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Numerical Model of Dual-Coolant Lead–Lithium (DCLL) Blanket

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The analysis of Dual-Coolant Lead–Lithium (DCLL) blankets requires application of Computational Fluid Dynamics (CFD) methods for electrically conductive liquids in geometrically complex regions and in the presence of a strong magnetic field. Several general-purpose CFD codes allow modeling of the flow in complex geometric regions, with simultaneous conjugated heat transfer analysis in liquid and surrounding solid parts. Together with a Magneto Hydro Dynamics (MHD) capability, the general purpose CFD is applicable or modeling of DCLL blankets. This presentation describes a numerical model based on the general purpose CFD code CFX from ANSYS customized to include MHD capability using a magnetic induction approach. Numerical model involves simultaneous modelling of two different liquids in different regions of the model: helium coolant, and lead lithium eutectic. Additionally neutron heating is included in the code using three dimensional heat source distribution mapped from the results of the Attila simulations. Surface heating of the front face of the blanket is also included. Geometry of the sample blanket is introduced directly from the CAD using step file. Most of the meshing was performed automatically using CFX mesher. Special grid generation methods were used to insure accurate resolution of the near wall boundary layers including several layers of large aspect ratio prismatic elements. DCLL design also includes some narrow flow regions between SiC insert and structure. These regions were meshed using sweep method two avoid high aspect ratio tetrahedral elements. The numerical model was tested against benchmarks specifically selected for liquid metal blanket applications, such as straight rectangular duct flows with Hartmann number of up to 15000. Results for a general three dimensional case of the DCLL blanket are also included.

Keywords: Computational Fluid Dynamics, Magneto Hydro Dynamics, Tritium Breeding Blankets

1. Introduction

A reliable blanket module design with adequate breeding ratio and heat removal must be available prior to construction to ensure initial success and long term operation of a FNSF, DEMO or Pilot Fusion Plant. There are many concepts that have been proposed with differing performance, reliability and safety characteristics. There must be ways available to down select appropriate concepts short of testing them all in a nuclear facility.

Present paper describes a multi-physics simulation of a preliminary generic DCLL design. Design includes stainless steel blanket structure with He cooled front wall, and four breeding containers where LiPb eutectic is circulating. Containers are lined with insulating SiC inserts to improve performance in a presence of a strong magnetic field. The design shown on figure 1 was used to demonstrate the analysis procedures..

Computational fluid dynamics code capable of MHD flow and heat transfer calculations in complex geometries is required for proper modeling of the DCLL. ANSYS CFX is a general purpose CFD code that allows solving hydrodynamics and heat transfer problems. It is used at PPPL for thermal analysis of complex systems involving fluid flow and heat transfer in liquids and solids [1]. The code was adapted for MHD problems using a magnetic vector potential approach. This paper presents in detail the modification of the code and preliminary results.

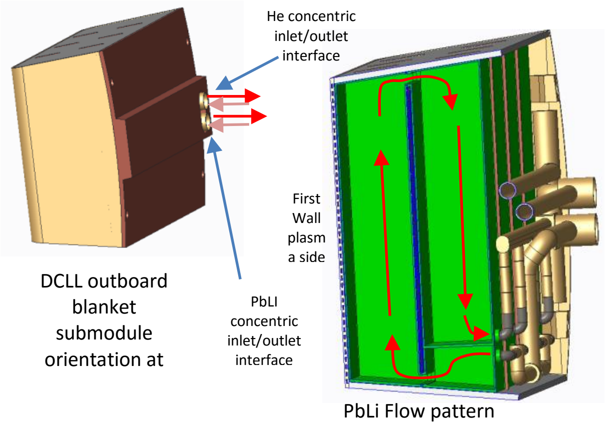

Figure 1. DCLL Blanket Design

2. Mathematical Model

2.1 Code Modification

To include components of magnetic vector potential three additional equations are added to the equations of momentum and energy:

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{A}\right) = \mu \vec{j} \tag{1}$$

where:

$\mu = \frac{4\pi}{10^7}$ - magnetic permeability of vacuum [N/A^2]

