Actively circulated liquid metal divertor (ACLMD)

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1. Introduction

The use of actively circulated liquid metal is proposed to facilitate heat handling of the divertor, which is a very serious and challenging issue in fusion reactors, especially since fusion power in a DEMO [1] reactor will be several times the fusion power of ITER and yet the reactor size will be similar. Furthermore, copper cannot be used for cooling tubes, and reduced activation alloys such as F82H will thus be the structural material even as its heat conductivity is substantially lower than that of copper. Deterioration of heat handling capability after melting and subsequent resolidification at unmitigated disruption, erosion and lifetime problem, cracking due to low DBTT and hydrogen implantation are also among the concerns with tungsten targets, for which a liquid metal divertor provides a solution as well.

2. Basic scheme

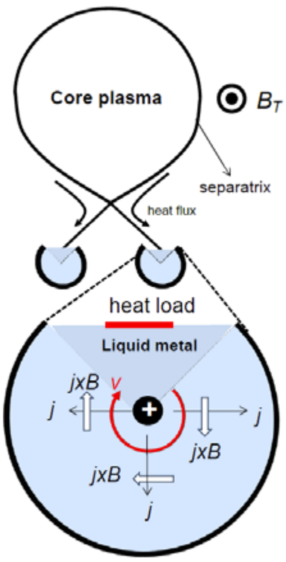

Figure 1: Cross-section of a diverted plasma with an expanded view of the divertor

The basic proposal is to replace the divertor plates with a liquid metal like Ga, Sn with a low melting point and low chemical activity (Fig.1). The electrodes, placed in the middle of the liquid metal, can be biased positively or negatively with respect to the module. The $j \times B$ force due to the current between the electrodes and the container wall actively drives a poloidal motion of the liquid metal in such a way that the temperature rise at the separatrix hit point is kept at an acceptable level (~200 degree C).

To avoid excessive current during the ramp-up, the voltage and the rotation should be ramped up rather slowly (e.g. in 1 minute). Insulating plates should be inserted at multiple toroidal locations to avoid short circuit along the field line and to reduce the toroidal current in the LM during the discharge start-up. This scheme may be adequate for an experimental device, but not feasible technically for a reactor because of the toroidally-linked structure.

3. Scheme for Slim-CS

Figure 2 (a) shows the cross-section in the divertor area of Slim-CS [1]. Fig. 2(b) shows a possible scheme for Slim-CS. The lower part of vacuum vessel is filled with LM. The toroidally-segmented divertor modules are immersed in the LM. The divertor modules are equipped with cooling tubes which are attached on the module wall. The electrodes are installed in the middle of LM and mechanically supported by the modules. The insulating plates can be installed between the modules.

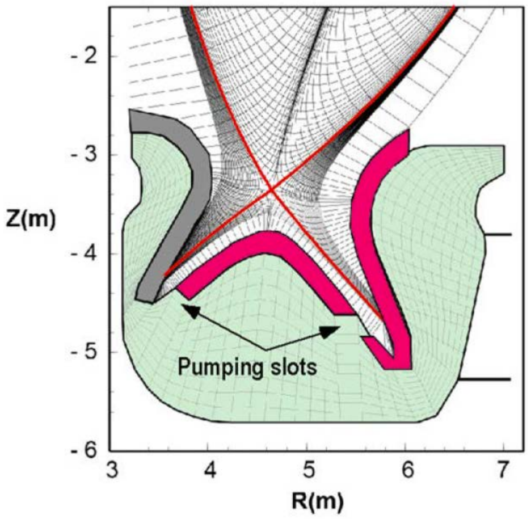

Figure 2 (a): cross section of original SlimCS [1]

