DESIGN, CALCULATION AND EXPERIMENTAL STUDIES FOR LIQUID METAL SYSTEM MAIN PARAMETERS IN SUPPORT OF THE LIQUID LITHIUM FUSION REACTOR

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Abstract

A new concept of a Liquid Lithium Fusion Reactor and the first experimental results were presented at the 16th IAEA Conference on Fusion Energy. During the past two years theoretical estimations have been made, and calculated and experimental results have been obtained in confirmation of this concept and supporting its progress. The main results of this work are given in the paper.

1. INTRODUCTION

A Liquid Lithium Fusion Reactor (LLFR) concept [1] was successfully developed by the authors on the basis of an integrated approach to the problems of divertor plates and first wall protection together with tritium breeding and blanket cooling that consists in the use of Li and of capillary porous structures (CPS) [2, 3, 4]. Development of the concept was continued along the following main lines: Li blanket and divertor design on the basis of 3-D calculations of neutronics and of analysis of energy transfer in the divertor region, design study and performance assessment of reactor Li systems, study of Li CPS interaction with tokamak plasma, study of CPS resistance to plasma disruption effects, study of CPS erosion mechanisms and protective properties, study of Li flow features in CPS in magnetic fields, study of V-Cr-Ti alloy compatibility with Li, design and development of experimental facilities for technological studies, and study of Li CPS materials and characteristics. The main outcomes of this work are reported here.

2. LITHIUM CPS STUDY UNDER STEADY-STATE AND PULSED POWER LOADS

Experiments in TFTR reported recently [5] demonstrated high efficiency of tokamak plasma performance improvement by introduction of Li into the plasma edge. It was shown that controlled injection of Li into the plasma significantly improves the discharge parameters, increasing τ_E, lowering plasma density at the edge etc. Li pellet injection was also proposed recently for mitigation of disruption consequences[6]. A series of experiments has been started in the T-11M tokamak (R = 0.7 m, a = 20 cm, B_T =1.3 T) with He plasma. The graphite rail-limiter was replaced by a movable Li CPS limiter with possible preheating up to 600^{o}C for investigations of tokamak plasma interaction with Li CPS (with Mo as the CPS material), probable erosion mechanisms of Li CPS, and integral effect evaluation (ion sputtering, unipolar arcs, instabilities characteristics of the plasma - liquid metal boundary, MHD effects). Li optical line intensity, plasma density, total radiation losses and main plasma parameters were simultaneously measured in two plasma cross-sections (shifted by 90^o in the toroidal direction) where Li and graphite movable limiters were placed entering the plasma column up to 5 cm. The preliminary conclusions of these tests are: physical sputtering of Li in liquid and solid phases by He ions is not very important in tokamak boundary conditions; arc erosion effects on the Li limiter are negligible; there is not a significant difference with respect to common plasma contamination effects for Li and graphite limiters.

The first experiments with Li CPS at high power loads in the linear plasma facility SPRUT-4 under a steady-state electron beam showed [2, 3, 4] that the studied mock-up of a capillary system could operate at 20 MW/m^2 in a quasi-stationary regime, and the part of the power removed by evaporation of Li varied from 50 to 70% in the 1-25 MW/m^2 power range. The use of an electron beam for these tests was found advantageous, namely, because of wide power range available - from 1 MW/m^2 to 200 MW/m^2 . Therefore, a liquid Li circuit has been designed, fabricated and mounted in the SPRUT-4 facility for investigations of the behavior of CPS under specific power loads up to 100 MW/m^2. The designed system provides for steady-state operation regimes of the capillary structure by forced cooling of the loaded elements, and this makes it possible to evaluate the main characteristics of CPS function - Li evaporation rate, evaporation temperature etc. - as functions of the applied power load and to study the features of Li evaporation from the porous surface. The circuit design is meant for the study of Li CPS of different types under the SPRUT-4 electron beam load.

