DEVELOPMENT OF THE LEAD LITHIUM (DCLL) BLANKET CONCEPT

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Liquid metal breeders such as Lithium or the eutectic Lead-Lithium alloy PbLi have the potential for attractive breeding blankets, especially if the liquid metal serves as breeder and coolant. However, cooling of first wall and blanket structure is a challenging task because the magnetic field degrades the heat transfer and can cause a really high pressure drop. To overcome these problems, dual coolant blankets with helium cooled FW/blanket structure and a self-cooled breeding zone had been proposed, with electrical insulation by ceramic-coatings or sandwich flow channel inserts. Such concepts are in principle simpler than helium cooled blankets, but the thermal efficiency is limited to ~ 35 % as in any helium cooled blankets with steel structure. A much higher efficiency up to about 45 % became feasible when the sandwich insulator was replaced by flow channel inserts (FCI) made of a SiC composite. This FCI serves as thermal insulator too, allowing an exit temperature of ~ 700° C, suitable for a BRAYTON cycle power conversion system.

The subject of this paper is a description of the Lead-Lithium blanket development and the major improvements on the dual coolant Lead-Lithium (DCLL) blanket concept achieved in the US during the last 10 years.

I. INTRODUCTION

Liquid metal (LM) breeders such as pure lithium or the eutectic Lead –Lithium alloy PbLi have a potential for attractive breeding blankets in fusion power plants because they can lead to tritium self sufficiency without additional neutron multiplier, they are immune to irradiation damage, have - compared to ceramic breeders- a high thermal conductivity, and they allow an in-situ adjustment of the breeding rate by modifying on-line the concentration of the Li-6 in the breeder.

Both liquid metal breeders are used in a large number of blanket and power plant studies, but in general the eutectic alloy is preferred for safety reasons because it is much less chemical reactive with air, water, or concrete.

The liquid metal can serve as breeder only, cooled by water or helium, or in addition as a coolant by circulating the liquid breeder to external heat exchangers for heat and tritium extraction. Such "self-cooled breeding blankets" are in principal the most simple blanket designs because no large cooling surfaces are required inside the blankets to transfer the volumetric heat generated in the liquid breeder to helium or water as a coolant. However, there is a strong impact of the magnetic field on flowing liquid metals, influencing to a large degree flow distribution, velocity profiles, and pressure drops. This makes especially the design of self-cooled lead-lithium blankets to be a difficult task. There are a number of ways to deal with this impact, and they will be described in the following section.

II. DESIGN CONCEPTS OF SELF-COOLED LEAD-LITHIUM BLANKETS

The eutectic lead-lithium alloy had been proposed the first time for mirror fusion power plants in the WITAMIR [1] study. Here the LM flowed slowly in poloidal direction in large cylindrical tubes made of ferritic steel, and a very low heat flux at the first wall (FW) surface was assumed. However, the flow distribution to a large number of breeding tubes, the high MHD pressure drop in the flow perpendicular to the strong magnetic field, and the corrosion between PbLi and the steel tubes remained as critical issues.

The first time self-cooled PbLi blankets in a TOKAMAK power plant had been evaluated was the US Blanket Comparison and Selection Study (BCSS) [2]. A rather complicated flow scheme was used here to overcome the impact of the strong magnetic field (B), based on low velocity in large poloidal ducts and a transition from poloidal direction (perpendicular to B) to toroidal direction (parallel to B) in the FW for effective cooling of the rather high heat flux in a Tokamak. However, more detailed MHD analyses showed later a multi-channel effect on the transition between poloidal and toroidal flow, causing excessive high pressure drops and unfavorable velo-city profiles for FW cooling ("Madarame effect" [3]).

The optimized coolant flow path concept described in BCSS was an important measure to improve the viability of liquid metal cooling for blankets, but the MHD pressure drop in un-insulated ducts perpendicular to the magnetic field was still high. Even without taking into consideration the multi-channel effect, it was difficult to keep the primary stresses induced by the coolant pressure within allowable limits.

