Modular Dual Coolant Pb-17Li Blanket Design For ARIES-CS Compact Stellarator Power Plant

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Abstract—This paper summarizes the results from the engineering effort during the second phase of ARIES-CS study on the conceptual design of the modular dual coolant blanket concept. The overall layout of the blanket module including the He coolant and Pb-17Li flow paths and the attachment of the blanket modules to the coolant manifolds behind the blanket (including the mechanical connections and the methods for cutting/re-welding of the coolant access tubes) are described. Results of the supporting thermal hydraulic analyses of such a blanket coupled to a Brayton cycle power conversion system are presented and discussed. Key issues are highlighted and an initial assessment of the suitability and attractiveness of such a concept for a compact stellarator is summarized.

Keywords—Compact stellerator; blanket design; maintenance; coolant manifold

I. INTRODUCTION

The ARIES-CS program consists of a three-phase effort that will result in the detailed design study of a compact stellarator power plant. The first phase of the ARIES-CS engineering study was focused on scoping different compact stellarator design configurations and maintenance schemes to identify the key issues and better understand the parametric design window and the engineering constraints associated with different designs and maintenance schemes [1-3]. This led to a down selection to a couple of most attractive combinations of blanket configuration and maintenance scheme for more detailed studies during the second phase of the study. The preferred blanket concept is a dual coolant blanket with a He-cooled ferritic steel first wall and blanket structure and a self-cooled Pb-17Li breeding zone with SiC/SiC flow channel inserts serving as electrical and thermal insulator [4]. An advanced self-cooled Pb-17Li blanket concept with SiC/SiC as structural material is maintained as a higher performance and higher risk back-up option [5]. The selected maintenance schemes include both a field-period-based maintenance approach and a modular maintenance approach with replacement of smaller modules through a small number of designated maintenance ports using articulated booms [3]. The main characteristics of the DC-blanket concept include:

1. Pb-17Li serving as breeder and coolant, flowing through the poloidal ducts with very slow velocity;
2. Helium cooling of the FW and the entire blanket structure;
3. Flow channel inserts (FCI) made of SiC/SiC composites serving as electrical and thermal insulator between the flowing liquid metals and the steel duct walls;
4. Subdivision of blankets into relatively small modules, to be attached/replaced through horizontal ports arranged between modular coils;
5. Exit temperature of the liquid metal breeder/coolant of \textasciitilde 700°C, allowing the use of a Brayton cycle power conversion system.

Table 1 shows an example radial build for the dual coolant power plant study. Such a dual coolant concept design was originally developed as part of the ARIES-ST study [6] and then at FZK in Germany [7]. A modular concept was adapted for the ARIES-CS compact stellarator geometry with a particular focus on developing a more efficient coolant routing configuration and on optimizing the design performance of the blanket coupled to a Brayton power cycle. The typical size of the blanket modules is about 2 m (tor.) \times 2 m (pol.) \times 0.63 m (rad.) in order to be compatible with modular replacement through a small number of designated maintenance ports using articulated booms [3].

TABLE 1. OVERALL RADIAL BUILD OF THE BLANKET MODULE

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First wall</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>FW cooling channel</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>Second wall</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>Pb-17Li Layer</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>Flow channel inserts</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>Breeding zone-I</td>
<td>25.0</td>
</tr>
<tr>
<td>7</td>
<td>Flow channel inserts</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>Pb-17Li Layer</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>Separation plate</td>
<td>1.5</td>
</tr>
<tr>
<td>10</td>
<td>Pb-17Li Layer</td>
<td>0.1</td>
</tr>
<tr>
<td>11</td>
<td>Flow channel inserts</td>
<td>0.5</td>
</tr>
<tr>
<td>12</td>
<td>Breeding zone-II</td>
<td>25.0</td>
</tr>
<tr>
<td>13</td>
<td>Flow channel inserts</td>
<td>0.5</td>
</tr>
<tr>
<td>14</td>
<td>Pb-17Li Layer</td>
<td>0.1</td>
</tr>
<tr>
<td>15</td>
<td>Back plate</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Total thickness</td>
<td>62.7</td>
</tr>
</tbody>
</table>

Table 1 shows an example radial build for the dual coolant
blanket module. The blanket modules are attached to the high temperature shield combined with the coolant manifolds. A 5-cm gap is used between the manifolds and internal vacuum vessel. Structures outside of the breeding blanket are lifetime components, and the helium-cooled steel shield allows for re-welding the manifold and vacuum vessel. Fig. 1 shows an overall layout of the modular DC-blanket design. All the coolant access tubes for helium and Pb-17Li are designed as concentric pipes.

