

Methodology of the Experiments to Study Lithium CPS Interaction with Deuterium Under Conditions of Reactor Irradiation

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Abstract

Problems of plasma-facing materials degradation and in-vessel element destructions, tritium accumulation and plasma pollution can be overcome by the use of liquid metals with low atomic number. The best candidate as a material for divertor receiving plates and other in-vessel devices is lithium. One of the problems associated with the use of such lithium systems in the fusion reactors is to determine the parameters of the working gases interaction with plasma facing surfaces under conditions simulating real operation, i.e. under conditions of neutron and gamma radiation. This paper describes a technique of the reactor experiments to study lithium capillary-porous systems (CPS) interaction with deuterium under neutron irradiation. The neutron-physical and thermophysical calculations were the basis for the design development and further manufacture of a unique irradiation ampoule device with a lithium CPS sample. Several experiments were performed to calibrate the deuterium fluxes through experimental cell with lithium CPS; and preliminary results of these experiments were obtained.

1. Introduction

Currently, in the world, during the implementation of ITER (International Thermonuclear Experimental Reactor) and DEMO (Demonstration Power Plants) international projects, large-scale studies of the properties of structural materials are being carried out. Operation of the existing thermonuclear reactors has shown that the use of W, Be and C as a plasma-facing material (PFM) does not fully solve such problems as: degradation of PFM and destruction of products based on them; plasma contamination by erosion products; accumulation of tritium in structural materials. However, these problems can be overcome by using liquid metal with a low charge number as PFM. Based on the results of earlier studies [1–3], lithium is the best for use as a structural material of the intrachamber devices of fusion reactor. The advantages of

using lithium as PFM are confirmed by the results of studies conducted at plasma-physical installations of T11-M (Troitsk, Russia), FTU (Frascati, Italy), NSTX (Princeton, USA), EAST (Hefei, China), T-10 (Moscow, Russia), TJ-II (Barcelona, Spain), KTM (Kurchatov, Kazakhstan) [4–11]. In most cases, the realization of the advantage of lithium over conventional PFM is based on the use of the so-called lithium capillary-porous system (CPS), a fundamentally new material in which liquid lithium is stabilized in a matrix of solid porous material by capillary forces [12].

An important task in the study of plasma-wall processes is to research the hydrogen isotopes interaction with lithium capillary-porous systems (CPS) under reactor irradiation [13–15]. The first phase of the studies was to develop a technique for lithium CPS sorption experiments at deuterium pressure of 0.1–100 Pa and samples' temperatures of 100–800 °C.

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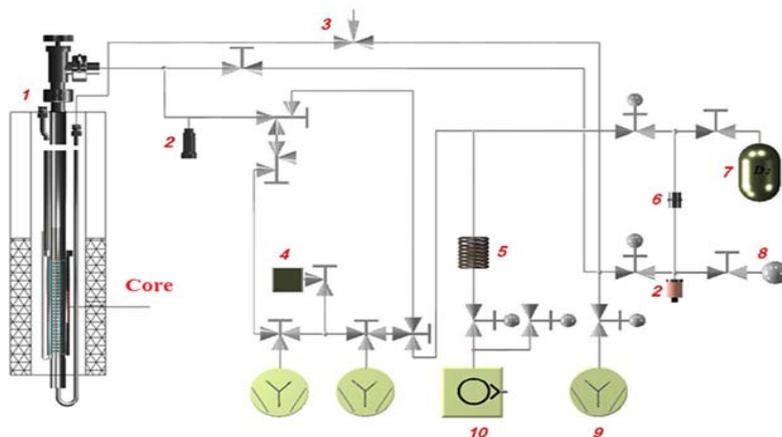


Fig. 1. The scheme of the LIANA experimental test-bench: 1 – ampoule device; 2 – pressure sensors; 3 – gas supply regulator (inlet valve); 4 – mass spectrometer; 5 – nitrogen trap; 6 – palladium-silver filter; 7 – gas cylinder; 8 – tank with spectrally pure gas; 9 – high-vacuum pumps; 10 – forevacuum pump.

2. Experimental facilities

As a source of neutron and gamma radiation in experiments the IVG.1M research reactor [16] was used. A flux of neutrons in the core center of the IVG.1M reactor at power level of 1 MW is given in Table 1 below.

