MODELING TRITIUM TRANSPORT IN PBLI BREEDER BLANKETS UNDER STEADY STATE

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Tritium behavior in the breeder/coolant plays a crucial role in keeping the tritium loss under an allowable limit and realizing high tritium recovery efficiency. In this paper, progress toward the development of a comprehensive 3D predictive capability is discussed and presented. The sequence of transport processes leading to tritium release includes diffusion and convection through the PbLi, transfer across the liquid/solid interface, diffusion of atomic tritium through the structure, and dissolution-recombination at the solid/gas interface. Numerical simulation of the coupled individual physics phenomena of tritium transport is performed for DCLL/HCLL type breeder blankets under realistic reactor-like conditions in this paper. Tritium concentration and permeation are presented and the MHD effects are evaluated. Preliminary results shows that the MHD velocity profile has the significant effect in preventing tritium permeation due to the higher convection effects near the wall.

I. INTRODUCTION

Tritium transport and permeation in fusion blankets are important to contribute achieving tritium self-sufficiency and to accurately characterize tritium inventory and losses. Tritium behavior in the liquid metal breeder blanket requires a thorough understanding of the sequence of transport processes leading to tritium release. Several complex phenomena, including diffusion and convection through the lead lithium (PbLi), transfer across the liquid/solid interface, diffusion of atomic tritium through the structure and dissolution-recombination at the solid/gas interface, seem to characterize the tritium behavior sequence in PbLi breeder blanket. All the proposed transport events are strongly influenced by the operating conditions, such as tritium generation profile, MHD effects, nuclear heating, and chemical reactions. A key aspect of tritium transport prediction of PbLi concerns modeling of permeation. Because of the low solubility of tritium in PbLi, once tritium reaches a PbLi/gas or a PbLi/metal interface, it would rather reside in almost any material other than PbLi. This may be a serious issue, especially for the helium-cooled lead lithium (HCLL) breeder concept due to its low mass flow rate and the lack of a high-performance tritium permeation barrier. Additionally, modeling of tritium transport and permeation inside the blanket requires knowledge of MHD for accurate estimation, which is particularly important for the dual-coolant lead lithium (DCLL) breeder concept because of its relatively high flow rate. In order to design, construct and operate effective PbLi breeder blanket components with adequate characteristics, it is necessary to develop an understanding of these phenomena in complex geometries. This requires a highly interactive program of theory, modeling and experiments.[1] In these concerns, the proposed model in this paper includes several physics phenomena, adequately coupled, such as convection-diffusion in liquid metal, mass transfer through interface and MHD analysis. A 3-D Sc/Tetra-based[2] CFD code has been developed, and appropriate boundary conditions have been selected to link the different mass transport mechanisms for the different regions. The tritium transport is simulated for DCLL/HCLL type of breeder blankets. Tritium concentration and permeation flux are presented and the MHD effects are evaluated.

II. FORMULATION OF THE PROBLEM

The tritium transport model presented in Fig. 1 includes the following controlling physical processes: 1. Convection-diffusion of tritium in the PbLi flow; 2. Tritium transfer across PbLi/solid interface; 3. Diffusion of dissolved atomic tritium through the structure; 4. Tritium movement across structure/gas interface; 5. Convection-diffusion of T_2 in the coolant.

For tritium transport modeling in the liquid PbLi, we assume tritium does not alter liquid metal properties nor flow behavior. Hence, a passive scalar transport equation has been implemented as:

$$\frac{\partial c_{T\_L}}{\partial t} + \mathbf{u}\nabla c_{T\_L} = \nabla \cdot (D_L(T)\nabla c_{T\_L}) + S_m \quad (1)$$

In the structure and helium coolant, the mass balance equations are defined as:

$$\frac{\partial c_{T\_S}}{\partial t} = \nabla \cdot (D_S(T)\nabla c_{T\_S}) \quad (2)$$

$$\frac{\partial c_{T2\_G}}{\partial t} + \mathbf{U}\nabla c_{T2\_G} = \nabla \cdot (D_G(T)\nabla c_{T2\_G}) \quad (3)$$

Where c_{T_L}, c_{T_S} and c_{T2_G} denote the tritium concentration (mol/m^3) in the PbLi, structure and He coolant. D_L, D_S and D_G are the diffusion coefficient (m^2/s) in the respective regions, $\mathbf{u}$ and $\mathbf{U}$ are the velocities (m/s) in the PbLi and He coolant, T is temperature (K), t is time (S) and S_m is the source term.