![Figure 1. Overall layout of the blanket module](image)

The layout of the helium cooling system is shown in Fig. 2. A helium inlet pressure of 8 MPa is assumed. The entire helium with an inlet temperature of ~360 °C enters the blanket box through the inner tube of the concentric pipe attached radially to the back plate of the box. A toroidal manifold, arranged at the corner between the back and bottom plates, distributes the helium flow to the two poloidal inlet manifolds arranged at the corner between the side wall and the back plate. The helium from these inlet manifolds is routed through the side wall and first wall in an alternating flow configuration to create a more uniform temperature (and reduce thermal stresses); the flow is then collected in the poloidal outlet manifolds. A toroidal manifold arranged in the corner between the top and back plates is connected to one poloidal outlet manifold, and the helium flow (~50% of total flow rate) in this manifold is distributed to the toroidal cooling channels in the separation plate, and in the top and bottom plates.

![Figure 2. Helium flow scheme](image)

![Figure 3. Pb-17Li flow scheme](image)

III. MECHANICAL ATTACHMENT OF THE BLANKET REPLACEMENT

One of the maintenance methods under investigation in the ARIES-CS study is the replacement of blanket modules through a small number of horizontal ports. The basic idea is to design a “hot” power core made of skeleton rings continuous in the poloidal direction, on which are attached the blanket modules. The skeleton rings are composed of a steel shield and the poloidal manifold region (see fig. 4), operating at nearly uniform temperature in order to minimize differential thermal expansions and thermal stresses. These skeleton rings are supported with sliding bearings by the vacuum vessel, and can freely expand. Each blanket module is connected to the manifold region by one concentric pipe for the Pb-17Li and one concentric pipe for the helium coolant. For blanket replacement only the outer pipe has to be cut/re-welded with tools coming from the outside while the inner tube uses overlapping zones with sliding seals. Removable shielding
blocks arranged at the outside of the outer coolant tube behave to be removed to provide access for cutting/re-welding (see fig. 5).

The coolants flow in concentric channels not only in the access pipes between module and manifolds but also inside the manifolds. The shield is cooled with helium at a temperature very close to the helium exit temperature (~ 450 °C). In the manifolds as well as in the access pipes, the “cold” helium (inlet) flows in the inner tube and the “hot” helium (exit) in the annulus. The flow directions are reversed in the Pb-17Li access pipes and manifolds with the “cold” Pb-17Li (inlet) at ~ 460 °C flowing in the annulus and the “hot” Pb-17Li flowing in the inner tube. By this layout, the shields and the entire manifold region can be operated at nearly uniform temperature in order to minimize differential thermal expansions and thermal stresses.

The blanket module replacement is based on the cutting/re-welding of the outer tube of the concentric pipes from the outside following removal of the neighbouring blanket module or of the divertor module. The steps to cut the coolant connections from the outside through an open window include:

1. Remove the bottom piece of the shielding block in the radial direction (plasma side);
2. Lower the middle piece of the shielding block down vertically, and remove it;
3. Turn the top piece of the shielding block 180 degree, and lower it down to position of the bottom piece; remove it then from the plasma side.

A crucial issue of such a design is the protection of the weld from neutrons with the criterion to keep the helium concentration in the welding zone below 1 appm over the lifetime of the power plant to allow for re-welding. This criterion was already used in determining the required thickness of the steel shield. However, the large diameter of the coolant access pipes causes the problem of neutron streaming, making the radiation damage in the weld located at the interface between steel shield and manifold considerably larger than in the undisturbed region.

