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

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**Abstract** : The DCLL is an attractive breeding blanket concept that leads to a high-temperature (T ~ 700°C), high thermal efficiency (η > 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 reviews the most important R&D results obtained in the US in the ITER DCLL TBM program (2005-2011) and more recently, including experimental and computational studies of MHD PbLi flows and corrosion of RAFM steel in PbLi in the presence of a magnetic field.

## 1. 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 (RAFM) steel as structural material. In this concept, a high-temperature lead-lithium (PbLi) alloy flows slowly (V ~ 10 cm/s) in large poloidal rectangular ducts (D ~ 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).

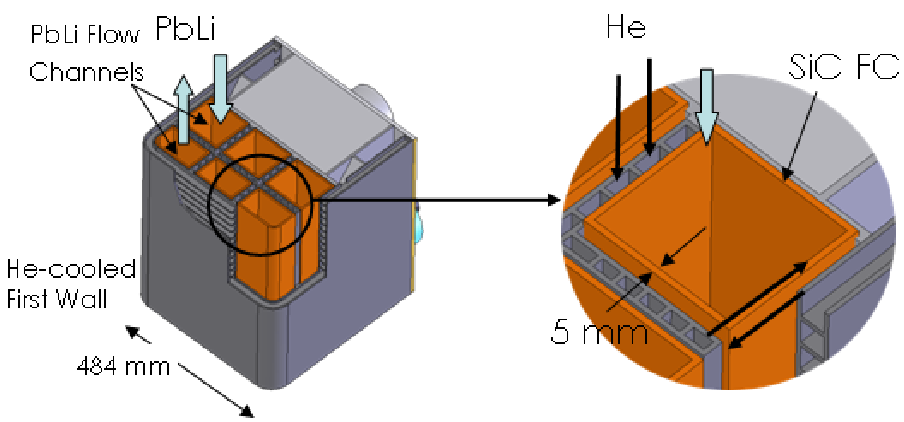


Figure 1: Schematic of DCLL blanket with poloidal PbLi channels, He-cooling channels and insulating SiC FCI.

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 [1], relies 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 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 [2], an FCI made of SiC, either composite or foam, was further proposed as a means for electrical and also thermal insulation to provide acceptable MHD pressure drops, to achieve a high PbLi exit temperature of ~700°C and, ultimately, to provide 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 associated with the flows of PbLi in a strong magnetic field 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 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 MHD thermofluids area. 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, (c) 3D computations of MHD flows with FCI, and (d) corrosion studies for the PbLi/RAFM system.

## 2. MHD instabilities in poloidal flows.

Two recent studies [3, 4] address quasi-two-dimensional (Q2D) MHD flows to elucidate possible MHD instability mechanisms in conditions relevant to DCLL. In the first one [3], direct numerical simulations (DNS) and a linear stability analysis are performed for a family of Q2D MHD flows with inflectional velocity profiles. 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. 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 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 [4] 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 is Q2D. 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.

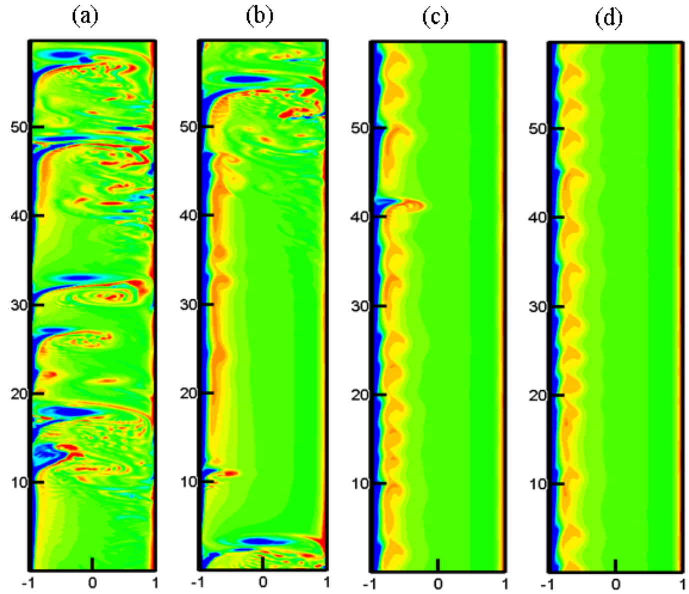


Figure 2: Vorticity snapshots in a turbulent mixed-convection flow at *Re* = 5000 and *Gr* = $10^8$. *Strong turbulence*: (a) *Ha* = 50, and (b) *Ha* = 60. *Weak turbulence*: (c) *Ha* = 100, and (d) *Ha* = 120.

Effects of *Ha*, *Re* and *Gr* on turbulent mixed-convection 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 [3], the key phenomena are vortex-wall and vortex-vortex interactions.

**3. Experimental studies of MHD PbLi flows.**

A new MHD PbLi facility called MaPLE (Magnetohydrodynamic PbLi Experiment) has recently been constructed and successfully operated at UCLA [5]. 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.

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. [5] and [6]. Intensive studies have been started to address MHD pressure drop reduction in PbLi flows using two different insulation techniques: (1) laminated walls [7] and (2) a SiC foam-based FCI [5]. 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 Section 4).

## 4. 3D computations of MHD 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 [8]. 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. These two segments are separated with a small 1-mm slit.

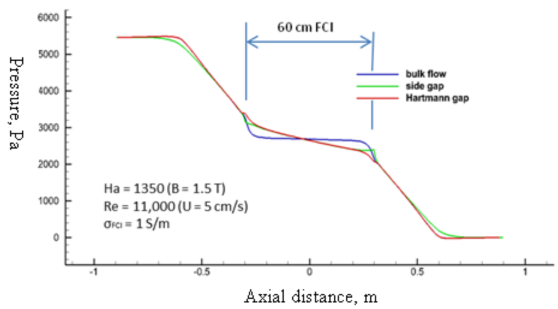


Figure 3: Typical pressure distribution in MHD flow with the FCI.

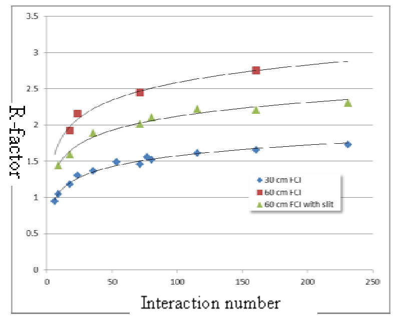


Figure 4: Simulations of the MHD pressure drop reduction in the FCI flows.

A pressure profile calculated for a 60-cm FCI is shown in Fig. 3. Figure 4 shows a trend found for the pressure drop reduction R-factor (the pressure drop without the FCI divided by the pressure drop with the FCI). Regardless of the *Re* and *Ha* values used in the computations, the R-factor is always described well as a function of the interaction number $N=Ha^2/Re$ only. 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.

## 5. MHD corrosion studies for PbLi/RAFM steel.

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 better characterized. Second, 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 demonstrate scattering of several orders of magnitude [9].

To address these issues, a computational suite called TRANSMAG (Transport Phenomena in Magnetohydrodynamic Flows) has recently been developed [9]. The computational approach is based on simultaneous solution of flow, energy and mass transfer equations, 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 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.

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. It was found that the corrosion behavior is 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: $ML \sim e^{pT} U_m^q B_0^s$ for the side wall, and $ML \sim e^{pT} U_m^q$ for the Hartmann wall, where $q, s \sim 0.5$.

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