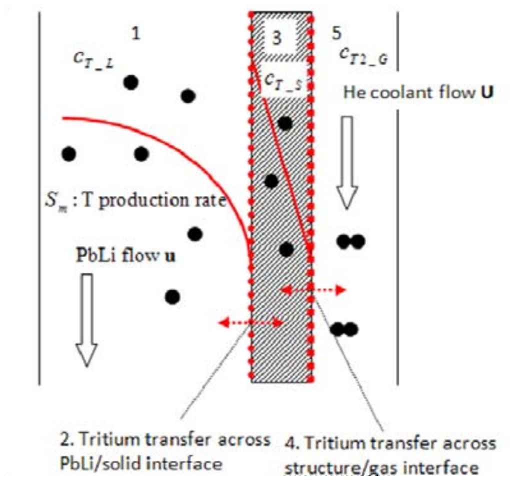

Fig. 1. Schematic of the tritium transport model.

To obtain the convective part of the flux in the PbLi region, the equations for the steady state, laminar, incompressible, viscous, MHD flow are given by:[3]

$$\nabla \cdot \mathbf{u} = 0 \quad (4)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \mathbf{u}\nabla \rho \mathbf{u} = \mu \nabla^2 \mathbf{u} - \nabla p + \mathbf{j} \times \mathbf{B} \quad (5)$$

$$\nabla \cdot \mathbf{j} = 0 \quad (6)$$

$$\mathbf{j} = \sigma(-\nabla \phi + \mathbf{u} \times \mathbf{B}) \quad (7)$$

By combining equations (6) and (7), a Poisson equation for the electric potential is obtained:

$$\nabla^2 \phi = \nabla \cdot (\mathbf{u} \times \mathbf{B}) \quad (8)$$

Where the variables B, j, ϕ, ρ, σ and μ denote the applied magnetic field, current density, electric potential, density, electric conductivity and the viscosity.

Characterization of the mass transfer at liquid-solid and gas-solid interfaces is a main concern. Considering the boundary between phase 1 and phase 2, the interfacial species balance is defined as:

$$J_{in}|_2 - J_{in}|_1 = R_{si} \quad (9)$$

Where the normal flux of species i is given by J_{in}, and R_{si} is the molar rate of formation of species i per unit surface area. Assuming local chemical equilibrium for the system, the concentrations of tritium at the interface are related by equilibrium partition coefficient, K. For PbLi-structure interface, the tritium equilibrium can be defined as:

$$c_{T\_S} = K c_{T\_L} \quad (10)$$

Where $K = K_{S\_S} / K_{S\_L}$ is determined by the relative solubility of tritium in PbLi K_{S_L} and structure K_{S_S}.

For the gas-structure interface, the surface concentrations are determined by Sieverts' law:

$$c_{T\_S} = K_{S\_S} P^{1/2} \quad (11)$$

Where P is the partial pressures, and S (mol/m^3·Pa$^{0.5}$) is the solubility coefficient for Sieverts' law.

Additionally, accurate boundary conditions at the interfaces are necessary to ensure the flux continuity.

$$D_L \frac{\partial c_{T\_L}}{\partial n} = D_S \frac{\partial c_{T\_S}}{\partial n} \text{ at PbLi-wall} \quad (12)$$

$$D_S \frac{\partial c_{T\_S}}{\partial n} = D_G \frac{\partial c_{T2\_G}}{\partial n} \text{ at gas/wall} \quad (13)$$

Where n is the normal direction of the interface.

III. NUMERICAL RESULTS AND DISCUSSION

The present numerical investigation is carried out using the commercial package Sc/Tetra. The magneto hydrodynamic equations and the appropriate boundary conditions between interfaces have been implemented in the code by means of C++ user functions.

The numerical analysis consists of three cases: (A) a 2-D simulation to evaluate velocity profile effect on tritium transport, (B) simulation of the tritium transport in a simplified DCLL type of flow, and (C) simulation of the tritium concentration in a HCLL concept geometry.

III.A. Velocity profiles effect on tritium transport

In order to more clearly see how the MHD flow affects the tritium distribution, three typical velocity profiles[4] are imposed according to various conditions:

1. Parabolic velocity profile as it would be obtained if no MHD effects were involved.
2. Hartmann layer velocity profile (flat) as it would be obtained on a Hartmann wall in MHD flow.
3. Side layer velocity profile (M-shape) as it would be obtained on a side wall in MHD flow.

The 2D problem is defined in two regions as shown in Fig. 2: the liquid PbLi region (1m×0.035m), and the structure region(5mm thickness ferritic steel).

