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Journal of Nuclear Materials 233-237 (1996) 650-654

journal of nuclear materials

Research of the capillary structure heat removal efficiency under divertor conditions

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Abstract

Experimental models of capillary structure for liquid metal fusion reactor divertor simulation have been designed, manufactured and tested in order to estimate the behaviour and possibilities of plasma-facing components based on lithium capillary system at long-pulse high heat load. The power load on the capillary target structures up to 50 MW/m^2 was provided by electron beam with electron energy $\leq$ 10 keV. The exposition-time was up to several minutes and was limited by the lithium quantity in the supply vessel. The operation parameters of the models determined in the experiments are in accordance with there design estimations. The tests of various model constructions at the divertor relevant power loads have shown promise for the new concept of a divertor taking into account long life and reliability.

1. Introduction

The resistance of structure materials in power receiving units of a thermonuclear reactor is one of the most important problems for the tokamak-reactor. The main part of thermonuclear energy in the ITER is supposed to be irradiated to the walls of the divertor and from the main chamber when argon or the neon are puffed into divertor. The total power load on the divertor plates will not exceed 5 MW/m^2 in a steady state operation and 15 MW/m^2 in pulsed mode with 10 s duration of pulses [1]. Nevertheless up to now, there is no self-consistent solution of the divertor problem because the heavy gas puffed in the divertor as well as the atoms of the divertor plates structure materials sputtered by the high energy particles will penetrate to the main reactor chamber and they can substantially impair the plasma burning regime. For example, in tokamak experiments, the neon puff in divertor loads to the rise of the hot plasma effective charge. The increase of the Z_{eff} in the reactor can extinguish the thermonuclear reactions. So, there are no reasons to suppose that the divertor problem will be solved in the ITER by applying the 'sacrificial' materials for the divertor plates such as tungsten, graphite and beryllium.

In the DEMO reactor, the situation is more complex because the heat loads on the divertor plates become essentially higher and the alternative divertor concept based on the evaporation and radiation seems low.

Here, some experimental results are given in validation of a new divertor concept. This concept is based on the capillary structure applied on the cooling of the divertor plates by evaporation of lithium [2].

As the first step of the new concept validation, tests have been done with a lithium capillary system under electron beam impact at the power load up to 50 MW/m^2, i.e. at the heat loads much higher than that for the ITER divertor.

2. Experimental

The experiments were performed in two devices — in the vertical electron beam welding machine ELU-9 with a power 10 kW in maximum, and in the SPRUT device with

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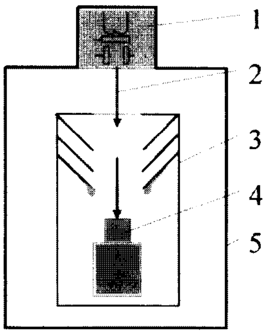
PII S0022-3115(96)00050-5

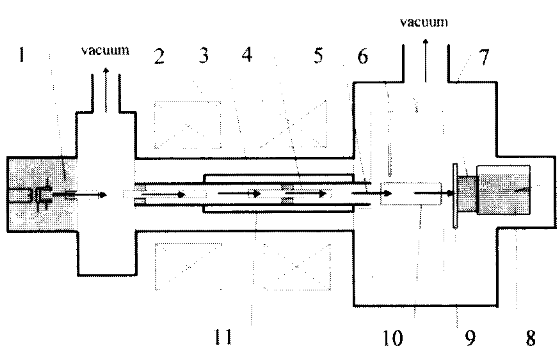


1. Electron beam source
2. Electron beam
3. Lithium vapor condenser
4. Target
5. Vacuum vessel

Fig. 1. The ELU-9 experiment scheme.

20 kW steady state horizontal electron beam in a longitudinal magnetic field of 0.25 T. The schemes of the experiments are given on Fig. 1 and Fig. 2. In both cases, electron beams were generated with tungsten cathodes and were accelerated to an energy up to 9 keV. The beams were transported to vacuum chambers equipped with refrigerating condensers. In the ELU-9, the condenser was not cooled. In the SPRUT device, the condenser had forced water cooling and was designed to condense lithium evaporated from the surface of the capillary system in order to limit the lithium ion flux into the electron gun.

In the SPRUT experiments, the electron beam after the condenser passed into the next zone surrounded with a none cooled cylinder shield. The lithium capillary target was mounted in it, the evaporating surface was turned to the electron beam. The evaporated lithium was condensed in the condenser and in the shield cylinder. The shield temperature and the lithium target temperature were registered in a number of points with thermocouples. The shield had a slot for optical observations and for video registration of the lithium radiation. A single Langmuir probe was installed in the shield zone close to the beam boundary. The shield and the lithium target itself were electrically isolated from each other and from the ground to enable the separate measurements of the currents.



1. Electron beam source
2. Magnetic system
3. Vacuum vessel
4. Differential vacuum resistance
5. Electron beam
6. Lengmur's probe
7. Lithium vapor condenser
8. Target
9. Capillary surface
10. Viewing window
11. Water cooling condenser

Fig. 2. The SPRUT experiment scheme.