Table 1

A flux of neutrons in the core center of the IVG.1M reactor at power level of 1 MW

Energy group	0.67 eV	0.67 eV- 0.1 MeV	0.1-10 MeV	Integral flux
Neutron flux, 1/(cm ² · s)	0.15 · 10 ¹⁴	0.07 · 10 ¹⁴	0.04 · 10 ¹⁴	0.25 · 10 ¹⁴

Reactor experiments were conducted at the LIANA experimental test-bench (Figs. 1 and 2). It allows to implement the experiments to study the

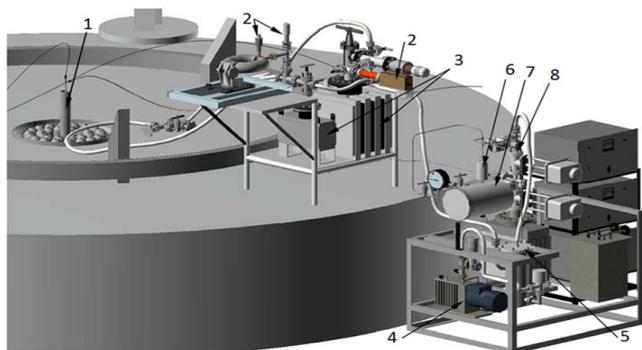


Fig. 2. 3D-model of the LIANA experimental test-bench: 1 – PEC; 2 – mass-spectrometers; 3 – high vacuum pumps; 4 – fore vacuum pumps; 5 – nitrogen trap; 6 – hydrogen filter; 7 – tank for spectrally pure hydrogen; 8 – vacuum valves.

processes of hydrogen isotopes interaction with structural materials of fusion and fission reactors using hydrogen permeability (HP), gas absorption and gas thermal desorption (TDS) methods in temperature range from 20 to 1300 °C.

2.1. Neutron-physical and thermal-physical calculations for determination of the parameters of reactor experiments

Neutron-physical and thermophysical calculations with proposed design of ampoule device (AD) were conducted during the development of the experiments (AD).

The graphical view of the developed model of reactor core for neutron-physical calculations is given in Fig. 3. The computational model was constructed using MCNP5 software.

The calculation model was prepared taking into account the characteristic design features of a fuel assembly of water-cooled technological channel (WCTC), the reactor core and control units, the temperature conditions of the reactor components, also it included the program options, which are most accurately simulating neutron-matter interaction processes. The main features of the calculation are given below:

- WCTC fuel assembly, reflectors, followers, control drums (CD), and physical experimental channel (PEC) have a heterogeneous structure;
- two-zone profiling of the fuel assembly along a radius;
- temperature of fuel and reactor's structural elements is assumed equal to 293 K;
- possibility is provided to change the position of the system rods, that compensate for reactivity, and to change the angular position of CD from

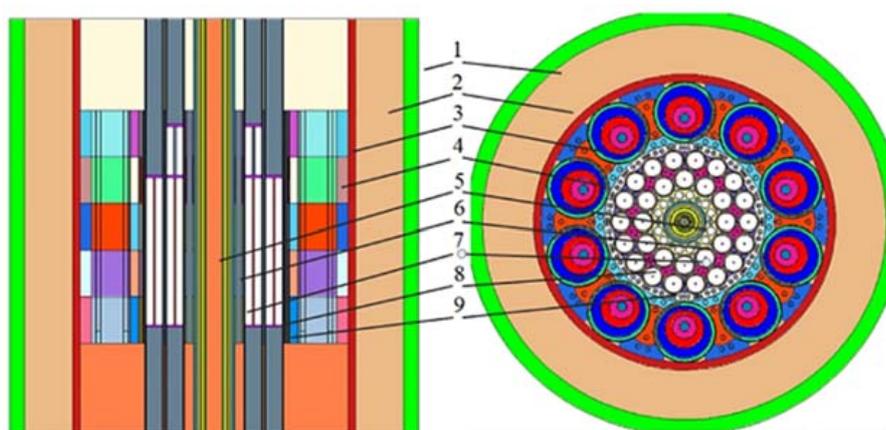


Fig. 3. Calculation model of the IVG.1M reactor: 1 – external body; 2 – side screens; 3 – reflector; 4 – control drums; 5 – physical experimental channel; 6 – central assembly; 7 – reactivity compensation rods; 8 – fuel elements; 9 – water-cooled technological channels.