A better way to reduce the pressure drop decisively would be to decouple electrically the coolant flow from the load-carrying walls. From an MHD point of view, it would be ideal to provide an electrical insulating layer to all duct walls. This layer, however, has to be compatible with the liquid breeder during the entire life-time of the blanket without cracking, peeling off, and wearing down in order to avoid direct contact between the liquid metal and the steel wall. Such layers have been proposed for a long time and were taken into consideration in BCSS. So far, however, no experimental results which indicate the feasibility of this method have been reported.

In the MARS study [4] a "laminated wall" design had been suggested which consists of a steel liner supported by the load-carrying wall via an electrically insulating ceramic layer. Since contacts between the liquid breeder and the ceramic layer can be avoided, the requirements on the insulation are not as stringent. However, the design and fabrication must be of the highest quality because with insuffi-cient support, e.g. corners, the stresses in the liner can reach unacceptable values.

A novel concept of Flow Channel Inserts (FCI) for self-cooled blankets was proposed in [5]. It offers several engineering advantages over the laminated wall design. These FCI's are made by sandwiching a thin ceramic layer between two steel sheets which are then welded at all edges to avoid any contact between the ceramic layer and the liquid breeder. Such inserts are fitted loosely into all ducts with liquid metal flow and thus decouple in this way the steel walls from the voltage induced in the flowing liquid metal when crossing the magnetic field. The Principle of such a FCI is shown in Fig. 1.

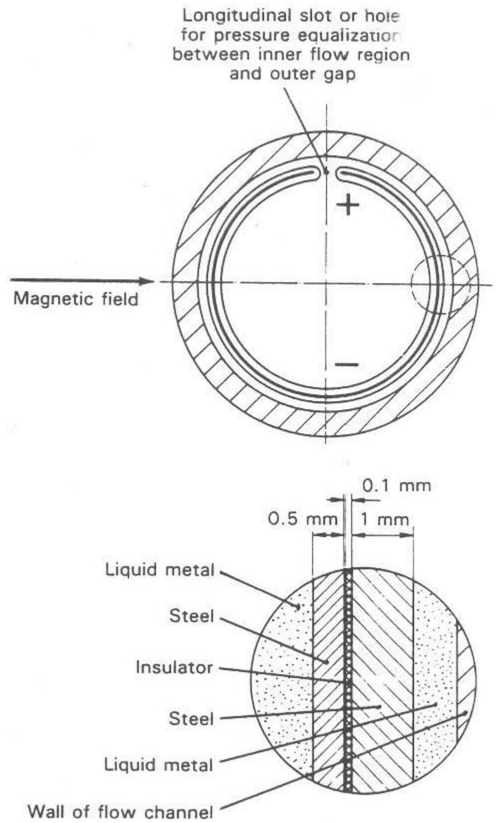

Fig. 1. Principle of Sandwich Flow Channel Insert [5]

A blanket concepts based on the use of such flow channel inserts is described in [6] and compared with previous concepts.

All the design studies of self-cooled lead-lithium blankets showed that there are ways to limit the MHD pressure drop to allowable values by the use of an optimized flow concept or by electrically decoup-ling the flowing liquid breeder from the load-carrying walls, but the cooling of the steel structure and especially the FW remains a critical issue. The high magnetic field generally degrades the heat transfer to the liquid metal by modifying turbulence, and the liquid metal temperature at the blanket exit has to be rather low in order to keep the temperature at the liquid metal/ steel interfaces below a limit given by corrosion.

To overcome these problems, the idea come up to cool the entire blanket structure including the FW with high pressure helium, and to flow the liquid metal breeder only in large poloidal ducts ("self-cooled" breeding zone). Such Dual Coolant Lead Lithium (DCLL) blankets are the subject of the next section.

III HISTORY OF DUAL COOLANT LEAD-LITHIUM BLANKET CONCEPTS

The first DCLL blanket concept was developed in the frame of the European blanket comparison and selection study and is described in [7]. Boundary conditions and basic lay-out of that DEMO plant were given in [8].This plant was characterized by 16 TF coils, and the FW/blankets were subdivided into 32 inboard and 48 outboard segments. The average neutron wall load was 2.2 MW/m^2, average surface heat load at the FW 0.4 MW/m^2.