The experiments were performed at pressure 10^{-3} Pa in the chamber. The current density radial distribution in the beam was measured with a moving probe in the SPRUT special experiments. The beam diameter at the irradiated surface was 18 and 15 mm. In the ELU-9, the beam cross section was 5×9 mm.

The following diagnostic methods were used in the SPRUT experiments with capillary targets: monitoring of the integral spectrum radiation of lithium atoms and ions in the vicinity of the receiving surface; videofilm of the process of the beam-target interaction in time; the time diagrams of the gun accelerating voltage, of the beam current and of the target current; ion saturation current measurement with Langmuir probe at $-(10–20)$ V bias in the plasma cloud at 7 cm from the evaporating surface; temperature measurements with thermocouples in the structure elements.

3. Lithium capillary targets

Three types of target have been developed and manufactured for these experiments. The targets are schematically shown in the Fig. 3. The target type 'a', Fig. 3a, was used in the ELU-9 device with the vertical electron beam. It had a vertical cylindrical vessel filled with lithium and a target assembly of 16 mm in diameter in line with the beam. A capillary system of the stainless steel descended from the target assembly to the bottom of the vessel, and it had increased lithium conductivity in the vertical direction. The target body was also made of stainless steel. The irradiated surface of the porous capillary system had an integral design with a given porosity and was made of refractory materials with high resistance to lithium. The volume of the lithium in a target vessel of this type was 30 cm^3.

The type 'b' of the target was designed for the experiments in the SPRUT device with horizontal electron beam. It had the same design and materials. The only difference in this case concerned the horizontal position of the large storage vessel and of the target. The target assembly was displaced lower from the axis of the vessel, Fig. 3b. This design ensured a higher pressure of the liquid lithium in the target assembly with the hydrostatic lithium pressure in

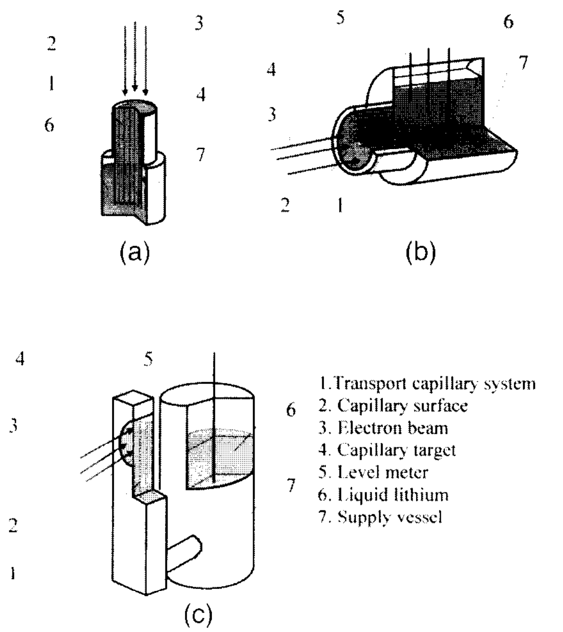


Fig. 3. Porous capillary system design options. a - for the vertical beam test. b,c - for the horizontal beam experiments.

the storage vessel. The target diameter was 30 mm. The lithium volume in the 'b' target was 130 cm^3.

The type 'c' of the design, Fig. 3c, had another modification. The target assembly was made of a rectangular tube with the internal cross section 5×20 mm^2 having internal arterial channels to reduce the hydraulic resistance of the capillary system. Niobium alloy was taken as a structural material for the type 'c' target, the irradiated surface and the capillary filler were made of molybdenum. The design of type 'c' prevented the lithium pressure excess in the irradiated surface of the target assembly. The lithium volume in the type 'c' target was 190 cm^3.

The full wetting of the capillary system was ensured by degassing operation in high vacuum at 1000°C before the loading of the vessel with lithium. The wetting of the capillary system after loading operation was accomplished in the vacuum annealing process during 1 h at a temperature up to 800°C.

4. Experimental results

A molybdenum target 20 mm in diameter and 40 mm in thickness was used as a reference for comparison of the irradiation results on the capillary targets with other objects. This target was irradiated with the electron beam at 8 keV with the power load 20 MW/m^2 during 20 s. The result of such an exposition was the surface melting of the target, a crater of more than 1 mm in depth was formed.

The study of the type 'a' target was performed with the vertical electron beam, Fig. 1, the two other targets 'b' and 'c' were used in the horizontal beam experiments, Fig. 2. Three tests were made in the first case, five experiments were performed in the second one. Two targets in the first case were pre-heated to 300°C and were exposed 20 and 30 s at the heat load up to 30 MW/m^2 until full evaporation of the lithium.

The first experiment on the SPRUT device with the type 'b' target had a long duration, 17 min, at low power up to 5 MW/m. The lithium evaporation from the target surface during the experiment was followed by its free flowing because of the non-compensated thermal loads and the capillary head. This has lead to drying of the target and its final damage.