$\vec{j} = \sigma\left(-\vec{\nabla}\varphi + \vec{V} \times \vec{B}\right)$ - current density [A]

σ - electric conductivity [S/m]

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Electric potential is introduced via Poisson equation:

$$\vec{\nabla} \cdot (\sigma \vec{\nabla} \varphi) = \vec{\nabla} \cdot (\sigma \vec{V} \times \vec{B}) \tag{2}$$

The Lorentz force is added to momentum transport equations as an additional source:

$$\vec{F}_{mag} = \vec{j} \times \vec{B} \tag{3}$$

Magnetic field is calculated as a sum of external field and the field defined by vector potential:

$$\vec{B} = \vec{B}_{ext} + \vec{\nabla} \times \vec{A} \tag{4}$$

Enforcing the Coulomb gauge:

$$\vec{\nabla} \cdot \vec{A} = 0 \tag{5}$$

equation (1) can be reorganized in the following way:

$$\vec{\nabla} \cdot (\vec{\nabla} \vec{A}) = \mu \vec{j} \tag{6}$$

Thus electromagnetic model adds 4 additional Joule heating hot source is added to energy equation:

$$S_E = -\vec{j} \cdot (\vec{\nabla} \varphi) \tag{7}$$

2.2 Loads and Constraints

DCLL blanket includes solid bodies as well as liquid coolant zones. Thermal and hydraulic analysis of the DCLL was performed using conjugated heat transfer approach, in which heat transfer was resolved in both solid and liquid parts, and simultaneously fluid dynamics analysis was performed only in the liquid part. This approach includes interface between solid and liquid part of the system. In such interface conservation of the heat flux is assumed together with the non-slip wall boundary conditions for the liquid. Since the flow in the He cooling system is for the most part turbulent, non-slip wall boundary conditions take the form of wall functions. He inlet flow rate is 0.89 kg/s

MHD equations were also solved in liquid and solid part of the domain, as well as in the internal vacuum region surrounding supply pipes. Zero value of magnetic vector potential was imposed on the external walls whereas; zero flux values for electric potential were used representing insulating external walls. Tangential external magnetic field was used in the analysis.

Volumetric heat source distribution representing nuclear heating is generated externally by Attila software can be imported into CFX as described in [1]. Distribution used in the current analysis is presented on Figure 2. Constant surface heat flux of 0.8 MW/m2 was imposed on a front wall. Surface heat distribution is presented on Figure 3.

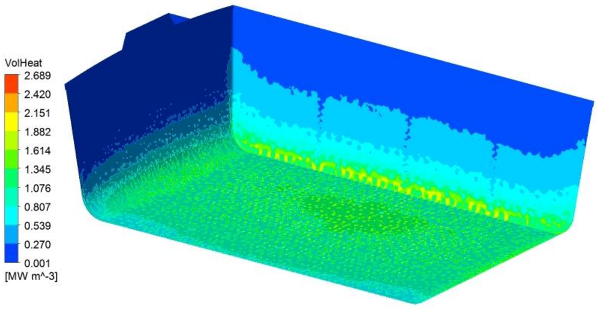

Figure 2 Volumetric heat source imported from Attila

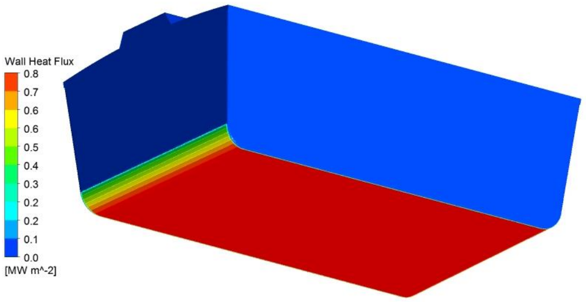

Figure 3 Surface heat flux distribution

2.3 Material properties

Material properties for LiPb, SiC, and RAFM steel are similar to those taken in [2]. Helium is considered perfect insulator. Magnetic properties of RAFM steel are ignored, so all materials are considered have relative magnetic permittivity of 1. Helium cooled channels inside the internal structural ribs are modeled as a blocks with smeared properties, having half of electrical conductivity of RAFM steel and constant temperature of 400ºC. Turbulent low of He in external wall cooling channel is resolved using SST model as in [1].

