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DUAL-COOLANT LEAD-LITHIUM (DCLL) BLANKET: STATUS AND R&D IN THE AREA OF MHD THERMOFLUIDS AND FLUID MATERIALS INTERACTION

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The DCLL is an attractive breeding blanket concept that leads to a high-temperature ($T \sim 700°$C), high thermal efficiency ($\eta > 40\%$) blanket system. In the DCLL, the eutectic alloy lead-lithium (PbLi) circulates slowly ($V \sim 10$ cm/s) for power conversion and tritium breeding, experiencing strong magnetohydrodynamic (MHD) interactions. The MHD effects are also expected to have a strong impact on heat and mass transfer processes in the blanket, including tritium transport and corrosion of structural and functional materials. The key element of the DCLL concept is a flow channel insert (FCI) that serves as an electrical and thermal insulator to reduce the MHD pressure drop and to decouple the temperature-limited steel structure 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 reviews the most important R&D results obtained in the US in the ITER DCLL TBM program (2005–2011) and more recently in the area of MHD thermofluids and fluid materials interaction, including experimental and computational studies of MHD PbLi flows and corrosion of reduced activation ferritic/martensitic (RAFM) steel in the PbLi in the presence of a magnetic field.

Introduction. The DCLL blanket of a fusion power reactor promises a solution towards a high-temperature, high-efficiency blanket system while using temperature-limited reduced-activation ferritic/martensitic steel as a structural material [1]. In this concept, a high-temperature lead-lithium 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 cool the ferritic first wall (FW) and other blanket structures in the self-cooled region, and a low-conductivity flow channel insert which is typically a few mm thick, with silicon carbide (SiC) as a suitable candidate material, is used for electrical and thermal insulation [2] (Fig. 1).

Several designs of the DCLL blanket have been considered in Europe, the US and China. Historically, the first DCLL version, known as a low-temperature (LT) DCLL blanket (see, e.g., [3]), relies on qualified materials and existing fabrication

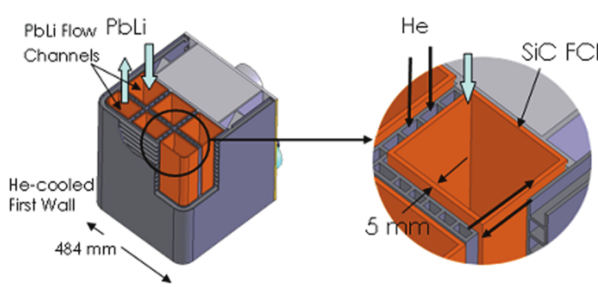

Fig. 1. Schematic of the DCLL blanket with poloidal PbLi channels, He-cooling channels and insulating SiC FCI.

technologies. A key component of this design is a sandwich-type FCI composed of steel/alumina/steel layers or of a thin alumina layer on the wall to be used as an electrical insulator for decoupling electrically conducting structural walls from the flowing PbLi. In the high-temperature (HT) DCLL blanket, first introduced in [4], an FCI made of SiC, either composite or foam, was further proposed as a means for electrical and also for thermal insulation to provide acceptable MHD pressure drops to achieve a high PbLi exit temperature of $\sim$700°C and, ultimately, to provide a high thermal efficiency of about 45% (as opposed to about 470°C and 34% in the LT design).

The unique features of the DCLL blanket are associated with the flows of PbLi in a strong magnetic field in the presence of the FCI. This suggests 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 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) [5] and more recent blanket studies in the US in the area of MHD thermofluids and fluid materials interaction. The particular topics reviewed in this paper are related to (a) theoretical studies of MHD instabilities in poloidal flows, (b) experimental studies of PbLi MHD flows using the MaPLE loop at the University of California, Los Angeles, (c) 3D computations of MHD flows with FCI, and (d) theoretical studies of corrosion in the PbLi/RAFM system.

1. Current studies for MHD thermofluids and fluid materials interaction. 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 [6]. The associated R&D studies mostly focused on the MHD pressure drop in typical blanket configurations. Among a number of concerns related to liquid metal blankets, reduction of the 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.

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 [7] and worldwide [8] is 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 [9]. These complex MHD flow processes can affect transport properties of MHD flows in drastic ways and have a significant impact on the blanket operation and performance. In spite of significant success in advancing our knowledge of blanket flows in the recent past via experiments [10] and computations [11], 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.

1.1. Instabilities in poloidal flows of the DCLL blanket. As suggested in [12], 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 [13]. Even though analysis of such Q2D MHD flows was started a few decades ago, the underlying physics of these flows and their impact on the blanket operation need further considerations [14].

Two recent theoretical studies [15, 16] address Q2D MHD flows and elucidate possible MHD instability mechanisms in conditions relevant to the DCLL blanket.

In the first one [15], 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 in the vicinity of the inflection 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 [16] 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 behavior is 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.