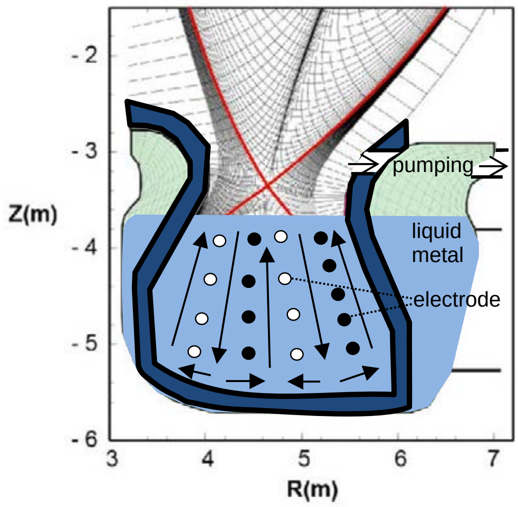

Figure 2 (b): ACLMD for downward motion of the liquid metal immediately after heating by the plasma. The electrodes shown with solid circles are biased negatively and those shown with open circles biased positively. The magnetic field is directed toward the reader.

The poloidal motion of the liquid will distribute the heat to a wide area, greatly enhancing the heat handling capability of the divertor. If the poloidal motion of the liquid metal distributes the heat load uniformly over the inner wall of the divertor module, the power density will be ~1.3 MW/m^2, which is easily removable with conventional technology.

4. Requirements on the flow speed

Next we discuss the requirements on the LM flow speed. With vertical movement as is depicted in Fig. 3, a following simple estimation suggests that a flow velocity of ~0.3 m/s may be adequate to keep the temperature rise ~ 200 degrees.

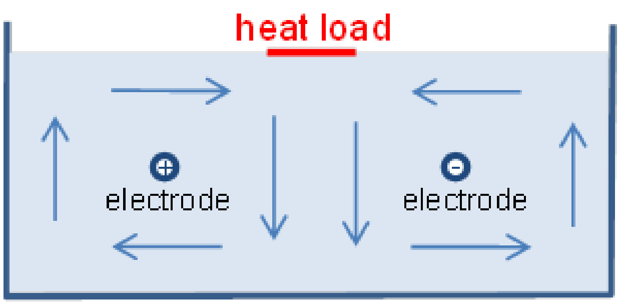

Figure 3: a flow pattern of liquid metal

$$v_\theta = \frac{P_{div}}{\rho C \Delta T A} \sim 0.3 \text{ m/s}$$

Where P_{div} (divertor heat load) = 200 MW; ρ (mass density of Sn) = 7 x 10^3 kg/m^3, C (heat capacity of Sn) = 228 J/kg/K, ΔT (temperature rise on contact of the plasma) = 200 degrees (e.g. 300ºC→500ºC: compatible with F82H); A(plasma-wetted surface area) = 2 m^2

5. Vapor pressure of some liquid metals

Vapor pressures of the three liquid metals (Sn, Ga and Li) are shown in Fig. 4 as a function of temperature. The divertor neutral pressure is in the range of 1-10 Pa. This result shows that the vapor pressure would not be problematic for Ga and Sn, if the temperature is controlled below 500 ºC.

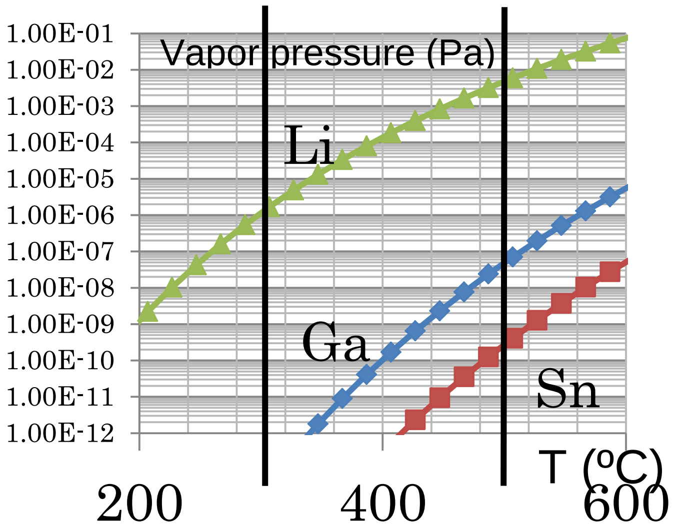

Figure 4: vapor pressures of some liquid metals
Two vertical lines indicate the temperature range of 300°C and 500°C, compatible with F82H.