Table 2
Parameters of Calculated Zone

Zone #	Zone Name	Material
1	External vessel	Steel 08Cr18Ni10Ti
2	Side screens	Steel 08Cr18Ni10Ti and water
3	Reflector	Beryllium
4	Control drums (CD)	Beryllium Titanium-gadolinium alloy + Boral
5	Physical experimental channel (PEC)	Beryllium
6	Central assembly	Alloy E125
7	Reactivity Compensation Rods (RCR)	Beryllium
8	Fuel elements	
8.1	Fuel element cladding	E110
8.2	Fuel element kernel	U-Zr (uranium-zirconium) alloy
9	Water-cooled technological channel (WCTC)	30 FA
9.1	WCTC Case	AlMg-5
9.2	Block	AlMg-6
9.3	End grids	AlMg-6+H ₂ O
9.4	Fillers for fuel element wrapping	E110
9.5	Central rod	E110

0° (the absorber elements are directed toward the reactor core) to 180° (the absorber elements are directed in the opposite direction from the reactor core). Rotation of CD is performed clockwise when overlook the reactor;

– ENDF/B-VI.6 libraries have tolerances with an error of less than 1% in linear interpolation (linear interpolation is used in the program to obtain cross sections at the required energy);

– for such elements as hydrogen and beryllium, thermal libraries $s(\alpha, \beta)$ are used, which in the best way describe the processes of thermal neutron scattering on molecules in crystal structures.

The materials of the reactor core elements used in the calculations are indicated in Table 2.

In calculations the effect of ⁶Li amount on the reactor reactivity was estimated; the results of calculations are shown in the Fig. 4.

It should be noted that the dependence of sample's weight on the reactor reactivity is nonlinear, so lithium CPS does not much affect the reactivity.

Thermal calculations of the AD were carried out using the ANSYS Fluent v.14 software complex, which is based on the finite volume method and allows to calculate the thermal and hydrodynamic parameters of the investigated system. During the

thermophysical calculations the temperature field in active cell of AD with lithium CPS for reactor power levels 1, 2 and 6 MW was calculated. The results of calculations are shown in Fig. 5.

According to the calculation results, it can be concluded that in reactor experiments with this AD design, the temperature gradient over the lithium CPS sample is almost the same for different reactor thermal power levels.

However, it should be noted that, as expected with increasing reactor power, the maximum temperature of the experimental cell increases, which in turn was 677, 843, 1170 °C for 1, 2 and 6 MW, respectively. Also, with a rise in the reactor power, a small change in the temperature profile of the experimental cell was noticed, which is most likely due to convective heat transfers associated with

an increase in the contribution to the overall heat balance of the nuclear reaction of thermal neutrons with ${}^6\text{Li}$.

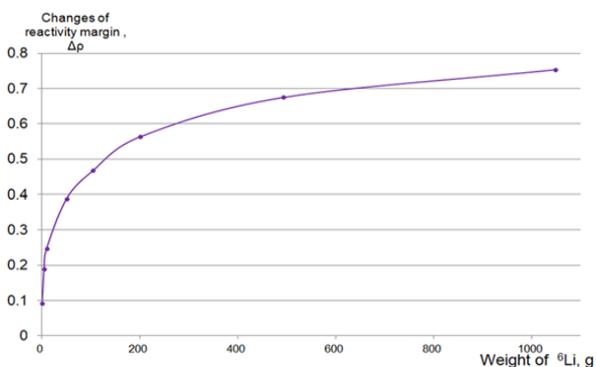


Fig. 4. Change of reactor's reactivity margin depending on the weight of ${}^6\text{Li}$ sample.

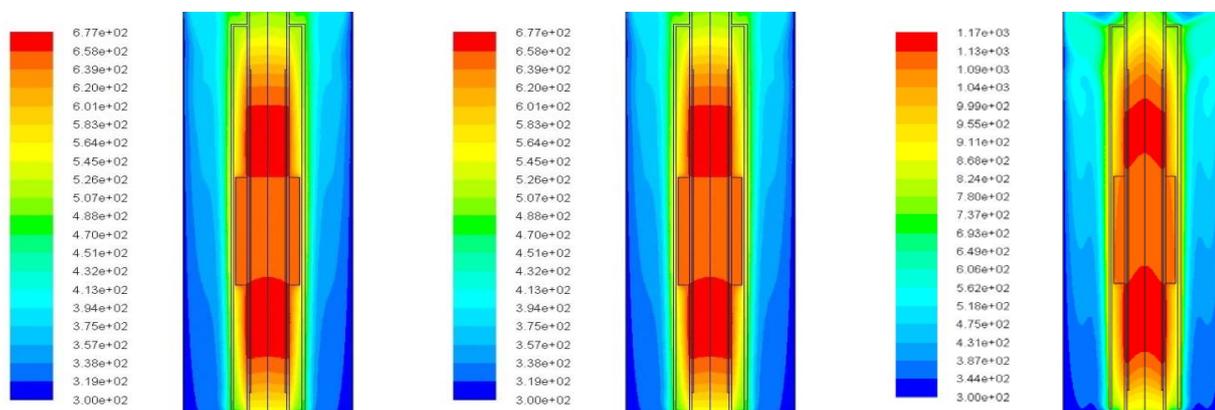


Fig. 5. Temperature field of ampoule device under various operation modes of reactor: (a) – reactor power 1 MW; (b) – reactor power 2 MW; (c) – reactor power 6 MW.

