Fusion Engineering and Design 100 (2015) 44–54

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Dual-coolant lead–lithium (DCLL) blanket status and R&D needs

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ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form
10 December 2014
Accepted 11 December 2014
Available online 14 February 2015

Keywords:
DCLL blanket
R&D
Test facilities
MHD
Liquid metal
Lead–lithium

ABSTRACT

The DCLL is an attractive breeding blanket concept that leads to a high-temperature ($T \sim 700\,^\circ$C), high thermal efficiency ($\eta > 40\%$) blanket system. The key element of the concept is a flow channel insert (FCI) that serves as an electrical and thermal insulator to reduce the magnetohydrodynamic (MHD) pressure drop and to decouple the temperature-limited RAFM (reduced-activation ferritic/martensitic) steel wall from the flowing hot PbLi. The paper introduces the concept, reviews history of the development of the DCLL in the US and worldwide and then identifies critical R&D needs prior to fusion environment testing in four research areas important to the successful development of the DCLL concept: (1) PbLi MHD thermofluids, (2) fluid materials interaction, (3) tritium transport, and (4) FCI development and characterization. For these areas, the most important R&D results obtained in the US in the ITER DCLL TBM program (2005–2011) and more recently are reviewed, including experimental and computational studies of MHD PbLi flows, corrosion of RAFM, tritium permeation, and silicon carbide FCI fabrication and material qualification. We also discuss required features of non-fusion facilities for DCLL blanket testing, where current lab experiments and modeling could progress to multiple effects and partially-integrated studies that approach as nearly as possible prototypic, integrated blanket conditions prior to testing in a fusion environment.

1. Introduction

The pathway to the successful development of a DEMO reactor and ultimately to a power plant requires an effective strategy for the development and qualification of a number of key fusion components, including identification of critical R&D needs followed by numerical computations and experimental studies in non-fusion facilities prior to testing these components in the fusion environment [1]. Among these components, development of a reliable, low-cost and safe blanket system that provides self-sufficient tritium breeding and efficient conversion of the extracted fusion energy to electricity, while meeting all material, design and configuration limitations is among the most important but still challenging goals [2]. In this paper, we focus on the status and critical R&D needs of a particular blanket system called DCLL (dual-coolant lead–lithium) blanket since this concept promises a solution towards a high-temperature, high-efficiency blanket while using temperature-limited reduced-activation ferritic/martensitic (RAFM) steel as structural material [3]. In this concept, a high-temperature lead–lithium (PbLi) alloy flows slowly ($V \sim 10$ cm/s) in large poloidal rectangular ducts ($D \sim 20$ cm) to remove the volumetric heat generated by neutrons and produce tritium, while a pressurized (typically to 8 MPa) helium gas (He) is used to remove the surface heat flux and to cool the ferritic first wall (FW) and other blanket structures in the self-cooled region, and a low-conductivity flow channel insert (FCI), which is typically a few mm thick, with silicon carbide (SiC) as a suitable candidate material, is used for electrical and thermal insulation (Fig. 1).

2. Characteristics and development of the DCLL blanket concept

Several designs of the DCLL blanket have been considered in Europe [4–7], the US [8–13] and China [14–16]. Historically, the first DCLL version, known as a low-temperature (LT) DCLL blanket [4], relied on qualified materials and existing fabrication technologies. A key component of this design is a sandwich-type FCI composed of steel/alumina/steel layers or a thin alumina layer placed on the wall to be used as electrical insulator for decoupling electrically conducting structural walls from the flowing PbLi. In the high-temperature (HT) DCLL blanket, first introduced in [9], an FCI made of silicon carbide (SiC), either composite [17] or foam [18], was further proposed as a means for electrical and also thermal insulation to provide acceptable MHD pressure drops, to achieve a

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http://dx.doi.org/10.1016/j.fusengdes.2014.12.031
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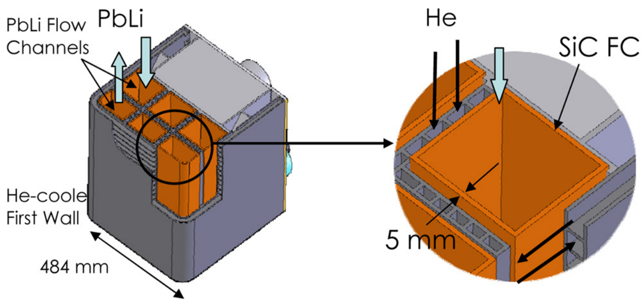

Fig. 1. Schematic of DCLL blanket with poloidal PbLi channels, He-cooling channels and insulating SiC FCI [9].

high PbLi exit temperature of ~700 °C (*i.e.* ~200 K higher than the maximum allowable temperature at the PbLi/RAFM interface, and about 150 K higher than the maximum allowable temperature of RAFM steel) and, ultimately, to provide high thermal efficiency of about 45% (as opposed to about 470 °C and 34% in the LT design) by enabling the use of a BRAYTON power conversion cycle. In practice, utilization of SiC as a functional material for these inserts requires substantial R&D efforts in both qualification of its thermo-physical/thermo-mechanical responses to neutron irradiation at high temperature and development of fabrication technologies for manufacturing complex shape FCIs. It also requires detailed studies of fluid materials (PbLi–SiC, RAFM) interactions in the presence of a strong (4–12 T) magnetic field and neutron volumetric heating. From this point of view, the low-risk LT concept can be viewed at present as an important intermediate step for implementation in an early DEMO blanket on the pathway towards a more attractive high-temperature blanket system, while the HT DCLL version can be utilized successfully afterward. To illustrate differences between the two DCLL versions, typical parameters of LT and HT DCLL blankets are summarized in Table 1 using the European blanket comparison and selection study (EU BCSS) [4], the US ARIES-ST study [8], the US ITER TBM [12] and the US HT DCLL blanket [11] as examples.

As demonstrated in Ref. [19], a 5-mm SiC FCI can reduce the MHD pressure drop in poloidal ducts by up to two orders of magnitude compared to non-insulated ducts. For example, for the outboard blanket (US ITER TBM [12]: magnetic field ~4–5 T) the overall pressure drop in the blanket module is ~0.4 MPa [20]. For the inboard blanket (US HT DCLL blanket [11]: magnetic field ~10–12 T), it is ~1.2 MPa [21]. Such relatively low pressure drops will require, however, sufficiently low FCI electrical conductivities: $\sigma \sim 1$ S/m for the inboard blanket, and $\sigma < 50$ S/m for the outboard blanket. It should be mentioned that FCIs will be less able to reduce the so-called 3D MHD pressure drops, associated with generation of 3D electrical currents in such blanket components as inlet and outlet manifolds as these currents are mostly closing in the flow domain. In conditions when sufficient electrical insulation of the blanket ducts is provided *via* FCIs, the manifolds and any gaps between adjacent FCIs and other blanket elements carrying 3D electrical currents will remain the most source of the pressure loss in the blanket and will be responsible for more than 90% of the total MHD pressure drop. It was also demonstrated [19] that in conditions of the HT DCLL blanket, the temperature drop across the FCI wall may exceed 200 K, possibly leading to intolerably high thermal stresses. To mitigate this problem a modification of the conventional FCI in the form of a nested FCI (nFCI) was proposed in [22]. In the nFCI design, the thermal insulation is shared between the inner and outer FCI, while the inner FCI provides most of electric insulation. The thickness of the FCI layers can easily be adjusted and the choice between one or four detached plates for the outer FCI can be made to meet concrete design requirements and heating conditions and, for example, to distinguish between flows in the front and return ducts. Compared to the single-layer FCI, electrical conductivity of the outer FCI is of minor importance, and a degradation of its electrical insulation due to cracks or LM filled pores is of no concern. As demonstrated in [22] *via* numerical computations in DEMO reactor conditions, nFCI mitigates the thermal stress while providing sufficient thermal insulation and reducing the MHD pressure drop.