In this blanket concept, the FW and the entire blanket structure was cooled with helium, the ferritic/ martensitc steel MANET served as structural material, and the walls of the large poloidal ducts for the flowing PbLi were electrically insulated by a layer of Alumina.

A perspective view of an outboard blanket segment is shown in Fig. 2.

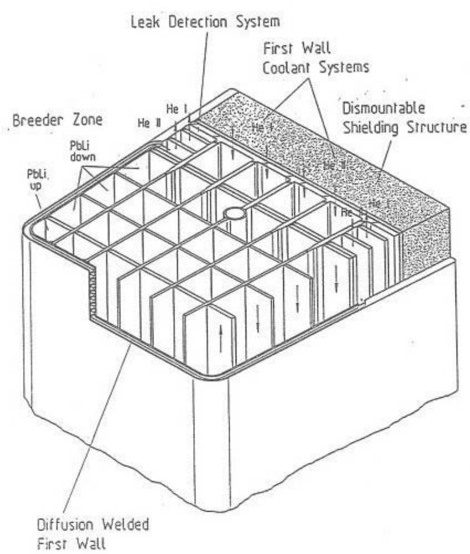

Fig. 2. Perspective view of an outboard blanket segment [7]

The inlet/exit temperatures of the helium coolant were 250/350° C with a system pressure of 8 MPa. Inlet/outlet temperatures of the liquid metal breeder were 275/425° C.

These coolant temperatures were used in the power conversion system to generate saturated steam with a pressure of 7 MPa and a temperature of 286° C, the same conditions as in light water fission reactors with a typical thermal efficiency of ~ 34 %.

Since the feasibility of alumina coating as the electrically insulation of the duct walls was in the selection exercise judged as a large development risk, a modified concept based on the replacement of the ceramic coatings by sandwich flow channel inserts as described in [5] and shown in Fig. 1 was evaluated.
The feasibility of such a concept was judged to be higher, but the liquid metal exit temperature in this concept was still limited to ~ 425° C in order to maintain the PbLi/steel interface temperature below an assumed limit of ~ 470° C for corrosion reasons..

The resulting thermal efficiency of 34 % in the power conversion system is typical for any helium cooled blanket concept (ceramic breeder as well as liquid metal breeder) if the class of ferritic/martensitic steels (for example Manet, Eurofer, or F82H) is used as structural material. The maximum allowable temperature of these steels is limited to ~ 550° C by creep considerations and the maximum allowable interface temperature steel/lead-lithium to ~ 470° C by corrosion.

For the selection of a blanket concept suitable for a spherical Tokamak in the ARIES-ST study an efficiency > 35 % was mandatory in order to compensate for the high re-circulating power (normal conducting TF-coils.). On the other hand, the use of a water-cooled center post in such a plant excluded the use of self-cooled lithium blankets for safety reasons even if such a concept promised a thermal efficiency of ~ 45 %.

The idea to replace in a DCLL blanket the flow channel inserts made of a steel/alumina/steel sandwich by an insert made of a SiC-composite was in that situation a real break-through. Such inserts with a thickness of 5-10 mm were arranged in all poloidal ducts in the blanket, serving as electrical and thermal insulator. This thermal insulation allowed the increase of the lithium-lead exit temperature to ~ 700° C, a value about 150 K higher than the maximum steel temperature and ~ 200 K higher than the maximum temperature at the LM/steel interface.

A cross section of a breeding cell with a SiC-FCI inserted is shown in Fig. 3.

The high LM exit temperature enables the use of a BRAYTON cycle power conversion system with a thermal efficiency of ~ 45 %. Such a closed cycle helium turbine system eliminates any potential for LM/water reaction caused by leaks in the primary loop HX, which is a large safety advantage.

Such a modified DCLL blanket concept was first published in October 1997 [9]. A more detailed description of the DCLL blanket concept developed in the frame of the ARIES-ST study is given in [10].

