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Richard E Nygren

Sandia National Laboratories[1] Albuquerque, NM, 17185 USA

E-mail: renygre@sandia.gov

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Abstract

Many ideas for liquid surface PFCs are for divertors. First walls are likely to be more challenging technologically because long flow paths are necessary for fast flowing systems and the first wall must be an integral structure with the blanket. Maximum tolerable heat loads are a critical concern. This paper describes several processes at work in walls with fast-flowing or slow-flowing liquid plasma-facing surfaces, and the considerations imposed by heat transfer and the power balance for the PFC as well as the structure needed for an integrated first wall and blanket, and uses thermal modeling of a generic PFC structure to illustrate the issues and support the conclusions.

Keywords: liquid surface, lithium, divertors

Introduction

The plasma facing components or PFCs in a D-T component test device, DEMO or reactor must receive power exhausted from the plasma, transfer it to coolant that passes out of the vessel for heat rejection and in a DEMO for power conversion, maintain structural integrity, retain tritium within safe levels, feedback only acceptable amount of impurities into the plasma, and provide a physical envelope that permits sustained confinement and adequate power production in the core plasma. PFCs include the divertor, a first wall (FW) that is an integral structure with the tritium breeding blanket plus any plasma facing structures necessary to protect the wall, such as poloidal limiters, or guards for launching structures. As the power input has increased, damage from higher than expected heat and particle loads in the vicinity of RF launchers and materials deposited on mirrors have raised concern.

The primary perceived benefits of a liquid surface PFCs derive from several motivations.

One benefit from self-replenishing surfaces (implicit in the concept of liquid surface PFCs for a fusion DEMO) is to eliminate several issues associated with solid surfaces such as melting and recrystallization, and radiation damage that affects the retention of tritium and the morphology of the plasma facing surface. This potential benefit was recognized early in the fusion program, for example in 1974 for the UWMAK design [1] for a flowing liquid wall and in a paper by Wells in 1981 [2]. These and other early efforts are summarized well by Mirnov [3]. More recent is the still developing understanding of disruptions and ELMS, their projected heat loads and methods of mitigation. Again liquid surfaces have a benefit in the heat loads due to transients that can be accepted and dissipated without damaging underlying structure.

Specific to lithium, and more recent in terms of its development, is the improvement in plasma performance observed when lithium is introduced at the edge of the plasma. Two recent and excellent reviews of liquid surfaces with an emphasis on lithium have been published by Jaworski [4] and by Hirooka [5].

Another motivation that could have significant impact but is quite speculative at this point is that liquid walls may offer the only solution for design in which the walls can conform closely to an outer magnetic flux surface. This point is expanded later in the paper.

The main point, covered in the second section in this paper, is to identify the critical aspects of development that are related to design integration of the subsystems and needed to bring a concept or idea to a point where a serious evaluation of their potential application in an FNSF or a DEMO

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would be possible. The paper first characterizes liquid surface systems in terms of their heat removal and technology, and then discusses the considerations imposed by heat transfer and the power balance for the PFC as well as the structure needed for an integrated FW and blanket. There is of course also a parallel set of critical aspects, not discussed in this paper, that derive from the impacts of liquid walls on the physics of the plasma edge.

Reactors and power exhaust

Various concepts have emerged for future fusion reactors for magnetic fusion and for inertial confinement fusion or ICF that have lithium or other liquid metals, e.g., gallium (Ga) or tin (Sn) or mixtures such as Sn–Li [6]. Before the beneficial effects of lithium at the edge of the plasma gained interest, Mirnov and others recommended Ga or a eutectic with Al and Si [3]. As noted above, schemes with sheets and droplets were suggested, and a concept with a network of lithium jets was initially suggested by Ralph Moir [7]. Later, the investigation of flowing liquid walls the ALPS and APEX Programs, which investigated PFC and blanket concepts respectively, also included molten salts with mixtures of the fluorides of lithium, beryllium and sodium [6, 8]. For the desired high power densities in an FNSF or DEMO, the maximum tolerable heat load of the PFCs is a critical concern. Most ideas for liquid surface PFCs are aimed at divertors, rather than the first wall, to maximize plasma contact for PSI effects and to provide a simultaneous solution for power handling. First walls are likely to be more challenging technologically because long flow paths are necessary and the FW must be an integral structure with the blanket (not separate as in ITER).

