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Numerical model of dual-coolant lead–lithium (DCLL) blanket

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ABSTRACT

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. 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 customized general purpose CFD code CFX from ANSYS. The model involves simultaneous modelling of two different liquids in different regions: 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 to 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 15,000. Results for a general three dimensional case of the DCLL blanket are also included.

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 [1], DEMO or Pilot Fusion Plant. There are many concepts that have been proposed with differing performance, reliability and safety characteristics. Numerical simulations allow selection of appropriate concepts short of testing them all in a nuclear facility.

Present paper describes a numerical model applied for multi-physics simulation of a preliminary generic DCLL [2] design including RAFM 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 Fig. 1 was used to demonstrate the analysis procedures. 2D flow analysis of the lithium-lead flow in DCLL blanket with SiC liner was presented in [3]. Present paper presents full 3D analysis including flow simulation of both He, and lead-lithium eutectic.

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 [4]. 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.

2. Mathematical model

2.1. Governing equations

Continuity, momentum and energy equations are solved simultaneously in two separate systems: LiPb breeding circuit, and He cooling circuit in the following form:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{V}) = 0 \tag{1}$$

$$\frac{\partial \rho\vec{V}}{\partial t} + \vec{\nabla}\cdot(\rho\vec{V}\vec{V}) = -\vec{\nabla}p + \vec{\nabla}\cdot(\tau) + \vec{j}\times\vec{B} \tag{2}$$

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$$\frac{\partial \rho c_p T}{\partial t} + \vec{\nabla}\bullet(\rho\vec{V}c_pT) = \vec{\nabla}(\lambda\vec{\nabla}T) + \tau\colon \vec{\nabla}\vec{V} + \vec{j}\bullet\vec{E} \tag{3}$$

where: ρ – density [kg/m^3]; $\vec{V}$ - velocity [m/s]; p – pressure [Pa]; $\tau = (\mu + \mu_t)\left(\vec{\nabla}\vec{V} + (\vec{\nabla}\vec{V})^T - \frac{2}{3}\delta\vec{\nabla}\cdot\vec{V}\right)$ - stress tensor; μ – dynamic viscosity [Pa s] ; μ_t – turbulent viscosity; $\vec{j}$ - current density [A/m^2]; $\vec{B}$ – magnetic field [T]; φ - electric potential [V]; $\vec{E} = -\vec{\nabla}\varphi$ – electric field [V/m]; c_p – specific heat [J/(kgK)]; λ – thermal conductivity [W/(mK)].

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

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

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

$$\vec{\nabla}\times\left(\frac{1}{\mu_0}\vec{\nabla}\times\vec{A}\right) = \vec{j} \tag{5}$$

where: $\mu_0 = 4\pi/10^7$ - magnetic permeability of vacuum [N/A^2]. Magnetic permeability of all materials in the model is considered equal to permeability of vacuum, though implementation in the code allows variable magnetic permeability. Electric potential is introduced via current conservation equation:

$$\vec{\nabla}\cdot\vec{j} = 0 \tag{6}$$

Ohm's law is used to define current density in (5) and (6):

$$\vec{j} = \sigma(-\vec{\nabla}\varphi + \vec{V}\times\vec{B}) = 0 \tag{7}$$

where: σ - electric conductivity [S/m]. Substituting (7) into (6) and (5), and using Coulomb gauge $\vec{\nabla}\bullet\vec{A} = 0$ leads to Poisson equations for magnetic vector potential and scalar electric potential. Eqs. (1)–(7) represent magnetic vector potential MHD formulation implemented in ANSYS CFX [5]. In LiPb breeding circuit laminar flow of incompressible liquid is considered: $\mu_t = 0$, whereas in He cooling circuit turbulent flow of ideal gas is calculated with turbulent viscosity defined using Shear Stress Transport (SST) turbulence model. This model is included in the code and was used in previous analysis [4]. Eqs. (3)–(7) were solved in the solid zones in the same form with zero velocity assumed.