The main characteristics of this concept are:

- Average neutron wall load 4 MW/m**2
- Average first wall heat flux 0.8 MW/m**2
- Helium system pressure 8 MPa
- Helium inlet/exit temperatures 350/500° C
- PbLi inlet/exit temperatures 480/700° C

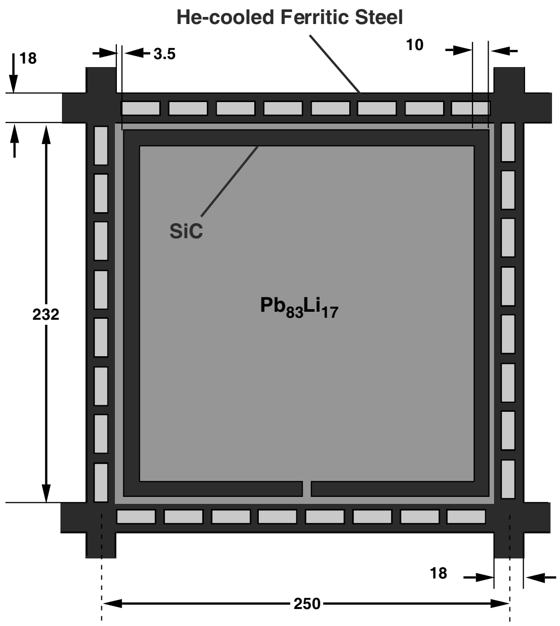

Fig. 3. Configuration of a breeding cell [9]

Two kinds of power conversion systems are possible, either an advanced Rankine steam turbine system or a BRAYTON cycle Helium turbine system. In both systems, thermal efficiencies up to 45 % are achievable.

This idea of a DCLL blanket concept based on the use of FCI made of a SiC-composite was also adopted in the European Power Plant Availability (PPA) study [11] where the ferritic/martensitic steel as structural material had been replaced by an ODS steel. An isometric view of an outboard blanket segment is shown in Fig. 4

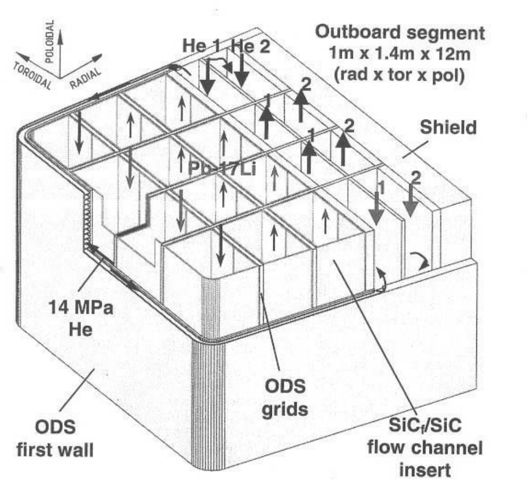

Fig. 4. Isometric view of an outboard blanket segment [11]

Following these early applications, the DCLL blanket concept was used in power plant studies in Europe [12], in China [13], [14], and in the US [15], and became a base concept for the development of ITER Test Blanket Modules (TBM) in the US [16], [17] and China [18], [19]

Compared to the first versions of the DCLL concept with SiC flow channel inserts, the feasibility as well as the performance of this concept was improved decisively by a number of innovations as described in the following section.

IV. MAJOR IMPROVEMENTS OF THE DCLL BLANKET CONCEPT

The work on the DCLL blanket concept performed in the US in the frame of the ARIES studies as well in the development of test blanket modules for ITER led to substantial improvements in the following areas:

a) Design evolution
b) Tritium extraction from the eutectic lead lithium alloy
c) Design of the SiC flow channel inserts
d) Analysis of the MHD impact on the liquid metal flow in the DCLL blanket

IV. A. Design Evolution

For the further adoption of the DCLL concept to the DEMO design a generic blanket configuration is described in [20] and shown in Fig. 5. A stream of PbLi is moving up in a row of large poloidal ducts at the front of the blanket, turning at the top of the module and is then flowing downward through two rows of poloidal channels to the bottom of the module. The inlet and outlet concentric pipe for the PbLi is located at the lower part of the module. FCI's are used in all the PbLi channels.