A currently unresolved issue, that has been very important for ITER, is the amount of convected power that transients might carry to the FW. The potential threat in large future D-T devices is that anything protruding into the plasma, such as the edge of a tile that is misaligned from its neighbor, would intercept a huge heat load from charged particles traveling along the edge of the plasma (‘leading edge’ problem). The mitigation in ITER is a set of Enhanced Heat Load modules that covers ~40% of the first wall [9]. The center portion of their front faces is closest to the plasma and the faces bend away at the sides. The lesson for an FNSF or DEMO appears to be that their confinement schemes cannot include many, maybe any, plasma disruptions and only very modest ELMS, which release bursts of particles at the edge.

Our understanding of the behavior of the plasma edge is still emerging and a solution for how to incorporate a quiescent edge plasma into a workable confinement scheme is not yet clear. This is important for liquid surfaces for the following reason. If significant power convected to the wall from charged particles remains as a threat for an FNSF or DEMO, then the following will likely be true: (1) a design requirement for shaped solid walls (e.g., poloidal limiters) that will restrict volume for breeding tritium and complicate the challenges in injecting and exhausting power and for remote maintenance, and (2) liquid walls may provide the best option for a conforming wall. These notions are clearly speculative since we have not yet proven liquid walls can provide this solution nor that a solid wall solution will have to be non-conforming. (MIT researchers have a clever and innovative approach that uses a unibody vessel created by additive manufacturing that eliminates leading edges but also depends upon demountable superconducting coils for its implementation [10].)

Cooling and liquid surfaces

Unless a design can rely solely on evaporative cooling, heat deposited in the FW must be removed either by thermal conduction to a secondary coolant or by physical motion that moves the heated liquid away from the heat source, or some combination of both. A related point for the near term suggested by PPPL researchers is that continuous vapor shielding of a lithium surface may be possible in NSTX-U based on the suppression of lithium evaporation [11] in experiments with the linear plasma source MAGNUM-PSI. Yet to be learned in a confinement experiment are (a) if this shielding can be effective on walls with limited escape of lithium into the core plasma, how much power will still reach the wall and how much will ultimately go to the divertor, and (b) if a heavily baffled divertor that would contain and redistribute power by radiation can be integrated effectively into a reactor design.

Fast flow systems

Some early concepts for fast flowing systems used pressure as a driver but the ability to predict the effects of liquid metal MHD on these flows was limited. While electrically insulated walls would reduce the effect, self-healing coatings were studied in the US in the 1980s, found to be hard to develop, and research was stopped.

In more recent FW concepts with fast flowing liquid, the liquid moves continuously along a relatively long flow path both propelled and stabilized using electric currents and $J \times B$ forces, as in a system proposed by Majeski [12]. Ruzic and co-workers [13, 14] have developed concepts that use $J \times B$ currents or thermo-electric currents and have built modules for deployment in Chinese tokamaks.

In fast flow systems liquid metal magneto-hydrodynamics (LMMHD) dominates the flow behavior, is used to advantage to drive the flow, but also brings potential complications. Without the use of electrically insulated flow channels to restrain the flow of electrical current within the liquid metal, the driving current also flows in the wall, as do MHD-generated currents.

After the liquid flow goes down (or across) the FW, the flow path must either (a) return within the vessel and transfer heat to another coolant through a heat exchanger, as proposed by Majeski [12], or (b) exit the vessel and transport the heat to an external heat exchanger. The latter option requires flow across both the strong toroidal field and the poloidal field as well as through strong gradients in the magnetic field. Even

Table 1. PFC-Blanket Cases.

Fast flow FW/Div.			Blanket				
FW	*Div.*	*Press.*	*breeder*	*coolant*	*P*	*structure*	
Li	Li	L	Li–Pb	He	H	RAFS	1
Li–Pb	Li	L	Li–Pb	He	H	RAFS	2
Li	Li	L	Li–Pb	He	H	RAFS + SiC	3
Li	Li	L	solid	He	H	RAFS	4
Li + HX	Li	H (HX)	solid	He	H	RAFS	5
Ga	Ga	L	solid	He	H	RAFS	6
salt	salt	L	salt	salt	L	RAFS	7
Fast Flow FW/Div.			Blanket				
Li–CPS	He	H	solid	He	H	RAFS	8

with the return flow path inside the vessel, LMMHD effects will dominate the flow during the redistribution of flow through the heat exchanger and manifolds. Design integration of such systems must deal with these factors and that the altered flow distributions can affect not only the required pressure to drive flow but also heat transfer and corrosion. The requirements for systems with thermo-electric currents may differ somewhat in that externally driven currents are not needed.