In the second experiment, the heat load reached the record value 50 MW/m^2 in first five s. Then the load was lowered and was controlled at 30 MW/m^2 during the following 15 s, and at 15 MW/m^2 during 10 s and for the last 4 s it was raised up to 30 MW/m^2.

The total experiment time of continuous operation was 34 s and it was stopped because of a break-down in the electron gun. The examination of the target after the experiment showed a little damage on the capillary surface in the centre (Fig. 4). The break-down in the gun could be one of the reason for this damage.

The capillary system was changed for the next three experiments. The type 'c' targets were manufactured on the basis of a rectangular niobium tube filled with a molybdenum capillary structure.

These experiments showed that in each case there was a normal operation phase and a damage of the target depending on the power load value of the beam. The analysis of the videofilms, of the integral radiation signals and the temperature of the receiving elements made possible the identification of the damage start moment. At the first phase of the target operation, an intensive crimson

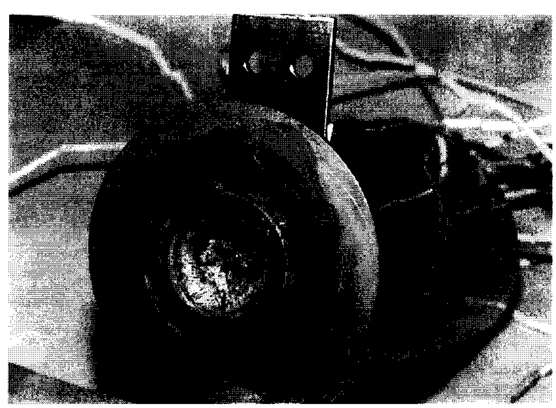


Fig. 4. The lithium target view after the experiment Nr. 2 in the SPRUT device.

Table 1
Summary of the lithium capillary target tests

Target type	Experiment number	Maximal heat load, MW/m^2	Total exposition time	The reason to stop the exposition	The operation time of the target before damage
	ELU-9				
a	1	20	20 s	Planned	20 s
	2	30	30 s	Planned	30 s
	SPRUT				
b	1	5	17 min	Drying of the capillary structure. Evaporation and flowing out	10 min
b	2	50	Break-down in the electron gun. Little damage	5 s	
		30		15 s	
		15		10 s	
		30		2 s	
c	3	20	80 s	Drying of the capillary structure. Evaporation and flowing out.	≅ 60 s
	4	20	70 s	Irradiated receiving surface damage in the target; capillary system defect	≅ 15 s
	5	35	50 s	Irradiated receiving surface damage in the target; unsufficient capillary pressure	≅ 30 s

light is observed. The molybdenum mesh damage start was identified as the white sparks appeared. All these results are summarized in Table 1. In the third experiment the target was damage in the last exposition period during 25 s. The system was dried completely because of the lithium evaporation and its flowing out. In the fourth and in the fifth tests the target had been operating for 15 s and for 30 s at power load 20 MW/m^2. The following sharp power rise up to 30 MW/m^2 caused the drying of the capillary system quite rapidly. We suppose that insufficient capillary pressure in this type of the target was the reason of this facts.

So, the tests of the type 'c' capillary target have shown that a stationary heat removal was maintained at the power loads (15–20) MW/m^2 with the tube thickness 5 mm and the beam diameter 15 mm. The target is dried when the power rises more than 20 MW/m^2 and the target is damaged. Several reasons can lead to such an event. First, when the beam diameter is much more than the thickness of the capillary target the vertical lithium supply is not sufficient in the central zone of the beam because the lithium capillary head along the beam axis is not high enough as the tube thickness, 5 mm, is too little for this beam, 15 mm in diameter.

Second, the lithium supply during the exposition of the target can be significantly decreased because of the impurities in the liquid lithium or because of some fabrication defects in the capillary system leading to the limitation of the capillary pressure. This was seen in the fourth and the fifth experiments when the lithium supply vessel was not dried completely in contrast to the other experiments.

5. Conclusion

For the first time, an open lithium capillary structure was made for the study of its application in the divertor of a tokamak-reactor.

The first results of the tests are given concerning different types of such an a structure behaviour under intensive electron beam impact.

The lithium capillary target has been successfully tested at thermal power loads up to 50 MW/m^2 during 5 s. Long-duration tests have been performed at 20 MW/m^2 and 30 MW/m^2 for 60 and 30 s, and at 5 MW/m^2 for 10 min. The tests have shown the lithium capillary structure to be promising for the high heat load removal so in a thermonuclear reactor as in other devices. An important data has been obtained concerning the lithium capillary structure operation under powerful electron beam impact which can be considered roughly to simulate the thermal conditions of the tokamak divertor as we suppose. The further study of the optimal parameters of the lithium capillary structure is needed to find necessary design options. The test methods must be also elaborated to make the test conditions the most close to these of the divertor in tokamak-reactor.

References

[1] ITER Design Report, June 1995.
[2] L.G. Golubchikov et al., these Proceedings, p. 667.