Effects of Ha, Re and Gr on turbulent flows are addressed in [16] via non-linear computations that demonstrate two characteristic turbulence regimes (Fig. 2). In

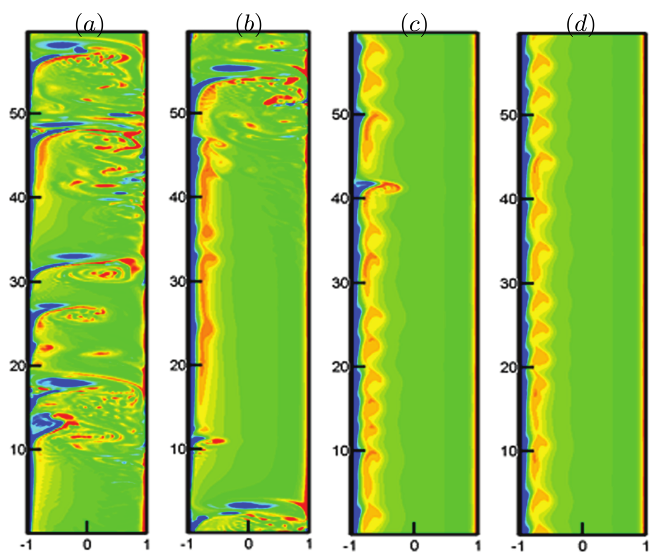

Fig. 2. Computed [16] vorticity snapshots in a turbulent mixed-convection flow at $\mathrm{Re}=5000$ and $\mathrm{Gr}=108$. Strong turbulence: (*a*) $\mathrm{Ha}=50$, and (*b*) $\mathrm{Ha}=60$. Weak turbulence: (*c*) $\mathrm{Ha}=100$, and (*d*) $\mathrm{Ha}=120$.

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 [15], the key phenomena are vortex-wall and vortex-vortex interactions.

Even though the parameters used in [15] and [16] in the computations are lower than the 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 [17] 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 finally been implemented in the US ITER TBM design and DEMO blanket.

1.2. Experimental MHD thermofluids studies using PbLi at UCLA. A new MHD PbLi facility called MaPLE (Magnetohydrodynamic PbLi Experiment) has been recently constructed and successfully operated at UCLA [18] (Fig. 3). 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 15/40 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

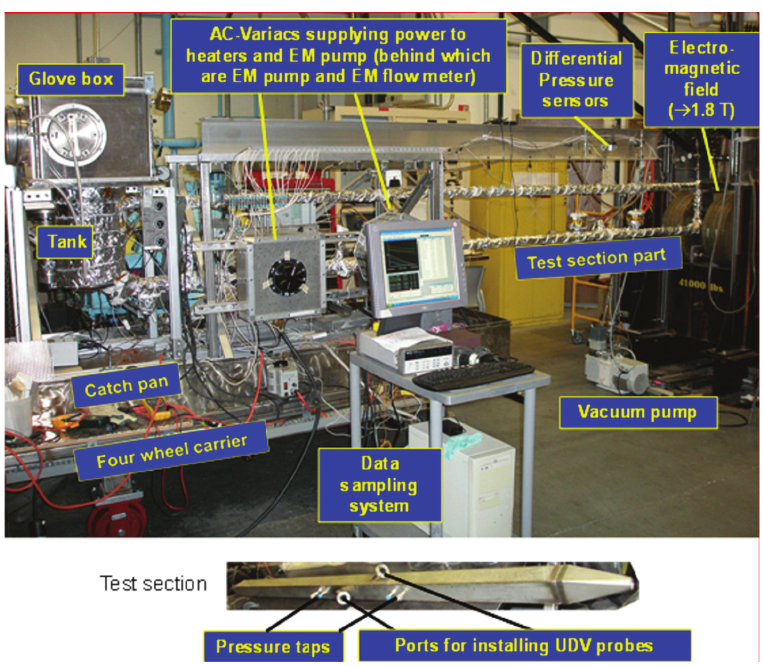

Fig. 3. The MHD PbLi loop MaPLE at UCLA, including the test-section (bottom).

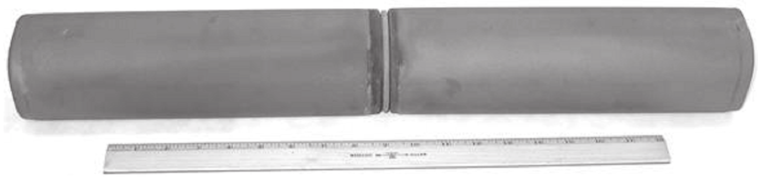

Fig. 4. Foam-based SiC FCI by ULTRAMET. The figure shows two 30-cm FCI segments connected together.