Based on the calculation results, an experimental irradiation device with a lithium CPS sample was developed. The scheme and 3D model of the AD are shown in Fig. 6.

The sample has a tubular shape, because this shape is the best way to perform reactor sorption experiments with lithium CPS.

To conduct the reactor tests of lithium CPS, the irradiation ampoule device with the manufactured sample was loaded into the central loop channel (PEC) of the reactor IVG.1M. Figure 7 shows the ampoule device connected with the systems of LIANA test bench, placed into PEC.

The ampoule device was loaded in such a way that the center of the reactor core coincided with the center of the tubular sample of lithium CPS. After loading and implementation of all the necessary preparatory pre-start procedures, a reactor experiment was conducted. The reactor experiment

was carried out by the differential sorption method at the experimental test-bench LIANA.

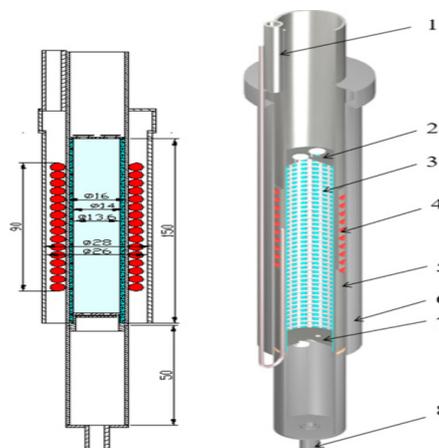


Fig. 6. Scheme and 3D model of the AD: 1 – cooling tract; 2 – top screen; 3 – CPS; 4 – heater; 5 – ampoule vessel; 6 – cooling case; 7 – bottom screen; 8 – deuterium supply tract.

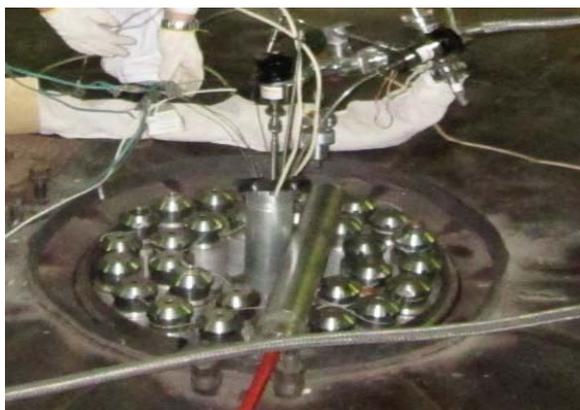


Fig. 7. Ampoule device placed into PEC.

3. Methodical experiments

The purpose of the methodical experiments was to test the technique of reactor experiments, and in particular to obtain time dependences of the partial pressure changes of deuterium in AD over lithium CPS, at a steady flow of spectrally pure deuterium through the sample at different temperatures.

The procedures of methodical experiments were as follows:

1) the chamber is continuously pumped out (at a pressure of residual gases less than 10^{-6} Torr), the gas phase spectrum in the chamber is registered during pumping process;

2) the deuterium flux is fed into the chamber with the partial pressure level about 10^{-5} – 10^{-3} Torr;

3) then, at the selected deuterium flow level, the sample is consistently heated in the range of temperatures from 250 to 550 °C, the change in the partial pressure of deuterium in the chamber is registered;

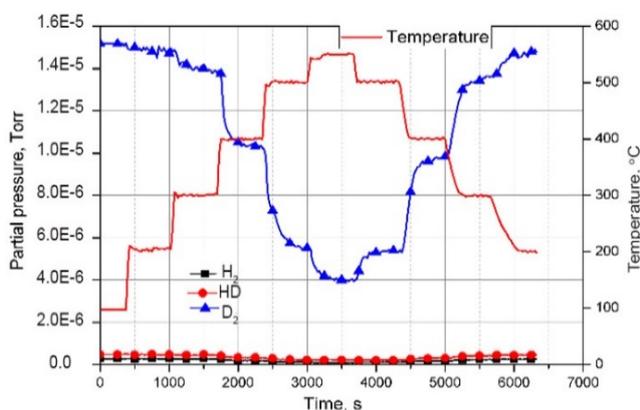


Fig. 8. Time dependence of deuterium partial pressure change in the chamber on a temperature of lithium CPS sample at a stationary deuterium flux into the chamber ($\sim 2.7 \cdot 10^{-11}$ mol/s) (for one experimental cycle).