3. Research needs for DCLL blankets

DCLL blankets have many issues in common with other blankets. Correspondingly, many requirements and research needs for DCLL blankets are not very different from other types of blankets. The associated considerations common to all liquid and solid breeder blankets include:

(a) Detailed modeling of tritium breeding and shielding in order to guarantee tritium self-sufficiency and adequate shielding of the reactor vacuum vessel and coils.
(b) Design for high reliability and fast maintenance.
(c) Design for effective after-heat removal in case of loss-of-coolant accident.
(d) Qualification of structural and functional materials in neutron irradiation conditions, including impact of high helium concentration.
(e) Fabrication of a large complicated structure of blanket modules or segments.
(f) Design and fabrication of FW armor required at locations with strong plasma-wall interactions.
(g) Development of non-destructive instrumentation tools to diagnose key physical processes in the blanket.

Similar to other liquid-metal blankets that utilize PbLi, including helium-cooled (HCLL) [23], self-cooled (SCLL) [24] and water-cooled (WCLL) [25] blankets, the DCLL blanket has critical issues associated with:

(a) Chemical reactivity of PbLi with water and air.
(b) Polonium (Po-210) generation in PbLi by neutrons.
(c) Corrosion of steel in the flowing PbLi and deposition of activated corrosion products in the "cold" section of the loop.

Many special features are also shared between the DCLL blanket and all blankets that use He-cooling. These common features are related to heat transfer in turbulent He flows in cooling channels. Associated considerations have to be given to:

Table 1
Key parameters of the DCLL blanket in the proposed LT and HT designs.

DCLL concept	Average neutron wall load (MW/m^2)	Average surface heat flux (MW/m^2)	He inlet/outlet temperature (°C)	PbLi inlet/outlet temperature (°C)	Thermal efficiency (%)
DCLL in EU BCSS [4]	2.2	0.4	250/350	275/425	34
DCLL in ARIES-ST [8]	4.0	0.8	350/500	480/700	45
US ITER TBM [12]	0.78	0.3	350/410	360/470	–
US HT DCLL blanket [11]	2.13	0.5	300/480	460/700	>40

(a) Effective cooling schemes of large internal heat transfer surfaces using turbulence promoters such as ribs, fins and surface roughening to provide heat transfer coefficient at some locations on the order of 10,000 W/m^2-K.
(b) Design for a large number of internal coolant ducts and tubes and associated large number of welds.
(c) Design for minimized pumping power in the He loop, usually <3% of the thermal power removed.

Compared to the entirely He-cooled blanket concepts, the required heat transfer area in the self-cooled breeding zone of the DCLL blanket is significantly smaller. Therefore, a significantly smaller number of coolant ducts and welds in the DCLL blanket and a lower He pumping power for heat extraction are required.

What makes the DCLL blanket unique compared to other blankets is the use of FCIs for electrical/thermal insulation. The FCI is a critical design component, first of all for the HT DCLL blanket. Requirements for a SiC FCI have been formulated in [20,21,26,27]. FCIs must have low electrical and thermal conductivity and be compatible with the flowing PbLi at elevated temperatures. They must retain structural integrity and desirable properties even under irradiation and large temperature gradients during operation. Any damage that may lead to PbLi ingress into the bulk FCI material, *e.g.* cracks, are not allowed due to possibly significant degeneration of electrical or thermal insulation. As currently envisioned, there is a thin (typically 2-mm thick) gap spacing between the FCI and the surrounding RAFM structure filled with PbLi (Fig. 1) to accommodate possible FCI thermal expansions. The FCIs float freely in the liquid metal and overlap loosely with adjacent FCIs and thus do not experience significant mechanical stresses. Furthermore, mechanical stresses that might be caused by the pressure difference between the gap and bulk (inside the FCI) flows are minimized *via* the pressure equalization mechanism. The pressure equalization in the flowing PbLi between the gap and the FCI interior occurs either electromagnetically (*via* the electric currents crossing the FCI) or hydrodynamically (*via* PbLi flows through the pressure equalization openings in the FCI) [19]. The impact of a magnetic field and multi-material environment on the transport processes in the gap has not been fully characterized yet. For instance, corrosion of RAFM steel, transport of corrosion products and tritium transport that occur here are known to be severely affected by MHD effects [28,29]. All these unique features of the DCLL blanket suggest special R&D tasks that run into four basic areas, such as: (1) PbLi MHD thermofluids, (2) fluid materials interaction, (3) tritium transport, and (4) FCI development and characterization. In particular, the following R&D studies in non-fusion facilities have been identified prior to fusion environment testing:

(a) Impact of a strong magnetic field on the flowing PbLi and heat transfer in the presence of electrically and thermally insulating FCIs.
(b) Corrosion of RAFM in the flowing PbLi in the thin gaps formed by the RAFM wall and the FCI and deposition of activated corrosion products in the cold section of the loop.
(c) Tritium transport in a multi-material DCLL blanket environment, including PbLi, RAFM and SiC.
(d) Development of complex-shape FCIs and characterization of SiC properties and FCI performance as an electrical and thermal insulator.

In the rest of the paper, we summarize the most important R&D results obtained over the last ten years, including the US ITER TBM program (2005–2011) and more recent blanket studies in the US in the particular areas important to the DCLL blanket and also discuss unresolved DCLL issues and future R&D needs prior to testing in fusion nuclear environment.

4. Current studies for MHD thermofluid and fluid materials interactions

For decades, liquid metal blankets were designed using simplified models based on limited experimental data, starting from a slug-flow approximation, followed by a more advanced “core flow” approach [30]. The associated R&D studies mostly focused on MHD pressure drop in typical blanket configurations. Among a number of concerns related to liquid metal blankets, reduction of MHD pressure drop still remains one of the most important issues, stimulating new ideas and efforts on decoupling the electrically conducting wall from the fluid. Even for relatively slow PbLi flows in the breeding zone of a DCLL blanket, without such a decoupling, the mechanical stresses in the duct walls caused by the MHD pressure drop can be intolerably high, especially for inboard blankets. These stresses cannot be reduced by making the duct walls thicker as thickening the wall will cause a proportional increase in the induced currents.

Beyond the MHD pressure drop and associated flow balancing, there are many important phenomena that have not yet been uncovered. Therefore current research in the US and worldwide [31,32] are focusing more on the detailed structure of MHD flows, including various 3D and unsteady effects associated with flow instability, MHD turbulence and buoyancy-driven convection [33]. These complex MHD flow processes can affect transport properties of MHD flows in drastic ways and have a significant impact on blanket operation and performance. In spite of significant success in advancing our knowledge of blanket flows in the recent past, the MHD thermofluid phenomena in blanket-relevant conditions are not yet fully characterized. For example, the mass transport in the DCLL blanket (*e.g.* tritium permeation and corrosion/deposition processes) is closely coupled with MHD flows and heat transfer, requiring much better knowledge of MHD flows compared to relatively simple pressure drop predictions.