Slow flow systems

Two examples of slow flowing systems are (1) the Capillary Pore System or CPS, and (2) the simple lithium surface flowing on a plate as advanced by Zakharov.

Russian researchers began developing the CPS systems started development in Russia in 1994 and are continuing, and CPS PFCs have been deployed in tokamaks in Russia, Italy and Kazakstan [15–20] and tested recently in Pilot-PSI [22]. CPS PFCs must transfer heat through the liquid (lithium) and its host structure to the primary coolant in the substrate that supports the CPS although some heat may be transported by evaporation at one location and deposition elsewhere. In the substrate, walls for gas cooling channels must handle the combination of gas pressure (4–10 MPa) and thermal stresses. The flow needed to replenish the liquid at the surface of a CPS is sufficiently slow as to mitigate significant LMMHD concerns at the plasma facing surface.

Zakharov's premise and approach is that a fully deployed system with lithium at the edge of the plasma would enable a radical increase in confinement, and he and co-workers proposed a system for the ITER divertor [21]. More recently, a concept by Zakharov with a thin film of lithium that adheres to a plate and flows slowly downward drawn by gravity was deployed for tests in the EAST tokamak. This uses a clever arrangement in the nozzles and manifold to initiate the pneumatically driven flow.

Design integration

With a liquid lithium divertor in a DEMO or reactor, what restrictions arise for the design of the wall? Let us expand this to a more general question. How does a set of basic features related to design integration place requirements on particular liquid surface concept?

Examples of these basic features are (1) a liquid FW integral with the front structure of a breeding blanket, (2) the driving and managing the movement of a liquid along a FW or divertor structure with full toroidal coverage and the necessary manifolds and provisions for filling and draining, and (3) interfaces with the systems to recover power (electricity) and to manage safely and recover tritium fuel.

A basic goal for the already complicated and interdependent subsystems in a tritium breeding D-T fusion device is to minimize complexity where possible, for example by limiting the number of working fluids that enter and leave the vacuum vessel as discussed further below. A related concern is the integration of the tritium handling and removal in these fluid systems. Where lithium results in very low recycling, the tritium throughput will likely be higher and the design must resolve the relationship between the confinement time, required fueling rate and the requirements for tritium processing.

All systems share the requirements to clean the liquid of impurities and remove tritium for processing. Fast flow systems can do this away from the FW location and have only a single fluid in the PFC. CPS systems transfer heat to a primary coolant within the PFC and must have processes for removing surface impurities that otherwise form slag and for processing tritium, and must mitigate tritium migration into the primary coolant.

Let us now examine the commonalities and differences when we combine the liquid for fast flow or the liquid and gas for the CPS to the breeding blankets and their working fluids in the examples in table 1.

1. Where $J \times B$ currents drive the fast flow of a free surface of liquid metal (e.g., Li), the needed containment of all or most of the driving current within the liquid metal requires that any alternate routes for the current have significantly higher electrical conductance. The conductance depends upon both the conductivity of the material and the cross section integrated along the current path. When the FW is part of an integral

Table 2. Parallel Currents With Resistance R *in* $\mu\Omega$ m, and Conductance C per unit depth.

	Mat'ls	R	W(mm)	C	%
A	Li	0.36	10	27.8	77%
	FS	0.60	5	8.3	23%
B	Li	0.36	10	27.8	53%
	FS	0.60	15	25.0	47%
C	Li	0.36	10	27.8	88%
	Inc	1.30	5	3.8	12%
D	Li	0.36	10	27.8	22%
	W	0.05	5	100.0	78%

structure with the breeding blanket, the current introduced to drive the FW will also distribute into the blanket structure unless there is some provision for electrical insulation. Inconel 600, ferritic steel (FS) and lithium have respective resistivities in micro-ohm-m of ~1.30, 0.6 and 0.36 at 20 °C. Relying simply on the higher resistance, for example of a RAFS, may not be sufficient. Table 2 shows some simple calculations. The conductance uses a unit depth for a given thickness, W, of material. Cases A and B compare a lithium wall with a 5 mm supporting solid wall of FS with the case where the thickness of FS has been increased to 15 mm to represent structures such as supporting ribs that would be present in a first wall that was integral with a breeding blanket. The main point is that for several combinations of materials that would seem likely choices, the currents along parallel paths in the structure are sufficiently high that the effects related to mechanical forces, corrosion, etc cannot simply be discounted.