Fig. 6 shows a conceptual design where the weld between the outer coolant access tube and the manifold is protected by a shielding ring inside the tube in order to reduce the neutron flux at the weld location. This ring as well as the removable shielding blocks at the outside of the pipe can be made of steel, W, or WC with 100 % density without any cooling channels. As shown in Fig. 6, there is an overlapping zone at the connection of the coolant access pipe with the manifold, employing piston rings as sliding seals. No cutting/re-welding of this tube is required for blanket replacement. Results of a 2-D neutronics analysis shows that a 28-cm thick high-temperature shield is required to protect the welds between the access pipes and the manifolds in this design concept.

IV. THERMAL-HYDRAULIC ANALYSIS

A parametric thermal-hydraulic analysis of the blanket coupled to a Brayton cycle was performed. The Brayton cycle is chosen to maximize the potential gain from high temperature operation of the Pb-17Li that, after exiting the blanket, is routed through a heat exchanger with the cycle He as secondary fluid [1, 4]. Another advantage of the Brayton cycle is the reduction of the potential for liquid metal/water reaction in case of accidents. Fig. 7 summarizes the results for
the performance of this blanket coupled to the Brayton cycle with 3 compression stages and a single expansion stage; it shows the cycle efficiency as a function of the required conductance between the bulk Pb-17Li in the inner channel and the FS wall in order to accommodate the assumed 500°C FS/Pb-17Li compatibility limit.

\[
\begin{align*}
\text{He/Pb-17Li fract. power} &= 0.42/0.58 \\
q''_{\text{plasma}} &= 0.5 \text{ MW/m}^2 \\
T_{\max,\text{Pb-17Li/FS}} &< 500^\circ\text{C}; \text{ He/Pb-17Li fract. power} < 0.03 \\
\Delta T_{\text{HX}} &= 30^\circ\text{C}
\end{align*}
\]

Figure 7. Cycle efficiency as a function of the required conductance

In addition, the He pumping power was limited to 3% of the total thermal power. For a 3 MW/m² wall load the cycle efficiency is about 43% if a conductance of 200 W/m²-K. For a maximum wall load of ~5 MW/m² (as roughly expected for ARIES-CS) and a reasonable conductance of 200 W/m²-K (e.g. corresponding to a 5-mm thick layer of porous SiC with a conductivity of 1 W/m-K assuming a uniform bulk Pb-17Li temperature with no additional heat transfer resistance between the liquid metal and the wall), the efficiency is slightly over 40%. In this case the corresponding inlet/outlet temperatures of He and Pb-17Li are 355/485°C and 475/690°C, respectively. Although the MHD pressure drop of the Pb-17Li in bare inner channels could be acceptable (~0.1-0.5 MPa), the uncertainty linked with turning flows could increase the total pressure to an unacceptable value. Thus, the SiC layer also plays an important electrical insulation function resulting in a negligible pressure drop in these large ducts. Further studies are being conducted to assess the possibility (and R&D needs) of increasing the cycle efficiency through measures such as utilizing ODS ferritic steel (with a higher temperature capability), assuming a higher Pb-17Li/FS compatibility limit in local areas, and reducing the SiC layer conductance.

V. DISCUSSION AND CONCLUSIONS

A modular dual coolant Pb-17Li blanket design has been evolved in the second phase of the ARIES-CS compact stellarator study. The overall layout of the blanket module including the He coolant and Pb-17Li flow paths and the attachment of the blanket modules to the coolant manifold behind the blanket (including the mechanical connections and the methods for cutting/re-welding of the coolant access tubes) have been summarized in this paper. This modular dual coolant blanket design is well suited for maintenance through a small number of designated ports by utilizing articulated booms. An important selection criterion for the modular maintenance scheme is the weight of a module to be replaced, limited by an anticipated capacity of articulated booms of ~5,000 kg or less.

Scoping thermal studies of the blanket coupled to the Brayton cycle indicate a cycle efficiency of about 43% for an insulator conductance of 200 W/m²-K and a neutron wall loading of 3 MW/m² with a constraint of maintaining the radial averaged temperature of the first wall FS within 550°C and the maximum interface temperature between FS and Pb-17Li < 500 °C. The maximum FS temperature limit in the FW makes it very challenging to accommodate higher surface heat fluxes. For a maximum wall load of ~5 MW/m² (as roughly expected for ARIES-CS), the efficiency is slightly over 40%.

The final selection of blanket concepts and maintenance schemes for the detailed phase–III design study will be made in coordination with results from the physics and system optimization studies.

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REFERENCES