4.1. Instabilities in poloidal flows of the DCLL blanket

As suggested in [33], in almost all liquid-metal-cooled blankets, including the DCLL, the MHD flows in poloidal ducts will most likely appear in a special form of quasi-two-dimensional (Q2D) turbulence [34]. Even though analysis of such Q2D MHD flows was started a few decades ago (see, *e.g.* [35]) the underlying physics of these flows and their impact on blanket operation need further consideration. Two recent theoretical studies [36,37] address Q2D MHD flows and elucidate possible MHD instability mechanisms in conditions relevant to the DCLL blanket. In the first one [36], direct numerical simulations (DNS) and a linear stability analysis are performed for a family of Q2D MHD flows with high-velocity near-wall jets. The generic basic velocity profile with points of inflection is produced by imposing an external flow-opposing force. By varying this force, various instability modes and transition scenarios are reproduced. First, a linear stability analysis is performed and then nonlinear effects are studied using DNS for Hartmann numbers 100 and 200 and Reynolds numbers from 1800 to 5000. Special attention is paid to the location of the inflection point with respect to the duct wall. Complex non-linear flow dynamics, including various vortex–wall and vortex–vortex interactions, and even negative turbulence production are observed and analyzed as the inflection point approaches the wall. The analysis lends insight into what is typically called “jet instability” suggesting that instability and transition to Q2D turbulence in blanket flows occurs as a two-step process. First bulk vortices appear at the vicinity of the inflection

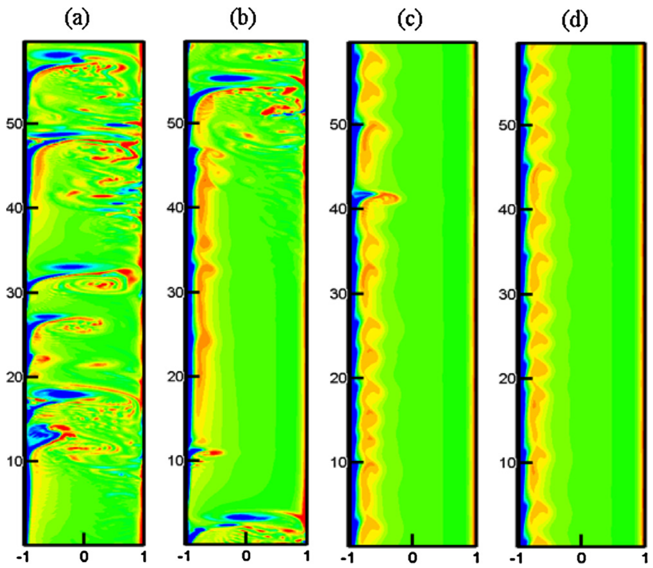

Fig. 2. Vorticity snapshots in a turbulent mixed-convection flow at $Re = 5000$ and $Gr = 10^8$. *Strong turbulence*: (a) $Ha = 50$, and (b) $Ha = 60$. *Weak turbulence*: (c) $Ha = 100$, and (d) $Ha = 120$.

point. Then, the bulk vortices interact with the side-wall boundary layer (at the wall parallel to the magnetic field) causing its destabilization and eventually turbulence.

The second study [37] considers MHD rectangular duct flows with volumetric heating (mixed-convection flows). The flows are upward, subject to a strong transverse magnetic field perpendicular to the temperature gradient, such that the flow dynamics are Q2D. The internal volumetric heating imitates conditions in a blanket of a fusion power reactor, where a buoyancy-driven flow is imposed on the forced flow. Studies of this mixed-convection flow include analysis for the basic (undisturbed) flow, linear stability analysis and DNS-type computations. The parameter range covers the Hartmann number (Ha) up to 500, the Reynolds number (Re) from 1000 to 10,000 and the Grashof number (Gr) from 10^5 to 10^9. The linear stability analysis predicts two primary instability modes: (i) bulk instability associated with the inflection point in the velocity profile near the "hot" wall and (ii) side-wall boundary layer instability. A mixed instability mode is also predicted. An equation for the critical Hartmann number that characterizes laminar-turbulent transitions has been obtained as a function of Re and Gr:

$$Ha_{cr} = P_1(\log Gr)^2 + P_2 \log Gr + P_3, \quad (1)$$

where

$$P_1 = -5.98 \times 10^{-8} Re^2 + 2.284 \times 10^{-3} Re + 2.308,$$

$$P_2 = 1.8277 \times 10^{-6} Re^2 - 7.3037 \times 10^{-2} Re - 22.787,$$

$$P_3 = -1.37 \times 10^{-5} Re^2 + 0.57516 Re - 95.8.$$

Based on this formula, flows with $Ha > Ha_{cr}$ are linearly stable, while for $Ha < Ha_{cr}$ bulk instability seems to be possible.

Effects of Ha, Re and Gr on turbulent flows are addressed *via* non-linear computations that demonstrate two characteristic turbulence regimes (Fig. 2). In the "weak" turbulence regime, the induced vortices are localized near the inflection point of the basic velocity profile, while the boundary layer at the wall parallel to the magnetic field is slightly disturbed. In the "strong" turbulence regime, the bulk vortices interact with the boundary layer causing its destabilization and formation of secondary vortices that may travel across the flow, even reaching the opposite wall. In this regime, similar to observations in [36], the key phenomena are vortex–wall and vortex–vortex interactions.

Even though the parameters used in the computations are lower than blanket conditions in DEMO and beyond where $Ha \sim 10^3$–10^4, $Re \sim 10^4$ and $Gr \sim 10^9$–10^{12}, extrapolating obtained trends to such high values suggests that observed instability modes, vortex–vortex and vortex–wall interactions as well as Q2D turbulence in the form of either weak or strong turbulence are likely to occur in DCLL blanket flows, but other new phenomena may be discovered as well. In addition to upward flows, similar studies have to be performed for downward flows. First analysis for downward flows [38] has demonstrated that reverse flows are likely to occur near the "hot" wall due to a strong flow-opposing buoyancy effect. Therefore, in a DCLL blanket, the PbLi flows should be routed in such a way that the liquid metal flows downwards in the ducts with lower volumetric heating and upwards in those ducts where volumetric heating is higher. Such a flow scheme has been implemented in the US ITER TBM design and DEMO blanket [11].

4.2. Experimental studies with PbLi at UCLA

A new MHD PbLi facility called MaPLE (magnetohydrodynamic PbLi experiment) has recently been constructed and successfully operated at UCLA [39] (Fig. 3). This is the only facility of this class in the US and one of a few in the world. The loop operation parameters are: maximum magnetic field 1.8 T, PbLi temperature up to 350 °C, maximum PbLi flow rate with/without a magnetic field 15/50 l/min, maximum pressure head 0.15 MPa. Testing of the loop and its components has demonstrated that the new facility is fully functioning and ready for experimental studies of MHD, heat and mass transfer phenomena in PbLi flows and also can be used in mock up testing in conditions relevant to fusion applications.