2. An idea proposed in APEX [6] was that Pb–Li would form a Li layer at the free flowing surface (segregation due to Gibb's free energy for this mixture of materials). This would provide a plasma facing surface of essentially pure lithium, and enable the FW and blanket to share the same working fluid. Sn–Li also exhibits surface segregation of Li and been suggested as a PFC liquid.
3. If the liquid wall were coupled to a blanket with a liquid breeder such as the dual coolant lithium-lead system, the huge cross sectional area of the blanket walls plus the liquid breeder would be a low conductance current path in parallel with the first wall (without use of an insulator). The US developed designs with SiC blanket liners called flow channel inserts for thermal and electrical isolation between the Pb–Li and the blanket walls [23]. The thermal insulation permits lower temperatures in the FW structure than in the Pb–Li and might also limit the parallel conductance in most of the blanket liquid if this requirement were included in the designs of the inlet and outlet manifolds. Confirming this would require a detailed LMMHD model that includes the structure and the driving current for the FW flow, but the magnitude of the parallel current suggests some significant impacts in the integrated design.
4. The FW may be a low pressure system but if the blanket coolant uses high pressure He, as is true for most blankets with solid breeders, then overall this is a high pressure system. High pressure is required for sufficient mass flow in the gas for efficient cooling. This is also true for the dual coolant Pb–Li blanket in the cases above. The smaller size of auxiliary systems that use CO_2 for power conversion has attracted interest in the fission industry but the potential for these systems in fusion has not yet been studied in depth.
5. Majeski's concept includes two interesting suggestions: a. a heat exchanger (HX) inside the vessel, and b. less than full spatial coverage of the liquid FW, e.g., an open toroidal slot at the top or bottom of the wall to be used for injection of power and for diagnostics.
6. Ga does not provide lithium's beneficial interaction with the plasma but its properties provide excellent heat transfer, and systems with Ga or a liquid metal alloy have been suggested, possibly for a liquid divertor in combination with a solid wall. In an FNSF or DEMO, this choice adds another working fluid and separate systems from the FW and blanket to exchange heat and to extract tritium.
7. Molten salts have been studied for fission applications. For the case here, the liquid surface is mixture of Li, Na and Be fluorides [24]. This system is the only low pressure system listed in the table and included for that reason.
8. Many favor solid breeders over liquid breeders, as reflected in earlier EU DEMO designs and choices for the ITER Tritium Blanket Modules [25]. This case is included as a likely representative of CPS systems applied to both the FW and divertor.

General conclusions

The main point in this paper is to apply the following rationale to R&D on liquid surfaces. The efforts that supply liquid surfaces for near term research, principally to enable interaction of the plasma edge with liquid lithium, are directed at the physics of the plasma edge and this motivation supports the research as appropriate. The extension of these and other ideas that purport to provide solutions for heat exhaust in a divertor or first wall or both are attempting to satisfy a different goal. To do so these concepts must pay attention to the constraints imposed by their integration into the overall design of in-vessel subsystems in a D-T device with a breeding blanket.

However, those proposing the concepts for liquid metal surfaces may not understand design integration. Those who do (as best we can now) are rather few in number with backgrounds in machine design or in fusion reactor design studies. The following recommendation was offered in the Plasma Interactions Workshop noted earlier. The US program (or others) should organize a small work group with the appropriate expertise on the design of fusion in-vessel subsystems to examine selected designs for liquid surface applications and evaluate the readiness of the technology in terms of the types of technical considerations described above. This group should work informally with those developing liquid surface comments and have informal web conferences or workshops in which the ideas and their limitations and implications are discussed. The scope might also include how the concepts could be deployed in near term experiments that were productive for long term development.

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