As indicated in Fig. 5, the concentric inlet and outlet access pipes of the helium coolant are also located at the lower part of the module. The helium coolant is used first for the cooling of the RAFM steel first wall in poloidal direction and then for all the metallic structures in the blanket.

For the further development, the US has selected DCLL as the base concept the for the ITER TBM program. The schematic of the US-DCLL-TBM design is shown in Fig. 6 [16].

The selection of downward PbLi flow at the back and the upward flow in the front of the module is for the adjustment to the buoyancy of the coolant to avoid MHD instability in the front channel.

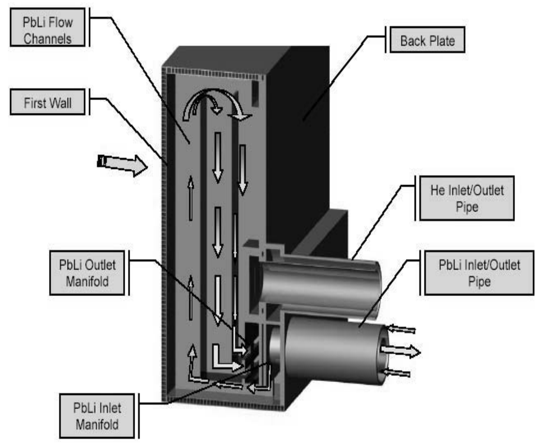

Fig. 5 DCLL blanket configuration with PbLi flow path [20]

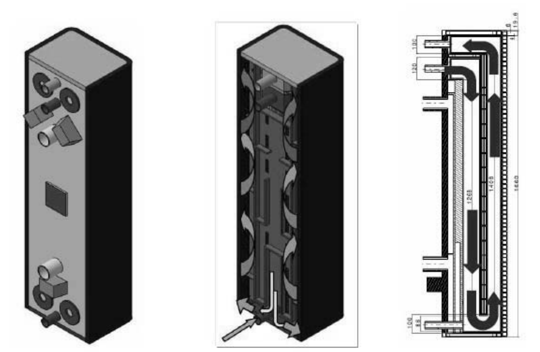

Fig. 6 DCLL ITER TBM module schematics

IV. B. Tritium Extraction from the Eutectic Lead Lithium Alloy

The tritium concentration in the lead lithium breeder is an important issue with a large influence on the tritium inventory in the blanket structure, the primary loops and the helium coolant. It determines to a large degree the tritium permeation losses inside the blankets, from the primary loop piping to the building atmosphere, and in the intermediate heat exchangers to the helium in the power conversion system.

First estimates of the conditions in a plant with DCLL blankets, a BRAYTON cycle power conversion system, and a LM/helium heat exchanger (IHX) with tubes made of a Niobium, Tantalum or vanadium alloy showed clearly, that the maximum tritium partial pressure in the PbLi must be maintained below 1 Pa in order to keep the tritium inventory in the blanket system in a tolerable range, and to avoid the need for highly efficient tritium permeation barriers on the primary loop pipes and the IHX.

For Helium Cooled Lead lithium (HCLL) blankets a tritium extraction system based on helium bubble towers or packed columns with counter flow of lead-lithium and helium has been under development for many years. All experiments showed that it would be very difficult with such a system to keep the tritium partial pressure in a DCLL blanket system to below 100 Pa in spite of the fact that the high LM circulation rate through the DCLL blankets, which is at least two orders of magnitude higher than in a system with HCLL blankets, results in an increase of the tritium partial pressure between blanket inlet and outlet of a few hundred mPa only.

In this situation, we started to evaluate a novel tritium extraction system based on permeation windows between the flowing lead lithium and a vacuum chamber [20]. Candidate materials for such a permeator are Nb. Ta, or V-alloys.

A lay-out of a plant with DCLL blankets and a permeator based tritium extraction system is shown in Fig. 7.