The facility was constructed in 2011 to serve experimental needs of the JA-US TITAN program to address important MHD/Heat Transfer phenomena relevant to basic PbLi blanket concepts in Japan and US [40]. Ongoing work on development and testing of flow diagnostics needed for high temperature PbLi flows includes ultrasonic velocimetry (HT UDV) and an indirect technique of differential pressure measurements as described in detail in Refs. [39,40]. Intensive studies have been started to address MHD pressure drop reduction in PbLi flows using two different insulation techniques: (1) laminated walls [41] and (2) a SiC foam-based FCI [39]. Initial studies were also performed to address material compatibility between SiC and PbLi. These include static testing at high temperature of 700 °C in a specially designed static chamber and dynamic testing of various FCI samples (see also Sections 4.3 and 5).

4.3. 3D computations for MHD PbLi flows with FCI

Prior to experimental studies on MHD pressure drop reduction in PbLi flows with an insulating FCI, computer simulations were performed using a 3D MHD, unstructured mesh, parallel code HIMAG [38,42]. In the ongoing experiments, a 30 cm SiC foam-based FCI segment manufactured by Ultramet, USA is tested first. The FCI is filled with either silica or carbon aerogel and then coated with a thin (~1 mm) CVD layer to prevent PbLi ingress into pores. In the next experiments, testing is planned on two coupled segments resulting in a total length of 60 cm (Fig. 4). These two segments are either separated with a small 1-mm slit or connected together with a "T-bracket" also shown in Fig. 4.

The FCI/FCIs are placed inside a long (2-m) thin-wall (3-mm) stainless steel host rectangular duct such that there is a 2-mm gap spacing between the steel wall and the FCI similar to the real blanket conditions. Prior to the experiments, computations were performed to evaluate the pressure drop reduction factor R (R-factor) defined as the ratio of the pressure drop due to MHD effects without an FCI relative to that with an FCI, and covers a range 4 cm fore and rear of the FCI. The simulations explore the 3D phenomena

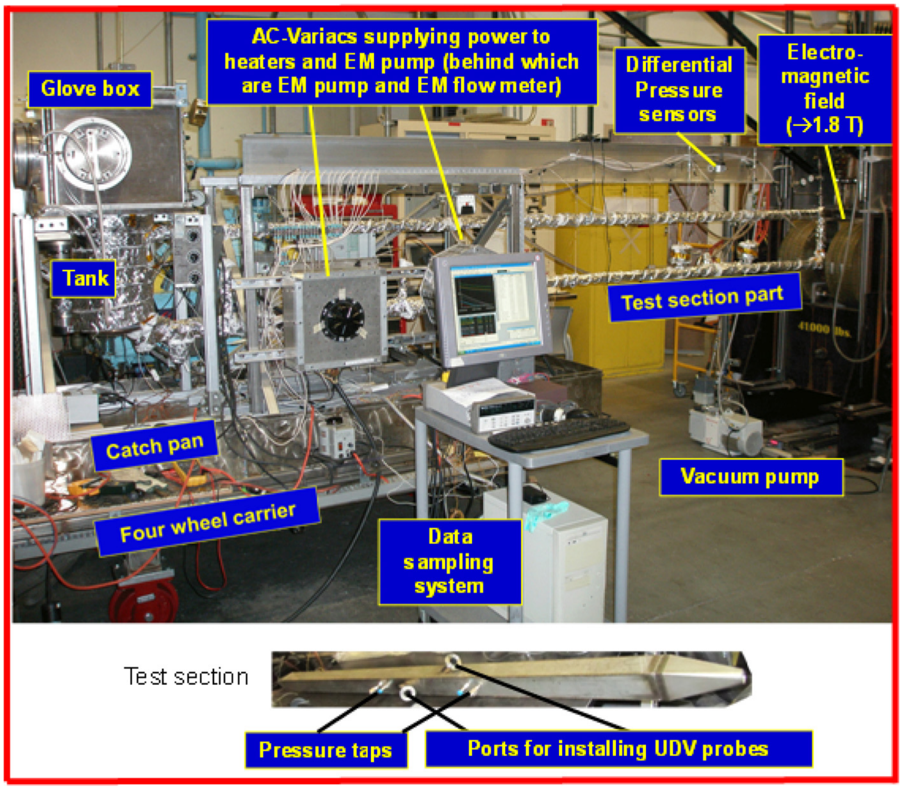

Fig. 3. Photograph of the MHD PbLi loop MaPLE at UCLA, including the test-section.

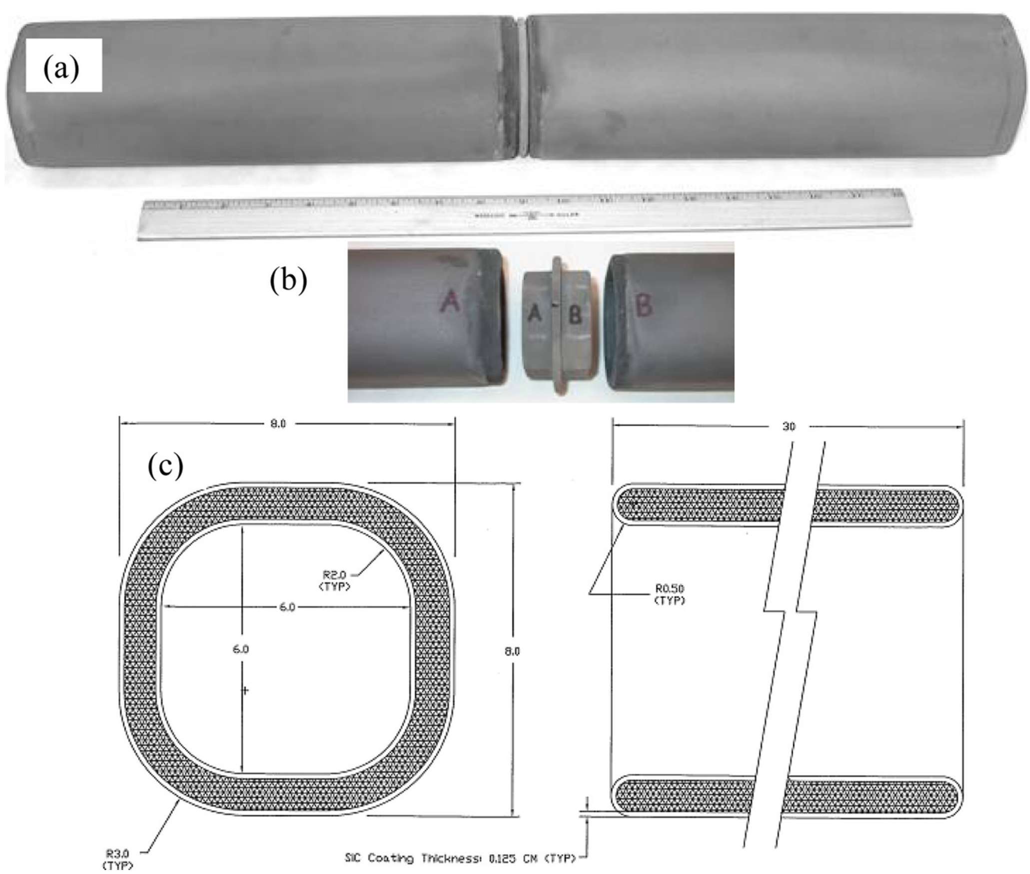

Fig. 4. Foam-based SiC FCI by Ultramet, USA: (1) two FCI segments connected together, (b) connecting FCI segments with a “T-bracket, (c) overall FCI segment dimensions.