6. Proof-of-Principle experiment

6-1. Aluminum setup

The very first PoP experimental setup employing a cylindrical chamber with aluminum side wall was interrupted since the side wall developed a small leak of GaInSn. After the liquid metal was removed from the container, some sludge was observed. Chemical analysis indicated that the sludge contained significant amount of aluminum, showing the importance of chemical reaction in the LM-wall interaction.

6-2. Stainless steel setup

Most recently, a series of proof-of-principle experiments have been carried out at NIFS. A cylindrical case containing a liquid metal (GaInSn) with a dimension of 6 cm in radius and 2.8 cm in height is used for these experiments. The cylindrical wall of the container is made of SUS304 and the top and bottom plates of acryl. A rotatable electrode is installed on the major axis, which can be biased against the wall. A magnetic field of about 1kGauss is provided by a pair of permanent magnets set on the axis, the radial profile of which is shown in Fig. 5. The electrode voltage is gradually increased up to about 3V, towards the end of which the liquid metal has been observed to rotate with a speed of 6~7 rpm. At this point, the electrode current is observed to be around 20 A at which point the applied voltage is found to be 2.9 V.

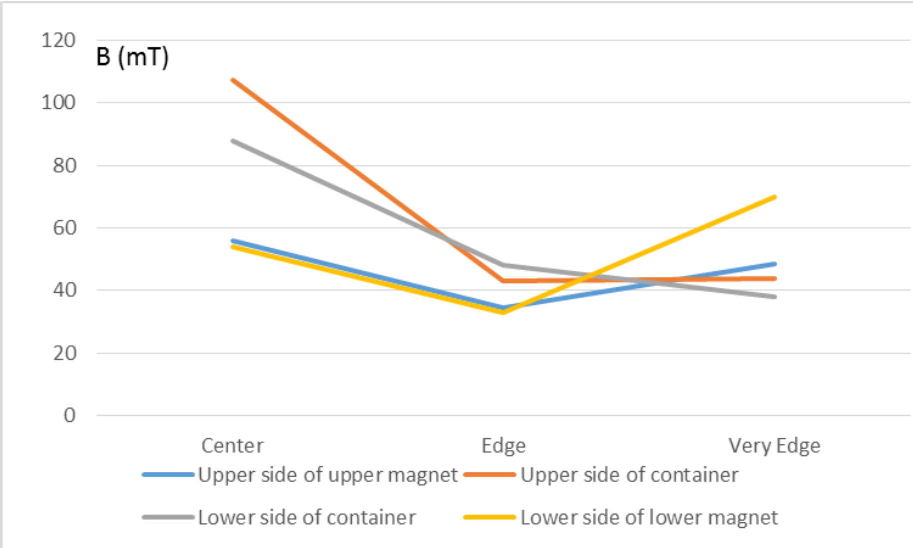

Figure 5: distribution of magnetic field (center: r~0 cm, edge: r~6 cm, very edge: r~10 cm)

7. Future work

1) Experimental demonstration of the rotating mechanism with the opening above LM
2) Measurement of particle trapping efficiency at relevant temperature
3) Investigation of divertor characteristics with ACLMD

1)-2) will be investigated in NIFS.

3) requires an experiment in a tokamak.

8. Summary

1) The new divertor concept ACLMD offers extremely high capabilities of heat removal and fast recovery from disruptions;
2) A series of proof-of-principle experiments have successfully been conducted, which, however, has opened up some of the new areas of research, including electro-chemical compatibilities between the liquid metal-structural materials.

Acknowledgement
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Reference

[1] K. Tobita et al., Nucl. Fusion 49 (2009) 075029, doi:10.1088/0029-5515/49/7/075029