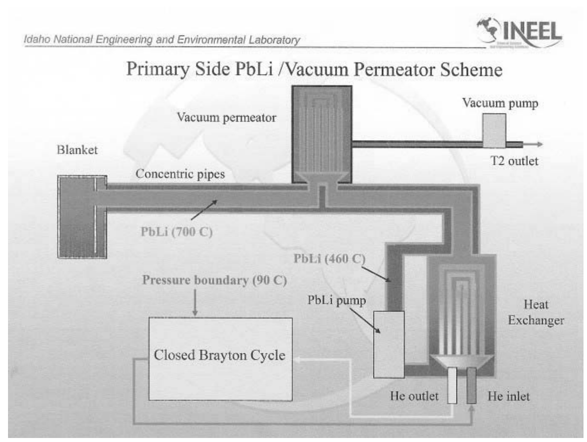

Fig. 7. : Primary loop system with permeator

Typical parameters for the permeation tubes in this permeator are:

- Tube inner diameter 0.01 m
- Tube wall thickness 0.5 mm
- Tube length 5 m
- Lead-lithium velocity inside the tubes 5 m/s
- Tritium partial pressure at blanket exit (permeator inlet) 300 mPa
- Tritium partial pressure at blanket inlet (permeator exit) 30 mPa

The performance of such a permeator based tritium extraction system in a power plant with DCLL blankets is compared with the tritium extraction system in a plant with HCLL blankets and is described for example in [21]. Scoping calculations showed that it should be possible to reduce the tritium concentration in the PbLi to a value of about 0.06 wppb, corresponding to a partial pressure of about 30 mPa.

With such an efficient tritium extraction system, there is no need for permeation reduction layers on the heat exchanger tubes because it is tolerable that the tritium partial pressure in the BRAYTON cycle helium loop increases until an equilibrium with the partial pressure in the lead-lithium loop is reached. There is also not a real problem with tritium permeation losses to the helium coolant inside the blanket or the building atmosphere of the primary loop.

IV.C. Design of the SiC Flow Channel Inserts

The SiC FCI's in a DCLL blanket concept serve as electrical and thermal insulator, decoupling electrically the flowing liquid breeder from the load-carrying steel wall. A crucial issue of such flow channel inserts is the temperature gradient across the wall, and the thermal stresses caused by this gradient. With liquid metal temperatures up to 700° C and the requirement to keep the temperature of the steel wall below 470° C for corrosion reasons, the large temperature difference between the inner and outer surfaces of the FCI wall can lead to thermal stresses exceeding given limits. Furthermore, these thermal stresses can cause local cracks in the wall which endanger the electrical insulation between the flowing liquid metal and the steel wall.

Attempts to control the velocity profile and the heat transfer between the flowing PbLi and the inner surface of the FCI by tailoring the electrical conductivity of the SiC showed that a tradeoff has to be made between thermal insulation, thermal stresses in the FCI, and the pressure drop in the liquid metal flow. Furthermore, it became obvious that it would not be realistic to require a precisely tailored value for the electrical conductivity, because this property can vary by orders of magnitude under irradiation.

In this situation, it was a break-through to split the FCI wall into two regions where an inner layer served mainly as electrical insulator and an outer layer as thermal insulator ("nested FCI"). Such an arrangement is described in [22] and shown in Fig. 8.

The inner layer has the shape of a rectangular duct decoupling electrically the flowing liquid metal from the load carrying steel walls. A thickness of 2 to 3 mm for this layer is sufficient for electrical insulation and optimal for the fabrication of a SiC-composite with high strength.

Depending on the local conditions, additional layers for thermal insulation can be arranged between the inner FCI and the duct walls at 1, 2, or all 4 wall surfaces. It is not necessary to connect the outer layers at the corners since they do not have to provide electrical insulation. They can expand and bend freely and allow therefore large temperature gradients without causing high thermal stresses.

Liquid metal filled gaps between the two SiC layers as well as between the outer layer and the steel wall allow for differential thermal expansion and large fabrication tolerances. A gap width somewhere between 0.5mm and 2 mm has to be maintained by spacers.