Table 1. Material properties

	Electrical Conductivity [S/m]	Thermal Conductivity [W/(m K)]	Viscosity [Pa s]
$Li_{17}Pb$	$0.7 \cdot 10^6$	$1.95+0.0196 \cdot T[K]$	0.001
RAFM steel	$1.4 \cdot 10^6$	33.0	
SiC	500	10	
He		$0.056+0.00031 \cdot T[K]$	$4.5 \cdot 10^{-7} (T[K])^{0.67}$

3. Mesh Generation

Meshing was performed using CFX method available within the framework of the ANSYS Workbench mesh generator. Application of tetrahedral elements for meshing the internal regions, allowed automatic mesh generation even in most complex cases. Advanced sizing functions were used with automatic mesh inflation depending on wall proximity and curvature. Combined mesh of 80 million elements was created with 6 layers of boundary elements. Figure 4 shows representation of the mesh.

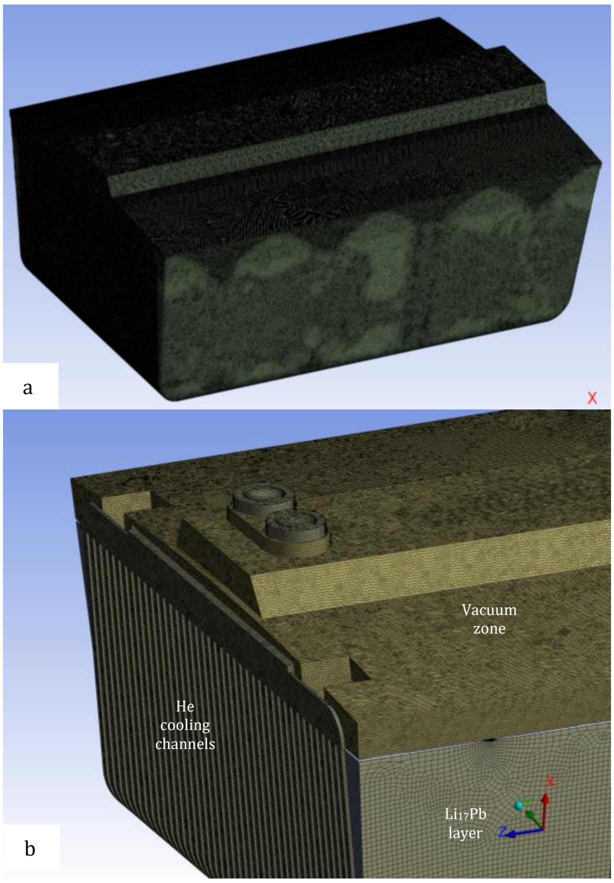

Figure 4 DCLL blanket mesh

Computational domain contains very narrow regions of $Li_{17}Pb$ between the SiC inserts and structural walls. In these regions automatic tetrahedral mesh generation produces mesh with very high aspect ratio elements with sharp angles, causing solution to diverge. To improve mesh quality computational domain was divided into blocks where structured hexahedral mesh was created in those narrow regions using sweep method. This procedure was not automatic, however it allowed creation of compact mesh of increased quality. Detail of such mesh is presented on Figure 3.