Stability of the Li CPS to disruptions, ELMs and transients is determined by the erosion of the CPS material. A theoretical study of solid homogeneous materials and an experimental study of physical processes of hydrogen plasma interaction ($n_e = 10^{22}$ m^{-3}, τ = 500 μs, q = 5 MJ/m^2) with Li CPS in the Quasi Stationary Plasma Accelerator have been carried out. It was found that a Li plasma cloud is formed which absorbs the largest part of the energy and re-radiates it, so that only a small part, ~1-3 %, reaches the surface as radiation and convective heat flow. Li evaporation in the first 5-10 μs with formation of a shielding plasma layer and during the further stages of interaction makes up only a small part of the total amount (~5-10 μm). The main part of the Li erosion might be due to splashing by the generation of “wind waves”, hydrodynamical instabilities and volume bubble boiling. The measured erosion yield attributed to ablation in the form of Li drops reached ~1-3 mm per pulse for free surfaces at 3 GW/m^2 and corresponded well to numerical estimations. It was then found to be essentially suppressed for porous structures (from 100 to 5 μm for pore radii from 200 to 15 μm) by capillary forces so that it became not dangerous as the layer of Li which is splashed away is immediately restored after disruption. However, drying of CPS material by ablation may disturb the heat removal from the surface by Li evaporation and by thermal conductivity to the internal layers thus causing melting and erosion of the CPS material. Studies of ablation processes using a laser dispersion technique have allowed it to be established that the fraction of large splashed Li drops (0.5-1 mm) strictly depends on the CPS material parameters (increases with pore radius) and on the orientation of the surface with respect to the plasma flow direction (it increases with deviation of the flow direction from normal). The greater part of the particle stream is concentrated in the plane of the surface though a normal component of the particle velocity also exists. The velocity of the drops was 0.1-10 m/s. A remarkable experimental finding was the increase of the erosion rate of initially solid Li ($T<T_{melt}$) in the CPS with increasing irradiation pulse number. This was not observed for CPS with initially liquid Li ($T>T_{melt}$). This effect may be related to the observed wave generation and to the characteristic relief formation of stiffened Li with initial $T<T_{melt}$ that results in the increase of ablation in the subsequent irradiation shots compared with the case of an initially smooth surface. There was no wave and relief formation on the surfaces with $T>T_{melt}$ because Li was absorbed by CPS and the roughness was smoothed away by capillary forces. This effect is one of the advantages of liquid metal CPS in comparison with solid materials considered for divertor plates application. Thus, theoretical analysis and experimental results show that for the optimal choice of CPS performance (with pore radius 10-100 μm) an acceptable value of Li erosion may be attained owing to suppression of Kelvin-Helmholtz hydrodynamical instability and of volumetric bubble boiling.

3. LITHIUM DIVERTOR AND BLANKET DESIGN OPTIONS

One of the critical issues of reactor development is divertor conceptual design and its technical realization. The proposed LLFR divertor concept taking Li CPS as a plasma facing material provides for a continuous self-sustaining and self-regulating liquid Li surface formed on facing elements of complex geometry and spatial orientation [1]. Furthermore, energy removal from the plasma to the divertor is carried out through two highly efficient channels - by evaporation of Li from the surfaces in contact with the plasma followed by its condensation on elements of much (an order) larger area and by radiation of Li atoms and ions. The fraction of the energy removed by each of these channels depends on the particular divertor design. Both of these channels are able to provide minimal values (~0.1-0.5 MW/m^2) for homogeneous energy flux distribution in the divertor region realized through thermal conductivity to the cooling systems. Li evaporation from the zone of plasma contact with the divertor plates may give hundreds of megawatts per square metre of heat removal. Radiation of Li neutrals and ions (the Li atom ionization expense being 57 eV) should enable energy removal from the divertor plasma layer to be homogeneous in length and controlled in value. These steady-state divertor operation conditions corresponding to high energy density might be realized as stable regimes for CPS surface heat load matching Li influx into the plasma. This is ensured by having the necessary area ratio of Li CPS elements and the plasma surface. For a 10:1 ratio at 700^{o}C, power removal 15 MW/m^2 is possible in these regimes. For minimal dimensions of the divertor zone, high values of this ratio may be obtained by a particular spatial arrangement of the Li CPS elements (Fig.1). Minimal influx of Li into the divertor volume may be obtained in this case.