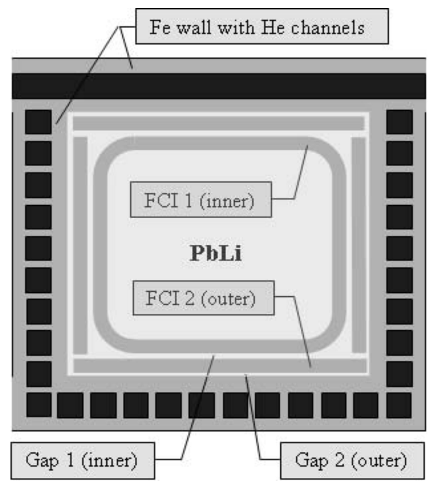

Fig. 8: Principle of nested flow channel inserts [22]

An important advantage of such nested FCI's is the possibility to use different SiC-materials for the two regions. Candidate materials are a SiC/SiC composite with a high density, offering relatively high strength, and a foam-based SiC with low density providing high thermal insulation. Taking benefit of these different features, the composite can be used for the inner layer, providing reliable high electrical insulation without the risk of cracking, and the foam-based SiC for the outer layer with maximized thermal insulation. Localized cracks would have not a large impact on the function of this layer as thermal insulator as long as the entire wall is not soaked with PbLi.

For all the liquid metal ducts outside the blanket (i.e. the concentric pipes connecting the blankets to the PbLi/helium heat exchanger) nested FCI's are not necessary because an increase of the electrical conductivity by small cracks as caused by thermal stresses can be tolerated since there is no magnetic field.

IV.D. Analysis of the MHD Impact on the Liquid Metal Flow in the DCLL Blanket

The high strength of the magnetic field in a fusion plant has a large impact on the liquid metal flow. It influences the flow distribution into parallel channels and the velocity profiles in the ducts, degrades the mass and heat transfer in the ducts by modifying flow turbulence, and increases the pressure drop in the liquid metal flow by orders of magnitude.

In the recent past, the available codes allowed a simplified analysis of MHD flows, limiting it to conditions of a fully developed flow, and neglecting changes of flow direction, field gradients, flow turbulence, and buoyancy effects.

Currently, more sophisticated computational tools and models are developed, where these effects are taken into account. A significant progress in modeling MHD flows and heat transfer for evaluation of DCLL blanket concept has recently been achieved at the University of California, Los Angeles [23].

Typical applications of the developed tools are described for example in [17] and [24].

Especially important results of this work are the understanding of the flow distribution in the region of the flow channel inserts including the main flow in the large ducts as well as in the gaps between FCI and duct walls, the pressure equalization between main flow and flow in the gaps, flow distribution in the feeding manifold, and the combination of forced flow and buoyancy flow in the poloidal channels of the DCLL blanket.

As a typical example it has been learned that the flow in the front ducts has to be in upwards direction as shown in Fig. 5 in order to avoid there stagnant or even reverse flow caused by buoyancy under the large gradient of volumetric heat generation and fluid temperature close to the blanket first wall. This finding led to considerable changes in the original lay-out of the blankets.

The ongoing work on modeling the transport of corrosion products from the steel surface into the liquid metal flow will lead to a better criterion on the allowable interface temperature.

V. CONCLUSIONS AND OUTLOOK

All the investigations during the last 10 years confirmed the feasibility of the DCLL blanket concept for attractive power plants, led to substantial improvements of its performance, and gave a better understanding of the detailed blanket behavior under realistic operational conditions.

The present DCLL blanket concept offers a good compromise between performance and development risk. A liquid metal exit of ~ 700° C allows a BRAYTON cycle power conversion system with a thermal efficiency of ~ 45 %, a value between the efficiency of very advanced self-cooled lead-lithium blankets based on the use of SiC-composites as structural material (~ 55%), and any helium cooled blanket concept based on ferritic/martensitic steels as structural material (~ 35 %).

Experimental investigations of the novel ideas employed in the present DCLL concept, for example the permeation based tritium extraction system and the nested flow channel inserts are mandatory.

In all blanket and power plant studies performed until now, the PbLi exit temperature had been limited to 700 C. In further studies it should be investigated, by which means this exit temperature can be raised by ~ 100 K or higher in order to enable the use of such a plant for hydrogen generation. There are indications that a better understanding of the compatibility between PbLi and ferritic steels as well as a plating of the FW with a 2 mm thick layer of ODS-steel could allow such a temperature increase.

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