdenum wire surface of the mesh.

Fig. 4. Tin capillary-porous system: (a) before testing, (b) after plasma irradiation in the PLM.

free path of Sn atoms is ~5–10 m and of Sn ions is ~10 cm within plasma are estimated for experimental plasma parameters in the PLM. These properties provide tin re-deposition on the walls and in-vessel components.

The redeposition of tin on the vessel and impact of impurities on near-wall plasma should be investigated to evaluate effect of tin CPS, see discussions on PSI in [15-17]. It should be mentioned as well that the possible changes in behavior of Sn ions are expected in H or D plasmas instead of He plasma. The observations of the tin CPS heated up to ~600 °C and melting of stainless steel holder are related to the problem of heat and mass transfer under powerful plasma load including local overheating. Boiling point of tin (2602 °C) is higher than melting point of stainless steel (1420 °C). At the same time heat of vaporization of tin (59 kJ/kg) is less than that of stainless steel (84 kJ/kg). The high boiling point of tin much above tin temperature of ~600 °C achieved in our experiment is likely the reason why is nearly no tin evaporated. In future experiments, an amount of evaporated tin and heat transfer will be estimated to consider a vapor shielding effect, which can be achieved in a reactor. Heat transfer under a plasma load on the tin CPS is not only a steady-state process: a pulse load dynamics is involved in the process developing on broad spatial and temporal scales starting from ~10 microns and microseconds during unipolar arcs. The damage of the tin

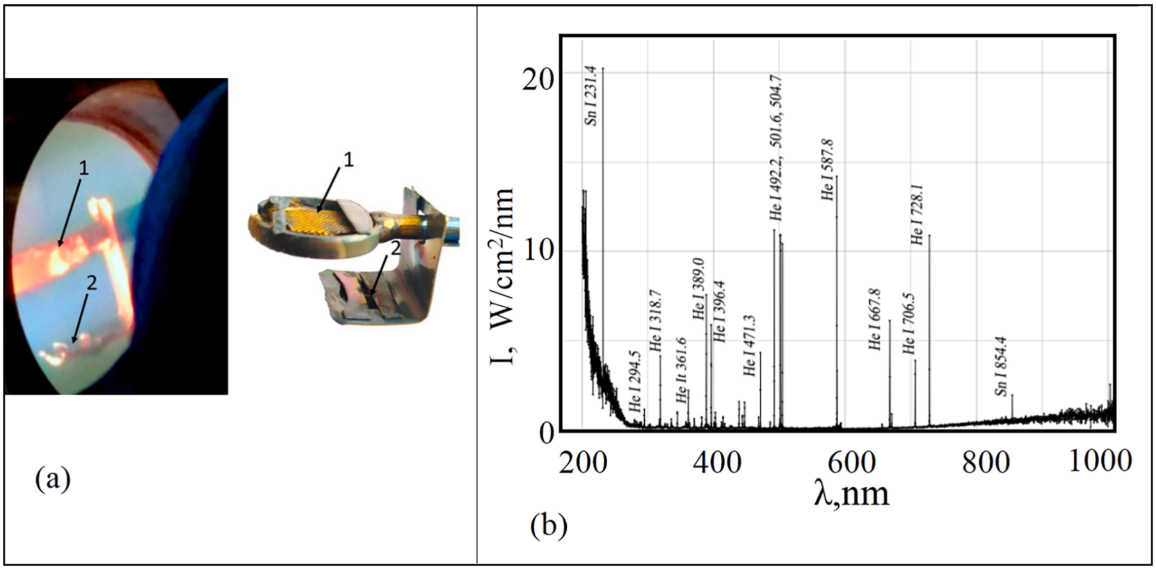

Fig. 5. Tin CPS test in helium plasma of PLM device: (a) view of plasma column and tin CPS (left) and the arrangement of the tin CPS after the plasma testing (right) 1 — the tin CPS fixed in stainless steel cylindrical holder and 2 — reference tin test plate in the holder fixed under the tin CPS holder. (b) emission spectrum of plasma radiation from location over tin CPS's surface, Sn II spectral lines - 362.05 nm and 371.5 nm

