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A review of the applications of liquid metals for plasma-facing components in magnetic fusion devices
液体金属の核融合装置プラズマ対向壁への応用に関するレビュー

廣岡慶彦*, G. Mazzitelli (ENEA), S. Mirnov (TRINITY),
小野雅之 (PPPL), 嶋田道也 (JAEA), and F. L. Tabares (CIEMAT)

*National Institute of Fusion Science, Graduate University for Advanced Studies, 322-6 Oroshi, Toki, Gifu 509-5292
核融合科学研究所・総合研究大学院大学　〒509-5292 岐阜県土岐市下石町322-6

The application of liquid metals as plasma-facing materials draws increasing interest as a potential solution to the issue assciated with exhaust power and particle handling in magnetic fusion power devices beyond ITER. However, our knowledge is extremely limited at present about the physics of the interactions between liquid metals and edge plasmas under strong magnetic fields. This paper is intended to provide a review over the present status and future propects on this subject.

1. Introduction

It is widely recognized that exhaust power and particle handling by plasma-facing components (PFCs) is a critical issue, affecting the successful development of magnetic fusion energy. The current divertor design of ITER employs tungsten as the plasma-facing material, brazed on a copper alloy heat sink to be actively cooled by water. This 2-metal structure is expected to withstand heat loads up to ~10MW/m^2 at temperatures around 1000^{O}C, and also to survive sputter erosion by D, T and He, perhaps at particle fluxes up to the order of 10^{23} ions/m^2/s [1].

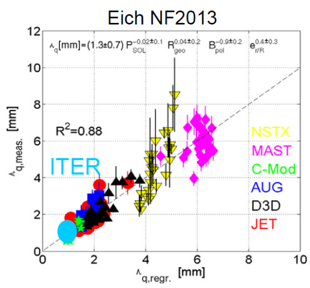

Fig. 1 Divertor power deposition e-folding length for existing devices and ITER [2].

As to heat loads, much attention has recently been directed towards the power deposition profile on the divertor plate. The ITER divertor plasma footprint used to be estimated to be 5mm wide, but now is only ~1mm wide [2], as shown in Fig. 1, which means that the power flux could be as large as ~50MW/m^2. One then predicts that the divertor heat flux would be even higher for a DEMO reactor to be heated with much more power. In addition, the use of reduced activation ferritic/martensitic steel (RAFMS) alloys will be enforced from the radiation safety point of view. Unfortunately, the thermal conductivities of these RAFMS alloys are typically from one third of those of copper alloys. It follows from these arguments that the use of 2-metal structure diverters for the heat removal in magnetic fusion power reactors may be suicidal.

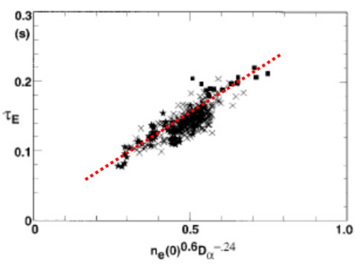

Fig. 2 The energy confinement time and the edge plasma density ($D_\alpha^{-2.4}$) in TFTR supershots [3].

Turning to particle control, it has been observed in a number of confinement devices that reduced recycling from PFCs leads to the improvement of core plasma performance. Shown in Fig. 1 is one good example, a TFTR database [3], indicating that the energy confinement time increases with decreasing edge density in "Supershots", achieved by wall conditioning with lithium coatings, etc. Since then, lithium coatings have successfully used in a large number of plasma confinement devices.

Unfortunately, reduced wall recycling will not last forever because the surface is saturated with fuel particles after several confinement experiments, which necessitates the shutdown of plasma operation for wall re-conditioning. Needless to say, this is not desirable for steady state reactors.

All these technical issues point to the need for an innovative PFC concept that provides an extremely high capacity of steady state heat and particle removal. The use of liquid metals for PFCs might possibly resolve these issues, although it will no doubt take several decades of effort because there are a long list of technical issues. Nonetheless, efforts have already been devoted into some of the confinement and laboratory experiments.