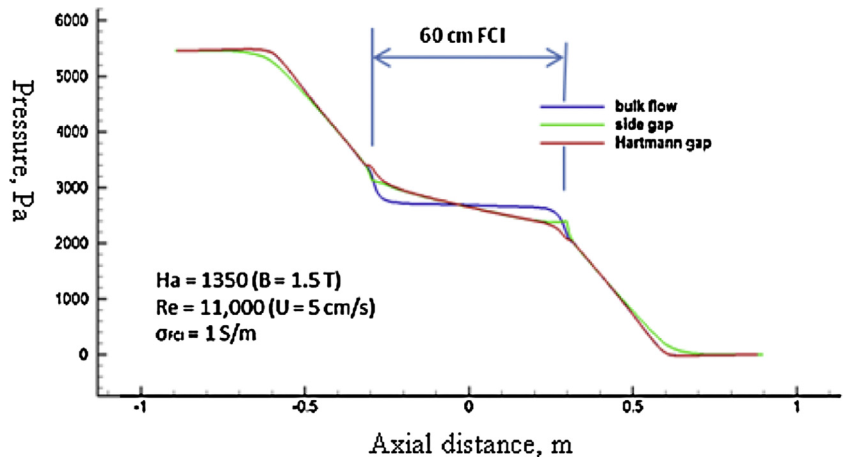

Fig. 5. Typical pressure distribution in MHD flow with an FCI.

associated with MHD flows that will be present in the experiments using the MaPLE facility at UCLA. The simulation configurations also match those of the DCLL blanket. Some results of this pre-experimental analysis are shown below.

The experimental parameter space is large, with uniform B-field strengths varying from 0 to 1.8 T, inlet velocity varying from 1 to 15 cm/s, and 30 and 60 cm FCI lengths, all of which have been numerically analyzed in the pre-experimental study. Accordingly, the Reynolds, Hartmann, and interaction numbers ($N = Ha^2/Re$) reach at least 3.4×10^4, 1.6×10^3, and 2.5×10^2, respectively. A sample pressure profile calculated for a 60-cm FCI is shown in Fig. 5. The pressure difference between the bulk and gap flows changes within the FCI length as these flows are electrically decoupled by the FCI and no pressure equalization openings are made in the FCI. However, this pressure difference is small compared to the overall FCI flow pressure drop. Fig. 6 shows a trend found for the pressure drop reduction factor. Regardless of the *Re* and *Ha* values used in the computations, the *R*-factor is always described well as a function of *N* only. In post-experimental analysis, the numerical simulations towards higher interaction numbers will be attempted. It is noticeable that the calculated *R*-factor for the FCI segment is typically around 2. Such modest MHD pressure drop reductions in the experiment are related to the significant increase in the MHD pressure drop due to 3D MHD effects at the FCI segment entry/exit and also due to electrical current leakages from the bulk flow into the gap in the junction region between the two segments. In the real blanket, where FCIs are continuously spaced inside the RAFM duct, and thus the noticeable 3D effects are not present, the *R*-factor in the range 50–100 can be expected as predicted in Ref. [19].

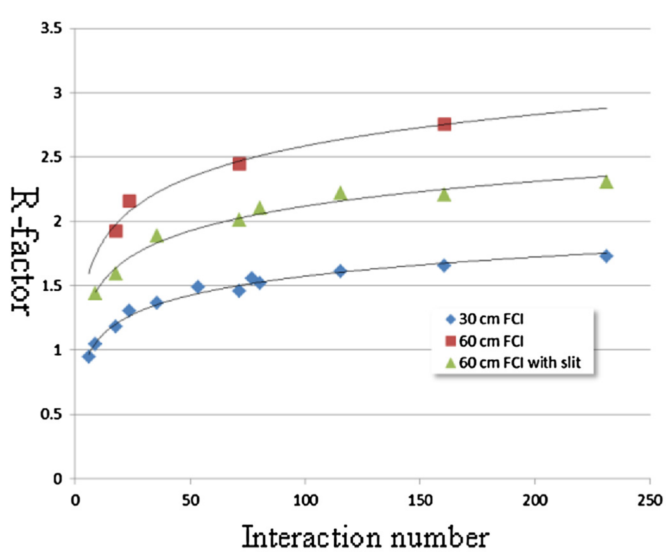

Fig. 6. Simulations of the MHD pressure drop reduction in the FCI experiments.

4.4. Modeling of corrosion in RAFM–PbLi system

Implementation of RAFM steels and PbLi in blanket applications still requires material compatibility studies as many questions related to physical/chemical interactions in the RAFM–PbLi system remain unanswered. First of all, the mass loss caused by the flow-induced corrosion of the steel walls at temperatures in the range 450 °C −550 °C needs to be characterized. Present PbLi blanket studies limit the maximum wall thinning to 20 μm/yr that corresponds to the maximum wall temperature at the interface with the liquid metal in the hot leg of about 470 °C. These limits were derived in the past in the US in the blanket comparison and selection study (BCSS) based on experience with sodium loops, where blocking of the liquid metal circuit by precipitated corrosion products was frequently observed in the cold section of the loop (see, *e.g.* [43]). Second, along with a possible deterioration of the mechanical integrity of the blanket structure due to the wall thinning at the interface with the flowing PbLi, another serious concern is the transport of activated corrosion products and their precipitation in the cold section of the loop. Third, an important modeling parameter, the saturation concentration of iron in PbLi, needs further evaluations as the existing correlations (Fig. 7) demonstrate scattering of several orders of magnitude. Fourth, effects of many parameters on corrosion/deposition processes in the presence of a magnetic field have not been characterized yet, such as Q2D MHD turbulence, a multi-material environment (*e.g.* presence of SiC), and magnetic field gradients.

To address these issues, a computational suite called TRANSMAG (transport phenomena in magnetohydrodynamic flows) has recently been developed [29]. The computational approach is based on simultaneous solution of flow, energy and mass transfer equations with or without a magnetic field, assuming mass transfer controlled corrosion and uniform dissolution of iron in the flowing PbLi. First, the new tool was applied to solve an inverse mass transfer problem, where the saturation concentration of iron in PbLi at temperatures up to 550 °C was reconstructed from the earlier experimental data on corrosion in turbulent flows without a magnetic field. As a result, a new correlation for the saturation concentration C^S has been obtained in the form $C^S = e^{13.604-12975/T}$, where *T* is the temperature of PbLi in *K* and C^S is in wppm. This new

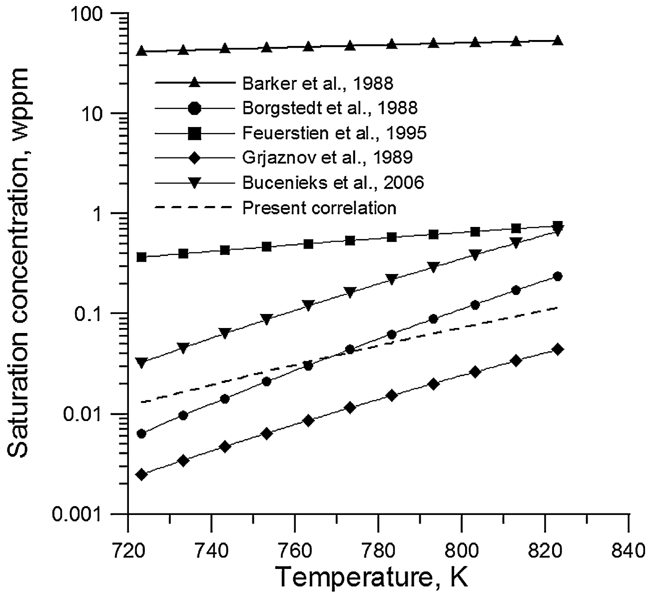

Fig. 7. New and earlier correlations for saturation concentration of iron in PbLi.

correlation is shown in Fig. 7 along with other correlations obtained earlier.