CPS components (such as the molybdenum mesh, the tin plate in the mesh, the holder) depends on vapor shielding effects of component material under powerful plasma load and thermal conductivity of the materials. A high level of thermal conductivity of molybdenum mesh is likely providing quick relaxation of the local overheating; the surface of the stainless steel holder is melted due to overheating and the lower thermal conductivity of stainless steel. A level of local thermal load depends on the plasma flux inclination angle regarding to the magnetic field. Further additional studies of heat transfer processes during testing of the tin CPS are required to explain the observations of inhomogeneous damage of the tin CPS components including melting of the stainless steel holder and the sustainability of the tin CPS. The results should be taken into account to choose an optimal arrangement of experiment and testing relevant to a condition expected in a reactor.

5. Conclusions

The lithium and tin capillary-porous systems were tested with steady-state plasma in the PLM plasma device which is the divertor simulator with plasma parameters relevant to divertor and SOL plasma of tokamaks. The CPSs consist of tin and lithium tiles fixed between two molybdenum meshs constructed in the module faced to plasma. Steady-state plasma load of 0.1 – 1 MW/m^2 on the CPS during more than 200 min was achieved in experiments on PLM device with plasma parameters relevant to far scrape-off-layer and far zone of the divertor plasma of a large tokamak relevant for a fusion reactor, see e.g. discussions and references in [19,20], The plasma load on the CPS up to 1 MW / m^2 led to surface heating up to 700 °C in experiment with lithium CPS and more than 600 °C in experiment with tin CPS. The heating of the CPS was controlled remotely including biasing technique which allows to regulate evaporated metal influx to plasma. Under such load liquid metal from the CPS surface vaporized to plasma column. After exposure, the materials of the tin and lithium CPSs were inspected and analyzed with optic and scanning electron micriscopy. The effect of evaporated lithium and tin on the plasma transport/radiation was studied with spectroscopy to evaluate changes of plasma properties and plasma-surface interaction. Lithium and tin ions was registered by optical emission spectra from plasma. The redeposition of vaporized lithium was detected on the PLM in-vessel components.

The observations of spectra and post-mortem analysis of CPS materials open the issue if the vaporized atoms / ions create a shielding effect over the CPS's surface.

The experimental tests have confirmed sustainability of lithium and tin CPSs' exploiting as plasma-facing components under steady-state plasma and promising in-vessel component of a fusion reactor. The results of this study can be used to assess the performance of the DEMO reactor in scenarios with liquid metal CPS in the far zones of the divertor, where the thermal load will not lead to the damage of the CPS components. In such scenarios, it is necessary to ensure the feeding of the CPS with liquid metals taking into account a vapor shielding effect. Such scenarios should be simulated in further experiments with liquid metal CPS under steady-state plasma loads in divertor simulators including the PLM.

CRediT authorship contribution statement

V.P. Budaev: Supervision, Conceptualization. **I.E. Lyublinsky:** Conceptualization. **S.D. Fedorovich:** Methodology, Investigation, Writing - original draft. **A.V. Dedov:** Project administration. **A.V. Vertkov:** Resources. **A.T. Komov:** Conceptualization. **A.V. Karpov:** Investigation. **Yu.V. Martynenko:** Conceptualization, Methodology. **G. Van Oost:** Methodology. **M.K. Gubkin:** Investigation. **M.V. Lukashevsky:** Software, Visualization. **A.Yu. Marchenkov:** . **K.A. Rogozin:** Investigation. **G.B. Vasiliev:** Visualization, Investigation. **A.A. Konkov:** Investigation. **A.V. Lazukin:** Investigation. **A.V. Zakharenkov:** Investigation. **Z.A. Zakletsky:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The plasma tests on the PLM were supported by the RSF grant No. 17-19-01469, the CPSs manufacturing were supported by ROSATOM, the material tests were supported by the RFBR grant No. 19-29-02020, the ASNI construction on the PLM was supported by the RF Megagrant No. 14.Z50.31.0042, optical measurements were supported by the Ministry of Science and Higher Education of the Russian Federation project No. FSWF-2020-0023.

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