4) after that the sample is cooled sequentially to the room temperature;

5) a series of experiments is carried out according to above scheme;

6) in the end of experiment the sample is heated to a temperature of 700 °C.

The results of methodical experiments on the sorption of deuterium by lithium CPS are shown in Figs. 8 and 9.

The results of methodical experiments on the thermal desorption of deuterium from lithium CPS are shown in Fig. 10.

After the analysis of the methodical experiments, it can be highlighted:

1. The deuterium partial pressure reduction in the continuously pumped chamber was observed when temperature of lithium CPS increased (at constant level of deuterium flow into the chamber);

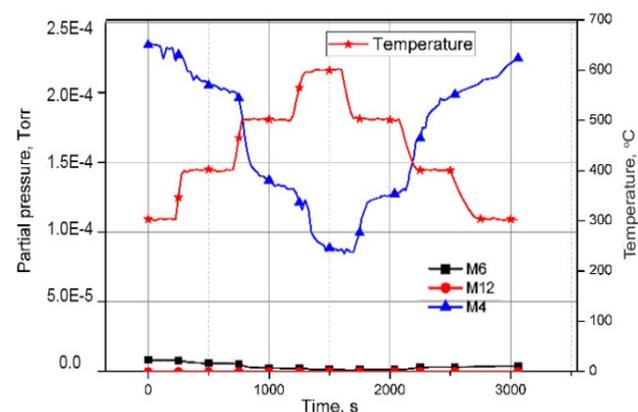


Fig. 9. Time dependence of deuterium partial pressure change in the chamber on a temperature of lithium CPS sample at a stationary deuterium flux into the chamber ($\sim 4.5 \cdot 10^{-10}$ mol/s) (for one experimental cycle).

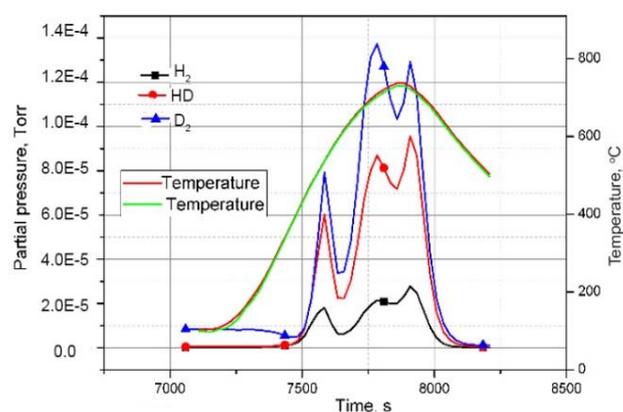


Fig. 10. Time dependence of deuterium release in the process of temperature desorption from a lithium CPS sample.

2. The time of establishing the equilibrium value of deuterium pressure in the chamber depends on the temperature of the lithium CPS and decreases with increasing temperature of the sample;

3. There was a well repeatability of experiments for all studied levels of deuterium flows into the chamber (for more than 10 cycles of experiments);

4. It was concluded, that the deuterium flow into the chamber in the range of 10^{-11} – 10^{-10} mol/s (corresponding to the deuterium pressure in the chamber 10^{-5} – 10^{-4} Torr) is methodically the most convenient pressure level for reactor experiments.

According to the preliminary estimations and the data obtained in thermal desorption experiments, it should be mentioned that:

1. When the lithium CPS was heated after saturation experiments, a complex pattern of H_2 , D_2 and HD release was observed, consisting of three peaks. The release peaks for different molecules have the same nature and temperatures.

2. The largest peak of deuterium release (at a temperature of ~ 820 °C) is probably associated with the moment of the beginning of LiD molecule dissociation.

4. Conclusions

As the result of this work the neutron-physical and thermal-physical calculations were performed; selection of the mode for reactor experiments was done. The new design of the experimental cell, which allows to carry out the experiments on tritium generation and release from lithium CPS under conditions of reactor irradiation at the temperatures above 500 °C was developed. The preliminary experiments on determination of the temperature dependence of gas composition changes in the chamber with lithium CPS under supply of different flows of deuterium were carried out. At the next stage of investigation using this methodology a series reactor experiments will be carried out, in which a pattern of tritium release in the form of tritium-containing molecules DT, T_2 will be obtained.

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