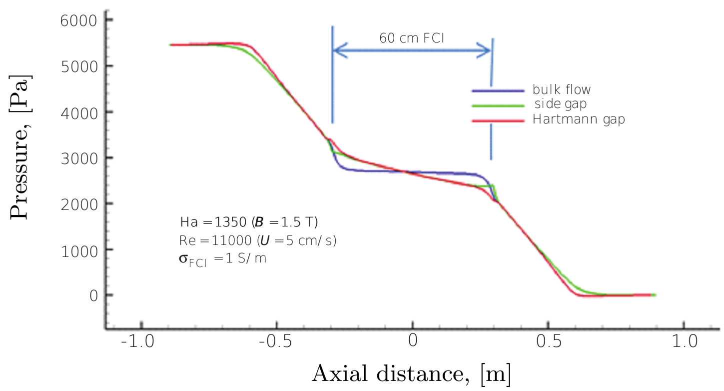

Fig. 5. Typical pressure distribution in MHD flow with an FCI.

studies of MHD, heat and mass transfer phenomena in PbLi flows and also can be used in mock up testing under conditions relevant to fusion applications.

The facility was constructed in 2011 to serve experimental needs of the JA-US TITAN program [19]. Ongoing work on the 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 [18, 19]. Intensive studies have been started to address MHD pressure drop reduction in PbLi flows using two different insulation techniques: (1) laminated walls [29] and (2) a SiC foam-based FCI [21]. Initial studies were also performed to address material compatibility between SiC and PbLi. These include static testing at a high temperature of 700°C in a specially designed static chamber and dynamic testing of various FCI samples.

1.3. 3D computations of 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 and the parallel code HIMAG [22]. 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).

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. The computations evaluate the pressure drop reduction factor R 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 of 4 cm fore and rear of the FCI. 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. Accordingly, the Reynolds, Hartmann, and interaction numbers ($N = \mathrm{Ha}^2/\mathrm{Re}$) reach at least $3.4{\cdot}10^4$, $1.6{\cdot}10^3$, and $2.5{\cdot}10^2$, respectively. In the study, all dimensionless parameters are constructed using the mean bulk velocity and the half-width of the duct. 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. It is noticeable that the R-factor 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 entry/exit and also due to electrical current leakages from the bulk flow into the gap in the junction region between the two segments. However, extrapolation to real blanket conditions, where FCIs are continuously spaced inside the RAFM duct, suggests much higher pressure drop reductions with the R-factor in the range 50–100.

1.4. Modelling of corrosion in the 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 450–550°C needs to be characterized. The 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 [23].

A computational suite TRANSMAG (Transport Phenomena in Magnetohydrodynamic Flows) has recently been developed [24]. 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. 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,

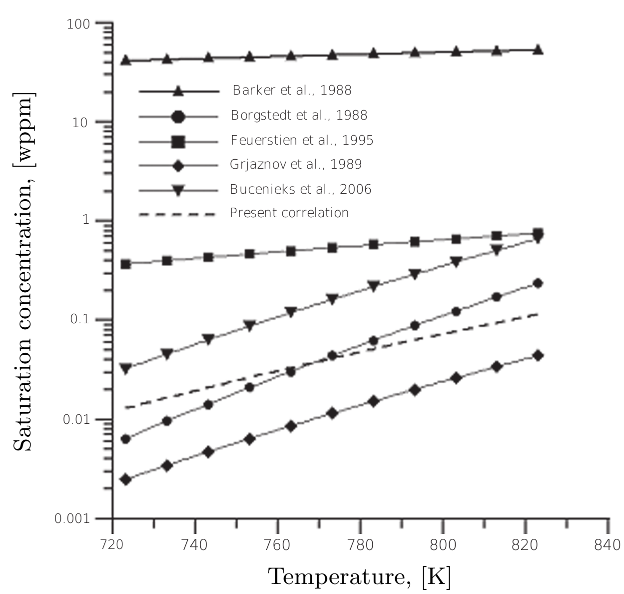

Fig. 6. New and earlier correlations for saturation concentration of iron in PbLi.

a new correlation for the saturation concentration C^{S} has been obtained in the form $C^{\mathrm{S}} = \mathrm{e}^{13.604-12975/T}$, where T is the temperature of PbLi in K and C^{S} is in wppm. This new correlation is shown in Fig. 6 along with the correlations obtained earlier.

This 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 [25], 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 the 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: $ML \sim \mathrm{e}^{pT} U_m^q B_0^s$ for the side wall, and $ML \sim \mathrm{e}^{pT} U_m^q$ for the Hartmann wall, where $q, s \sim 0.5$.

2. Concluding remarks. In the paper, we identified research areas where R&D studies in non-fusion facilities are still needed for a DCLL blanket prior to testing in a fusion environment. In the area of MHD thermofluids, further studies are required to qualify and quantify the 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 materials interaction, the main focus should be placed on the effect of a multi-material environment and a magnetic field on the 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 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.

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