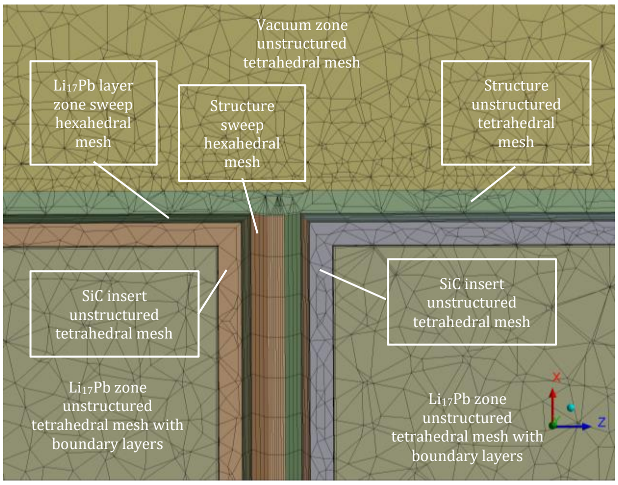

Figure 5 DCLL Blanket mesh details

4. Results and Discussion

4.1 Temperature distribution in blanket structure

Surface heating is a dominating energy source in the conditions considered in current analysis. Thus configuration of the He cooling system near the front face of the blanket determines maximum temperatures in the blanket structure. Figure 6 shows that further optimization of Helium cooling system is needed to avoid excessive temperatures in the corners of the front face down stream of the He flow.

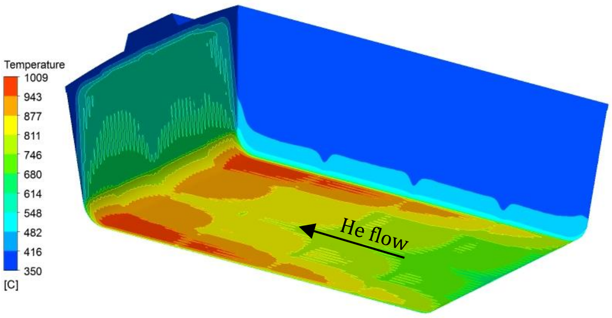

Figure 6 Temperature distribution in blanket structure

Helium cooling system presented on figure 7 can be rearranged so Helium enters front face from the center so that coolant path along the front wall is shorter and distribution is symmetric. Additionally manifolds distributing coolant into the front wall channels could be made uniform, so that equal amount of coolant is distributed in each front wall channel. In current design there are narrow portions of the manifolds leading to less coolant in the channels on the sides of the front face. This can be confirmed by pressure distributions presented on figure 8, and results in hot spots at the corners of the front face seen on figure 6. Note that internal cooling system modeled as solid at 400°C in current analysis, absorbs only very small amount of heat and can be eliminated

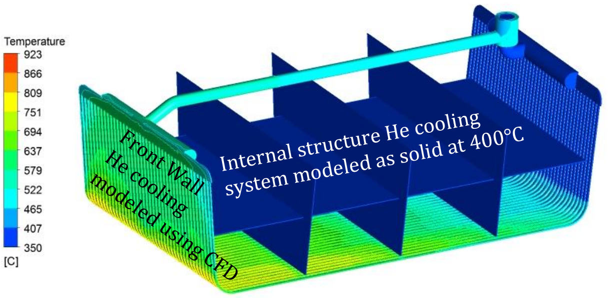

Figure 7 Helium cooling system

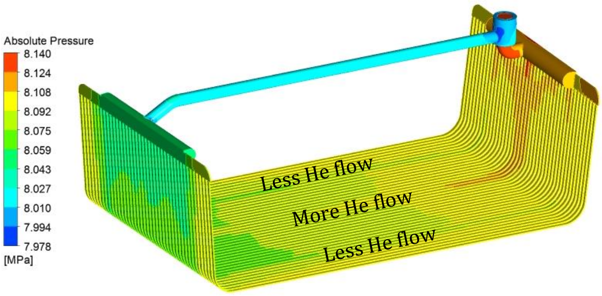

Figure 8 He coolant pressure distribution

4.2 Flow and heat transfer in $Li_{17}Pb$ system

Pressure distributions in lithium-lead system presented on figure 9 shows that majority of the 2MPa pressure drop occurs in the supply tubing perpendicular to the magnetic field direction, where it follows the formula presented for example in [2]:

$$\nabla \mathrm{p} = -\sigma V B^2 \frac{c_w}{1 + c_w} \tag{7}$$

where:

$$c_w = \frac{\sigma_w (R_0 - R_i)}{\sigma R_i} \quad \text{- wall conductivity ratio}$$