Second, the new correlation was used in the computations of corrosion in laminar flows in a rectangular duct in the presence of a strong transverse magnetic field. In agreement with earlier experimental data for corrosion in MHD flows [44], the mass loss increases with the magnetic field such that the corrosion rate in the presence of a magnetic field can be a few times higher compared to purely hydrodynamic flows. In addition, the corrosion behavior was found to be different between the side wall of the duct (parallel to the magnetic field) and the Hartmann wall (perpendicular to the magnetic field) due to formation of high-velocity jets at the side walls. The side walls experience a stronger corrosion attack demonstrating a mass loss up to 2–3 times higher compared to the Hartmann walls. This analysis suggests scaling laws for the mass loss in rectangular ducts in the form: $ML{\sim}e^{p^T} U_m^q B_0^s$ for the side wall, and $ML{\sim}e^{p^T} U_m^q$ for the Hartmann wall, where $q, s \sim 0.5$. This analysis suggest that the corrosion rate and associated maximum allowable temperature at the RAFM/PbLi interface in the conditions of the DCLL blanket need to be revisited taking into account MHD effects and temperature variations in specific gap flow conditions.

5. SiC FCI development and characterization

5.1. SiC materials

For the SiC FCI material, the goal is low thermal conductivity of 1–2 W/m-K and low electrical conductivity of about 1 S/m for the inboard DCLL blanket. Higher electrical conductivities of about 50 S/m are allowed for lower magnetic field outboard blanket modules. When using such materials, MHD pressure drop reduction in poloidal flows by a factor of 50–100 times is expected compared to bare ducts. Two different approaches to development of SiC materials with desirable thermomechanical properties and to fabrication of FCI parts of required shapes and dimensions are presently considered worldwide. In the first approach, 2D fiber-reinforced SiC composite material (SiC/SiC composite) is proposed to allow for a relatively thin FCI wall of about 5 mm. Such composites can be produced by either chemical vapor infiltration (CVI) or nano-infiltrated and the transient eutectic-phase (NITE) method. In irradiation conditions at 400–600 °C, the thermal conductivity of such materials will most likely rapidly reduce to about 2–3 W/m-K regardless of the initial value (that is typically higher), as analyzed in Ref. [45]. The effect of irradiation on electrical conductivity is more complex as measured recently in Ref. [46]. For the assessment of MHD impacts on the flowing PbLi it is important to know the electrical conductivity of the FCI in realistic operating conditions. This includes changes in electrical conductivity by a strong ionizing gamma-field and also due to neutron fluxes, which are known to modify the electrical properties of SiC composites very significantly, resulting in orders of magnitude lower room temperature conductivity and a steeper temperature dependency.

In the blanket conditions, SiC materials should be able to withstand both thermal and irradiation-induced stresses caused by thermal expansion and differential swelling, respectively [47]. The allowable thermal stress in the FCI is typically limited to 120 MPa, wich corresponds to the maximum temperature drop across the FCI wall of about 150–200 K. Mostly, these temperature limitations can be met using a conventional one-layer FCI. In some cases, for example for FCIs located in the front poloidal ducts, nested FCIs [22] may be needed to tolerate a temperature drop greater than 200 K. Differential swelling occurs as the result of accumulation of radiation-produced defects at an atomic scale. In certain conditions (*e.g.* in the low temperature range), differential swelling in SiC/SiC composites may dominate over thermal expansion causing substantial internal stress and/or deformations when a significant temperature gradient is present within the FCI. Swelling of high-purity monolithic SiC has been studied in detail over a wide temperature range of 303–1873 K [48]. Analogous studies for SiC composites have just been started [49]. Recent investigations for SiC/SiC composites at intermediate (390–540 °C) to high (790–1180 °C) temperatures and 2 dpa [50] suggest a linear relationship between the differential swelling and the irradiation creep strain. The present R&D results are, however, not sufficient to formulate a realistic constitutive equation for SiC/SiC composites to include irradiation effects. Therefore, full computations of stresses and deformations in the FCI are presently not possible.

A foam-based SiC material is also considered as a possible candidate for blanket applications [18]. The idea is to utilize a core of low-density SiC foam, sealed at all surfaces with a layer of CVD SiC. A potential advantage of this foam-based SiC is that it does not require costly high-quality fibers, can internally absorb thermal and irradiation swelling, and can have low thermal and electrical conductivity. Using foam materials may, however, result in significantly thicker FCIs, displacing PbLi from the breeder region, and thus reducing the tritium breeding ratio (TBR). At present, FCI segments with 8 mm core and 1 mm thick CVD layers resulting in the overall FCI thickness of 1 cm have been successfully manufactured by Ultramet, USA. Thinner foam-based FCIs approaching 5-mm thickness seem to be possible in the future as the fabrication technology matures. As measured in [18] at room temperature in non-irradiation conditions, the electrical conductivity of foam-based SiC is 0.1–10 S/m and thermal conductivity is 4–7 W/m-K depending on materials and surface pre-conditioning. A main concern about the use of SiC foam-based material is, however, the potential for massive infiltration of PbLi into the foam through the cracks that may develop in the CVD layer.

5.2. FCI fabrication and testing

Development and fabrication of SiC foam-based FCIs have been started in the US by Ultramet, and both static and dynamic (in the flowing PbLi conditions) testing of FCI samples is in progress using the PbLi MaPLE facility at UCLA (see also Sections 4.2 and 4.3). The FCI samples tested in dynamic conditions are shown in Fig. 4. In the static tests, two nominally 12 cm long FCI segments were placed in the specially designed hot-temperature PbLi test chamber. The samples have 15 vol% density. To protect the samples from PbLi

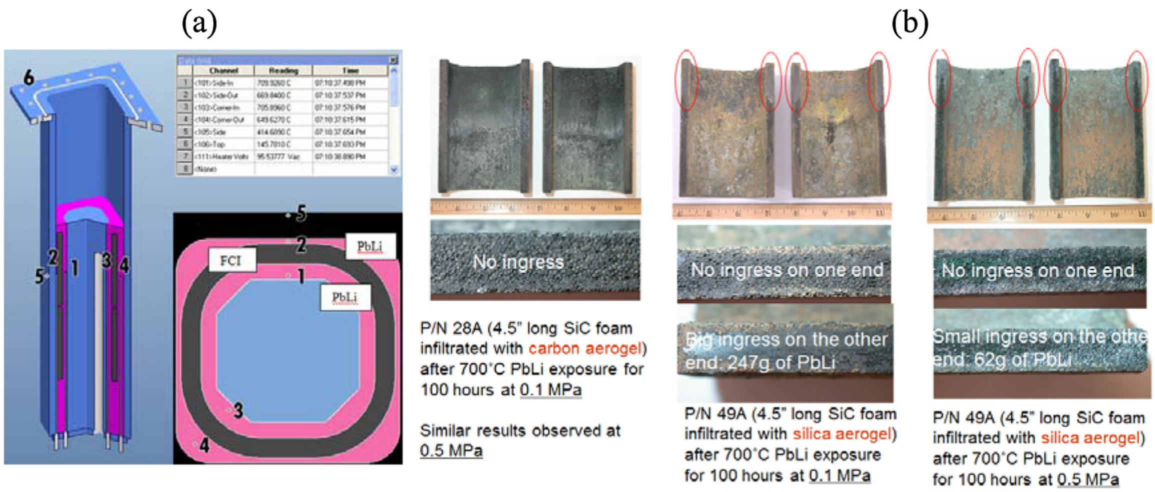

Fig. 8. Static testing of SiC foam-based samples filled with silica and carbon aerogel: (a) high temperature test chamber, (b) results of microscopic studies after exposing FCI samples to hot PbLi at two pressures 0.1 and 0.5 MPa.