The design, main performance characteristics and structural composition of the self-cooled Li-Li blanket for the LLFR concept are realized in an alternative design of the ITER blanket test module [7]. A blanket with poloidal slot cooling has a breeding zone with Be of required porosity as a breeding material and a WC-based shielding zone. This minimizes the quantity of Li in the blanket for K_T>1 and it ensures the necessary radiation shielding for minimal blanket thickness. The Li flow velocity is 0.2-0.5 m/s for heating to 200-300^{o}C. Low hydraulic loss in the Li circuits would be ensured by formation of insulating coatings based on AlN. For the module with the achieved coating performance [8] the hydraulic loss in the Li circuits would be not higher than 0.4 MPa. The blanket structural materials V-4Ti-4Cr and V-10Ti-5Cr alloys can operate at temperatures up to 650^{o}C.

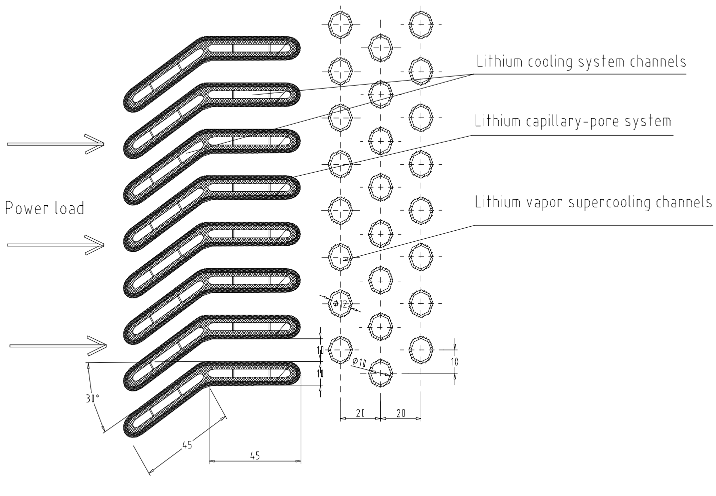

FIG.1. Toroidal section of lithium divertor CPS receiving elements.

Liquid metal systems have been developed for a reactor thermonuclear power of 3 GW, different schemes of heat conversion into electricity and a tritium removal system based on non-equilibrium molecular distillation method have been analyzed. The optimal energy conversion scheme provides 30-35% net efficiency. The safety of the LLFR is ensured by using NaK in the intermediate heat exchange circuits and to provide cooling for the reactor vessel.

4. EXPERIMENTAL STUDY OF TECHNOLOGY

A special facility has been established for investigation of Li flow in a homogeneous magnetic field up to 1.6 T. Comparative experiments have been carried out in a smooth cylinder channel and in a CPS mock-up. Preliminary analysis has shown that: Li flow resistance in CPS is determined by the relative effect of suppression of oscillations and of the Hartmann effect, the same as for a cylindrical channel, resulting in an insignificant increase of the CPS hydraulic coefficient at low magnetic fields ($N_\delta<10$), and in the studied range of Hartmann and Reynolds numbers there are no MHD anomalies which would lower the potential of CPS applications in magnetic fields.

Corrosion tests of the vanadium alloys V-4Ti-4Cr, V-10Ti-5Cr and V-15Ti-7Cr at 700°C in homogeneous (V alloy-Li) and heterogeneous (V alloy-Li-SS) systems simulating reactor liquid metal system operating conditions have been performed and they have shown the high resistance of these alloys to a Li environment. Negative aspects of different materials combinations are neutralized by generation of particular conditions encouraging the formation of AlN-type self-healing coatings in a Li system [8, 9].

A project for an in-pile V/Li loop facility, including external service systems and heat and tritium removal systems and based on the main principles of reactor Li systems has been designed for an integrated study of the materials and technology of development and exploitation [10].

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