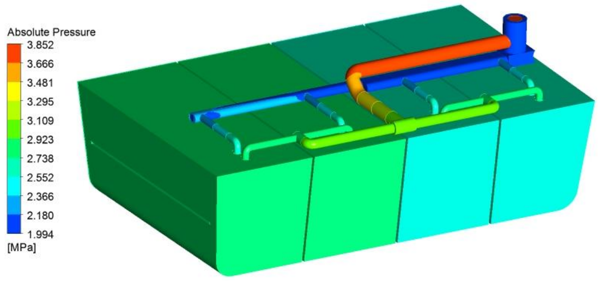

Figure 9 Pressure distribution in $Li_{17}PB$

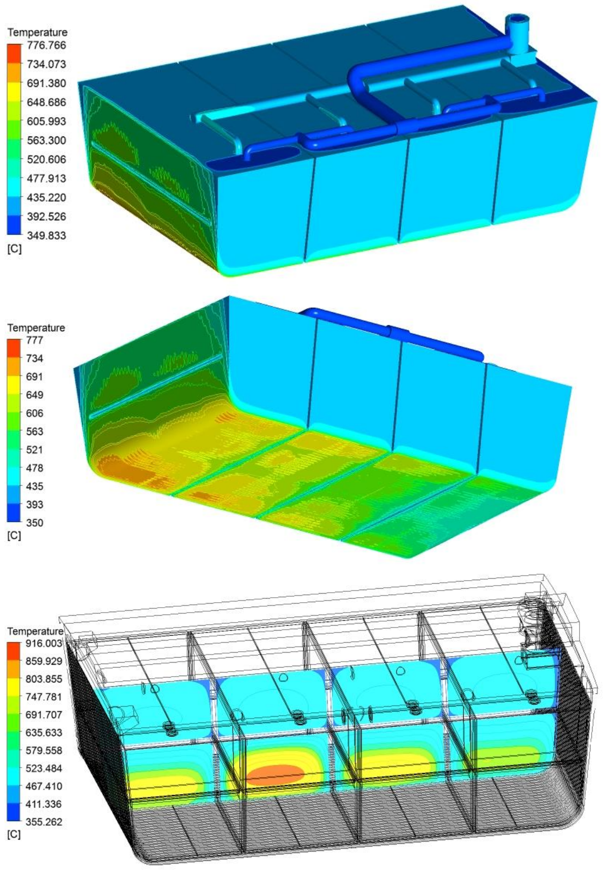

Figure 10 Temperature distribution in $Li_{17}Pb$

This pressure drop can be significantly reduced if supply channels are designed in a way that the total length of the channels perpendicular to the magnetic field direction is reduced. In predominantly toroidal field with radial supply and removal of lead lithium coolant channels perpendicular to the magnetic field are unavoidable. In this case increase of channel cross-section will lead to reduction of the velocity and thus reduction of the pressure drop according to the formula (7). Another approach is in insulating the walls of the channels perpendicular to magnetic field.

Temperature distributions in lithium lead region presented on Figure 10 show uneven temperature distributions in different flow channels. This may be caused by unequal flow rate distribution in the four branches of the lithium-lead cooling system. Introduction of natural convection can additionally increase mixing in the breeding channels.

4. Conclusions

Numerical model capable of analyzing flow and heat transfer in DCLL blankets was created. The model allows CFD analysis of the non-conductive turbulent coolant flow, and simultaneous CFD-MHD analysis of conductive flow of tritium breeding medium. Conjugated heat transfer analysis is performed in all components of the model using conjugated heat transfer approach. Imported nuclear heating load is also included.

The model was used to analyze preliminary design of the DCLL test blanket. Analysis has shown the avenues of improvement in the design, which can lead to significant reduction of the pressure drop and improvement in temperature uniformity.

Acknowledgments

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References

[1] A. Khodak, et al. Numerical Analysis of Coolant Flow and Heat Transfer in ITER Diagnostic First Wall, Fusion Sci. Technol., 68, 10, 521-525 (2015)..

[2] S. Smolentsev et al. Code development for analysis of MHD pressure drop reduction in a liquid metal blanket using insulation technique based on a fully developed flow model, Fusion Engineering and Design 73 (2005) 83–93.

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