The liquid metal waterfall concept was first proposed about four decades ago in the UWMAK reactor study reports [4]. After a long silence, liquid metal PFC concepts have been revaluated as part of the coordinated program in the States, referred to as APEX [5], with the emphasis on the interactions between the magnetic field and flowing liquid metals. The general conclusion is that the use of flowing liquid metal might resolve some of the technical issue, but it would take an extreme caution not to be disturbed by the MHD drag: **v**x**B**, where **v** is the flow velocity and **B** is the magnetic field. Particularly when the liquid metal flow crosses the magnetic field, the MHD drag force is generated in the counter direction to the flow, which then increases the driving power. Interestingly, the MHD drag force is also a crucial issue in the design work on self-cooled blankets, employing liquid metals such as lithium.

Intended for an increased hydrogen absorption capacity, relative to coatings over PFCs, standing liquid lithium was as the divertor material in NSTX [6], being upgraded to NSTX-U. The liquid lithium surface has been found to be extremely reactive to oxygen-containing impurities such as water vapor to form LiOH and/or LiO_2, both of which tend to buoy, blocking the arrival of hydrogenic species. As a result, liquid lithium ends up acting essentially in the same way as solid coatings in terms of hydrogen recycling. This is presumably because the surface of liquid lithium tends to be warmer than the bulk due to divertor heat loads, which will not induce natural convection, leading to the surface saturation. One then conjectures that forced convection would be necessary for flowing liquid lithium.

2. Present status and future prospects

To investigate the effects of liquid convection, a series of first-of-a-kind experiments have most recently been conducted, using the VEHICLE-1 facility [7] at NIFS. In these experiments, under steady state plasma bombardment, molten lithium at around 250℃ is stirred mechanically to observe its effects on hydrogen recycling. As shown in Fig. 3, results indicate that liquid stirring de-saturates the surface to re-generate the hydrogen absorptivity of molten lithium. Also observed is that liquid stirring can break impurity films to expose fresh lithium to hydrogen plasma, recovering reduced recycling (data not shown in this document).

The next step is to discover a new scheme that can overcome the MHD drag and provide forced

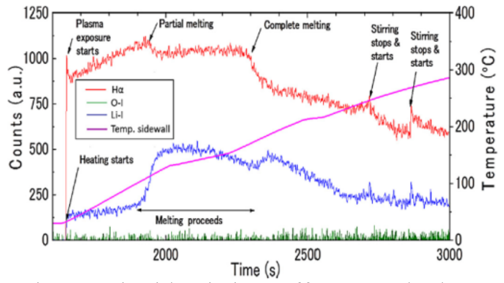

Fig. 3 Liquid stirring effects on hydrogen recycling from molten lithium [7].

convection at the same time. One such scheme is the thermo-electric MHD divertor concept [8]. In this concept, the temperature gradient due to the divertor heat loads in the depth direction of liquid generates a current by the Seebeck effect, which then interacts with the magnetic field to generate a Lorentz force via **J**x**B**, cancelling the MHD drag via **v**x**B**. This concept has already been examined both in a laboratory setup and in a confinement device, the latter of which, however, has employed a TE-MHD test unit as the limiter.

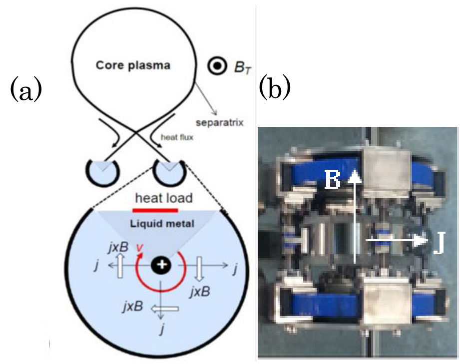

Fig. 4 The ACLMD concept (a) and the laboratory experimental setup (b).

Shown in Fig. 4 is the ACLMD concept for the Actively Convected Liquid Metal Divertor, which has most recently been proposed [9], based on a similar **J**x**B** force whereby the current is drawn between electrodes. The beauty of the ACLMD concept is that the rotation speed is externally controllable, unlike the TE-MHD divertor concept. Laboratory PoP experiments have successfully been conducted [10] although much remains to be done.

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