ingress, the 85% porosity material is filled with aerogel: one sample was filled with silica aerogel and the other with carbon aerogel (no. 49A and no. 28A in Fig. 8). No protective CVD layer was applied. In the experiments, a prototypic temperature gradient of about 150 K is applied to the FCI walls by using an internal heater and forced air cooling on the outer side. The SiC test parts were first exposed at a temperature that approaches 700 °C and an over-pressure of 0.1 MPa for 100 h. In the second test, the two samples used in the first experiment were replaced with two new samples and exposed to the same conditions but with a higher over-pressure of 0.5 MPa.

The results of these tests for both pressures are summarized in Fig. 8. In all cases, no visible FCI cracking was observed. The FCI samples filled with carbon aerogel have demonstrated no or insignificant ingress of PbLi into pores. One silica filled sample demonstrated pronounced PbLi ingress at one end and no ingress at the other end of the sample at 0.1 MPa. Surprisingly, similar tests of the silica-filled sample at 0.5 MPa show insignificant ingress. It is most likely that PbLi ingress into pores of the silica filled sample at 0.1 MPa occurred because of incomplete filling of the sample with aerogel. To conclude, the results of static testing look promising as they show no (or just insignificant) PbLi ingress (even though the protective CVD layer is not applied) and no FCI cracking.

6. Tritium transport in the presence of SiC FCI

In the DCLL blanket, tritium losses from the PbLi into cooling He streams may occur when the liquid metal breeder is moving in the poloidal ducts. Quantitative analysis of the mass transfer processes associated with the tritium transport in the breeder as well as tritium diffusion through the structural and functional materials is important for two main reasons. The first is that there can be a substantial difficulty in extracting tritium from high temperature helium coolant. The second is that tritium can make its way from the helium stream into the environment. In the recent study [28] for the US reference DCLL blanket [11] (see also Table 1), tritium transport is analyzed in the front section, where PbLi moves poloidally in a rectangular duct with an insulating 5-mm CVD coated SiC/SiC FCI in the presence of a strong plasma-confining magnetic field. The numerical procedure involves two steps: the computation of the flow field with the already mentioned MHD code HIMAG, followed by the solution of the mass transfer equation with a transport code CATRIS (Corrosion And Tritium Transport Solver). The analyses included a sensitivity study to investigate how uncertainties in the properties of the materials (diffusion coefficient D, solubility constant, SiC electrical conductivity σ) affect the results and to assess the effect of the FCI on tritium permeation into He streams.

There is considerable uncertainty in the material properties, especially in the solubility coefficient of tritium in PbLi [51], and a set of simulations was performed with different values, covering the range found in the literature. The effects of solubility, diffusion coefficient and FCI electrical conductivity on tritium losses into He streams are shown in Fig. 9. The important finding is that the main tritium losses into helium occur from the Hartmann gaps (those perpendicular to the toroidal magnetic field) where the liquid is almost stagnant, while the tritium generated in the bulk flow inside the FCI remains there. Although the data for solubility in PbLi vary by two or three orders of magnitude, the corresponding variation in the loss rate is only about 5. Therefore, the FCI can be considered as a tritium permeation barrier due to the very low diffusion coefficient of tritium in the FCI. This, however, doesn't mean that tritium losses into the helium streams are fully eliminated. Tritium permeation still occurs from the gap spacing.

These losses were computed without any pressure equalization openings or overlap regions in the FCI. More detailed analysis that takes into account additional tritium fluxes through the pressure equalization slot into the gap is performed in [52] leading to roughly the same conclusions and similar estimates for the tritium loss of less than 2% of all tritium produced in the blanket. Also, it should be mentioned that in the computations, zero tritium concentration was assumed at the blanket inlet. This assumption is in agreement with the current analysis of the tritium extraction process from PbLi using a vacuum permeator [53] that shows that the partial pressure of tritium at the blanket inlet can be limited to a low value about 30 mPa (0.059 wppb). With such a low tritium partial pressure at the blanket inlet and high PbLi circulation rate, the tritium concentration at the exit of the blanket and tritium permeation losses in the He streams in the power plant will be significantly smaller compared to the HCLL blanket concept. However, efficient tritium extraction from the He-coolant is still necessary to meet the limit on tritium release in the environment of 1 g/yr as established in safety studies.

7. Near-future R&D and facilities required for DCLL

Admittedly, recent R&D for breeding blankets has mostly been focusing on studies of basic separate effects in the lab. Considering a scientific framework where experiments and modeling could progress to multiple effects and partially-integrated studies, it is