To achieve convergence at high Hartmann numbers typical for fusion applications the source coefficient was introduced for momentum equations. This coefficient introduces implicitness in the treatment of the source terms. Consider extrapolation of the source term for the variable v_i for the next iteration:

$$\dot{S}_{v_i}^{n+1} = \dot{S}_{v_i}^{n} + \frac{\partial \dot{S}_{v_i}}{\partial v_i}(v_i^{n+1} - v_i^n) \tag{8}$$

Implicit treatment (8) can be introduced in the equation for v_i using iterative time step modification:

$$\frac{1}{\widetilde{\Delta\tau}} = \frac{1}{\Delta\tau} - C_{S_{v_i}} \tag{9}$$

where $C_{S_{v_i}} = \frac{\partial S_{v_i}}{\partial v_i}$ is source coefficient, which can be introduced directly in the code. Relation (9) shows that negative values of the source coefficient will reduce the time step and thus will only contribute to stabilization of the solution. The source term in the momentum Eq. (2) can be rewritten using Ohm's law in the following way:

$$\dot{S}_{v_i} = \vec{j}\times\vec{B} = -\sigma\vec{\nabla}\varphi\times\vec{B} - \sigma\vec{V}\,|\vec{B}|^2 + \sigma\vec{B}\,(\vec{V}\bullet\vec{B}) \tag{10}$$

Second term on the right hand side can be used to define source coefficient which will always have negative value:

$$C_{S_{v_i}} = -\sigma\,|\vec{B}|^2 \tag{11}$$

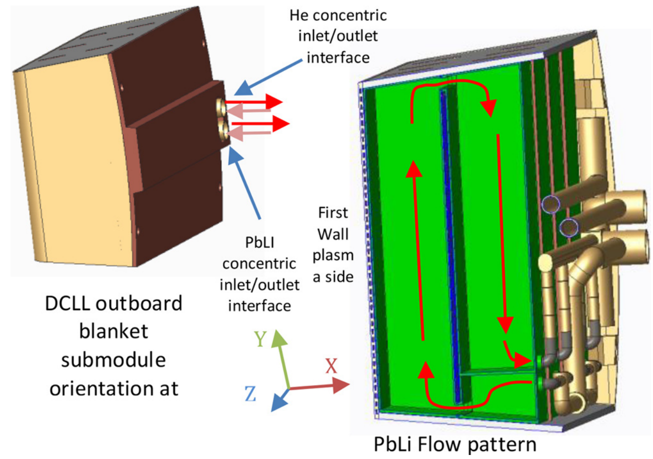

Fig. 1. DCLL Blanket Design.

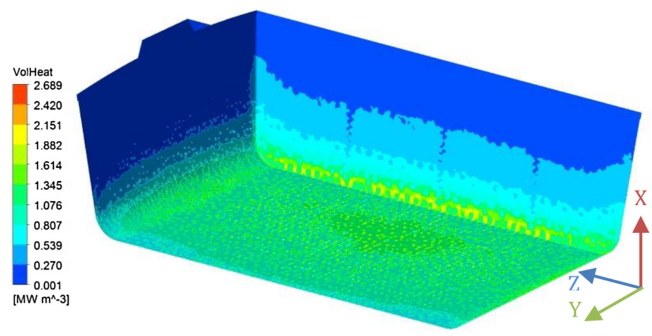

Fig. 2. Volumetric heat source imported from Attila.

Application of this form of the source coefficient allowed numerical simulations for flows with Hartmann numbers of up to 15,000 [6].

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 conjugate 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 parts 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. Constant surface heat flux of 0.8 MW/m2 was imposed on a front wall.

MHD equations were also solved in liquid and solid part of the domain, as well as in the internal vacuum region surrounding supply

Table 1
Material properties.

	Conductivity			
	Electrical [S/m]	Thermal [W/(m K)]	Viscosity [Pa s]	Density [kg/(m^3)]
$Li_{17}Pb$	$0.7{\cdot}10^6$	1.950.0196·T[K]	0.001	
RAFM steel	$1.4{\cdot}10^6$	33.0		
SiC	500	10		
He	10	$0.056+3.1{\cdot}10^{-4}{\cdot}$T[K]	$4.5{\cdot}10^{-7}$(T[K])0.67	Ideal gas
Vacuum	1	0.001		