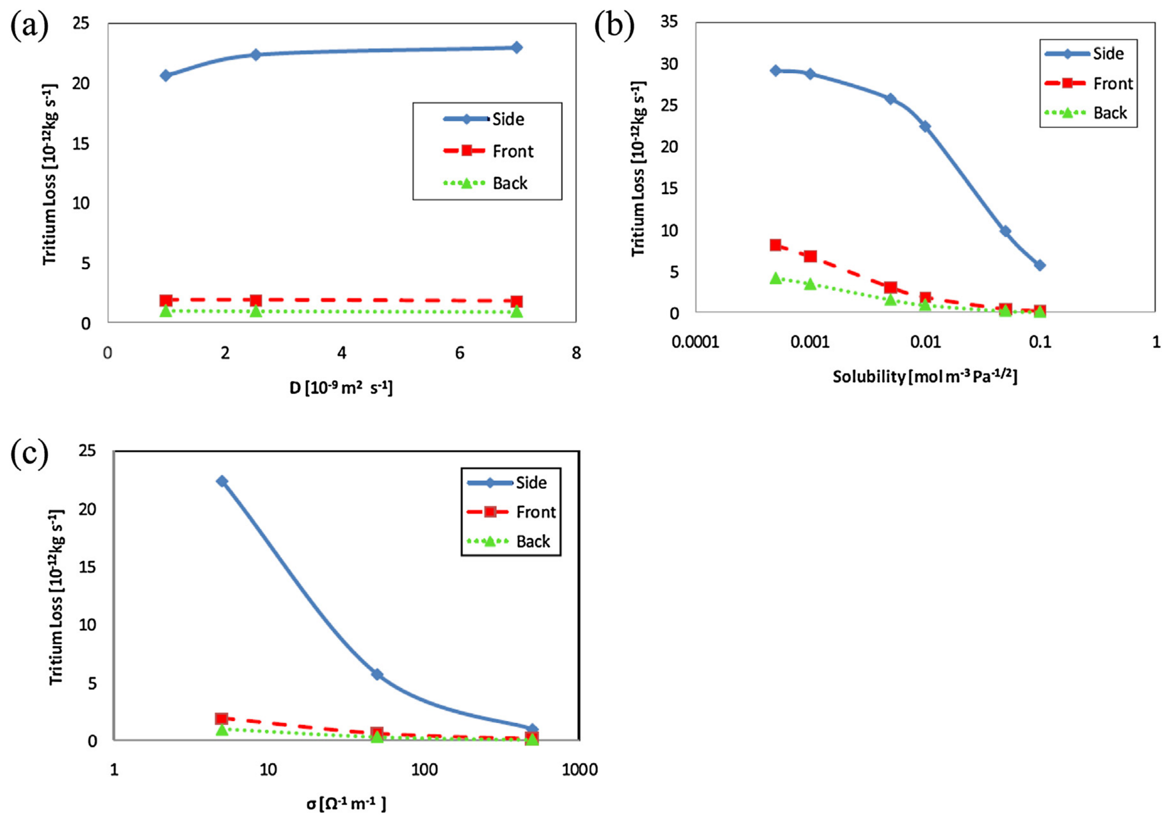

Fig. 9. Tritium loss rate as a function of: (a) diffusion coefficient, (b) solubility, and (c) FCI electrical conductivity. In the legend, “side” means Hartmann gap, while “front” and “back” are used for two side gaps.

timely now to establish the required features of specially designed test facilities that approach as nearly as possible prototypic, integrated blanket conditions prior to testing in fusion environment. To achieve these goals a number of testing facilities attempting to safely simulate the most important blanket conditions, in particular those in a DCLL blanket, has recently been proposed in the US [54,55] and are more fully described in Ref. [2]. Two particular facilities have been identified that could be used for DCLL blanket testing.

7.1. Blanket mockup thermomechanics/thermofluid test facility

This facility brings together simulated surface, volumetric heating and reactor-like magnetic fields with blanket/FW (and divertor) test mockups having prototypical size, scale and materials operated at prototypical flow rates, pressures and temperatures for extended periods. While volumetric nuclear heating cannot be perfectly simulated, the facility will employ various heating techniques such as specialty internal electrical heaters to mock up volumetric heating effects. A magnetic field of 4–5 T is required to reach *Ha* numbers of about 5000 typical to outboard blankets.

There is no partially-integrated blanket facility of this type in the world, though there are some smaller scale liquid-metal flow facilities, some of which are paired with limited magnetic field capabilities and some with surface or volume heating. Bringing together these conditions of blanket systems is an essential step to understand DCLL blanket thermomechanics and thermofluid behavior prior to and as a complement to complex, fully integrated fusion environment testing.

7.2. Blanket unit cell and tritium extraction test facility

This facility is proposed to irradiate breeding blanket unit cells with neutrons, and extract the resulting tritium. The current vision is for an actively controlled unit cell module irradiated by a neutron source such as a fission reactor (ATR, HFIR) linked by a liquid metal coolant loop to an out-of-pile tritium extraction and chemistry control systems. The in-pile unit cell will be used to study issues related to neutron irradiation effects on blanket functional materials and tritium release and permeation in breeder materials, while the external systems will be used for experiments on bred tritium extraction and processing, chemistry control, and transmutation product removal.

These two partially integrated testing facilities together bring coupled capabilities in thermo/electromechanical loading and thermo/irradiation loading in order to drive a range of synergetic effects that come from bringing together the elements of the complicated and extreme fusion environment (volumetric heating, surface heating, magnetic field, neutron irradiation) with high-temperature, geometrically complex, prototypic material component mockups. Such experiments are designed to provide data for validating modeling developed based on separate effects tests and begin to establish the database for safety and reliability including failure modes, effects, and rates. Performing this scale of testing is an essential link between laboratory scale experiments and full fusion environment testing where unnecessary failures must be avoided and limited access and complex conditions can make interpreting experimental results much more difficult. Especially in the case of FNSF, partially integrated experiments on component mockup will be essential to the licensing of this aggressive nuclear test facility with experimental components, both in terms of establishing a performance database and in validating computer codes used to design the facility.

8. Concluding remarks

Certainly, significant R&D is still required to develop a DCLL blanket to the level where reliable operation of a fusion reactor can be guaranteed and testing in the fusion environment started. The required R&D efforts seem, however, to be comparable with the R&D needs for other main blanket concepts. Moreover, the same facilities can be used for testing different liquid-metal blanket concepts. Stages of R&D in non-fusion facilities and in the fusion nuclear environment, *e.g.* FNSF, are discussed in Ref. [2].

In the paper, we identified four specific research areas where R&D studies in non-fusion facilities are still needed for a DCLL blanket prior to testing in a fusion environment. They are: (1) PbLi MHD thermofluids, (2) fluid materials interaction, (3) tritium transport, and (4) FCI development and characterization. We also identified generic R&D issues associated with development of RAFM steel, fabrication of blanket structures and He cooling. Although recent work on the DCLL and HCLL blanket concepts in the US, China and Europe has contributed significantly to the overall database for PbLi blanket development, future R&D efforts are still needed to focus on special topics associated with MHD phenomena, corrosion/precipitation processes, tritium transport and permeation in conditions specific to the DCLL blanket.

- In the MHD thermofluids area, further studies are required to qualify and quantify impact of SiC FCIs on the MHD pressure drop and flow distribution and to fully address unsteady phenomena in PbLi flows, including Q2D turbulence and buoyancy-driven flows in a strong magnetic field.
- In the area of fluid-material interactions, the main focus should be placed on the effect of a multi-material environment and a magnetic field on interfacial processes between flowing PbLi and structural (RAFM) and functional (SiC) materials under various blanket operation conditions. This includes effects of a strong multi-component magnetic field, high temperature and temperature gradients and the flow geometry on corrosion of RAFM steel, PbLi ingress in the SiC bulk material, possible hydrodynamic slip phenomena, transport of corrosion products in the flowing PbLi and precipitation of corrosion products in the "cold" section of the PbLi loop.
- In the area of tritium transport, many uncertainties still exist due to incomplete databases on material properties, such as tritium diffusion coefficients and solubility. Also, the physics related to tritium behavior in the flowing PbLi is not well understood. For example, processes associated with recombination of tritium atoms into molecules when tritium diffusion into the He streams occurs, and trapping tritium in helium bubbles in the PbLi require further work on development of phenomenological models and their verification that in turn requires new experimental data.
- In the area of FCI development and SiC characterization, further experimental and theoretical studies could be very favorable for the construction of a realistic constitutive equation for both SiC/SiC and foam-based materials such that stresses and deformations in FCIs due to thermo-mechanical loads and differential swelling in neutron irradiation and temperature gradient conditions could be accurately predicted *via* computations.

Also, it should be mentioned that all these studies, especially those in the MHD thermofluids area, would be important for advanced self-cooled PbLi blanket concepts based on SiC/SiC composites as structural materials that offer a power conversion efficiency higher than 50%.

Acknowledgements

This work was performed with support from the US Department of Energy, Office of Fusion Energy Sciences, under grant no. DE-FG02-86ER52123. We acknowledge technical contributions from the MHD thermofluid group at UCLA, including Naveen Vetcha, Jack Young, Damien Sutevski, Sheida Saeidi, Feng-Chen Li, Yoshitaka Ueki and Tomas Sketchley. We are also grateful to Ultramet, USA (personally to Brian Williams) for providing us with FCI samples for dynamic and static testing.

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