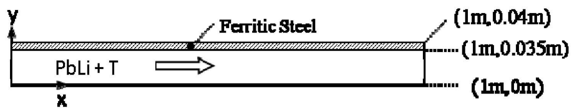

Fig. 2. Diagram of the 2D geometry: the liquid region (1m×0.035m) and the 5mm structure region.

Fig. 3 and Fig. 4 show the three velocity profiles and the corresponding tritium concentration along y-direction at x=0.8m at same mass flow rates. Tritium accumulates near the wall region for parabolic velocity profile, which results in a high tritium permeation flux (Fig. 5), and consequently a high tritium leakage rate. On the contrary, for the MHD type velocity profiles (side layer and Hartmann layer velocity profiles), the tritium concentration increase near the wall region is no more present. This means that a lower tritium permeation flux can be maintained because of higher convection effect near the wall.

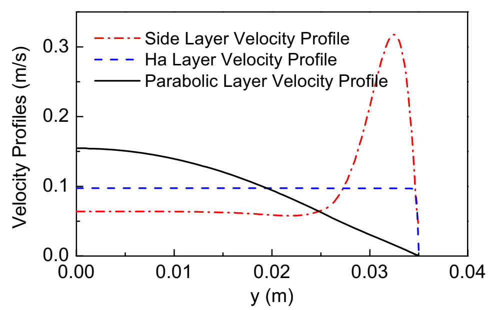

Fig. 3. Parabolic, side layer and Hartman layer velocity profiles along y-direction at same mass flow rates 22kg/s.

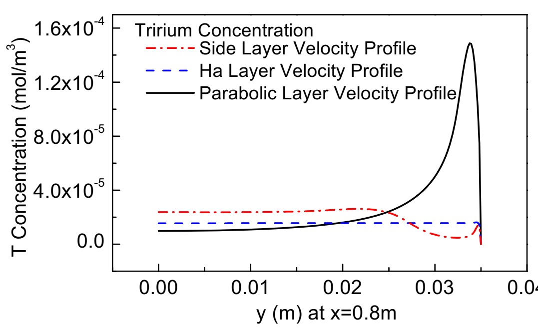

Fig. 4. Tritium concentrations along y-direction at x=0.8m for parabolic, side and Hartman layer velocity profiles.

The permeation flux (Fig. 5) shows a significant reduction for MHD type velocity profiles. This is reasonable since the velocity distribution close to the wall governs the tritium permeation. Side layer velocity profile here is the best for representing the tritium distribution. It provides a higher convection effect due to its higher velocity near the wall, and consequently keeps most tritium in the PbLi bulk and reduces tritium permeation through the wall.

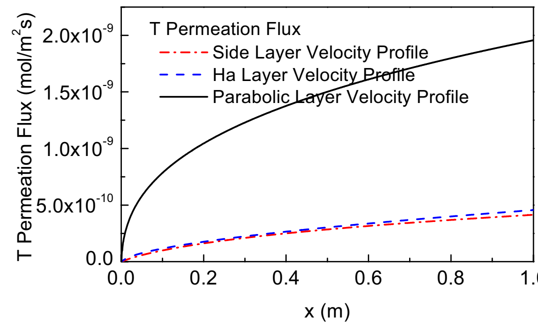

Fig. 5. Tritium permeation flux along wall for parabolic, side layer and Hartman layer velocity profiles.

III.B. Simulation of the tritium concentration in a simplified DCLL type of MHD flow

A number of blanket designs exist involving the use of PbLi flows, in which the PbLi can be used both as coolant and breeder (self-cooled) or exclusively to produce tritium (separately cooled). Currently, two primary concepts are US DCLL and European HCLL blanket concepts.

The US DCLL blanket concept has the potential to be a high-performance DEMO blanket design. Reduced activation ferritic steel is used as the structural material. Helium is used to cool the first wall and blanket structure, and the self-cooled Pb-17Li breeder is circulated for power conversion and for tritium breeding and extraction.

Computations were performed here for tritium transport in a simplified DCLL TBM channel exposed to toroidal magnetic field. Three U-bent duct flow with conducting walls connected through inlet/outlet with manifolds are analyzed (Fig. 6). PbLi starts in the feeding circular pipe, then the PbLi expands in the manifolds and it distribute into three channels. The liquid metal flows among three back channels and flows into the front channels by passing through the U-turns. After distributing into the front channels the fluid is collected in the outlet manifold. For more details on the complete DCLL-TBM geometry see P. NORAJITRA et.al. 2002 (Ref. 5). Fig. 6 shows the simulated MHD flow distribution. M-shape velocity profile due to MHD effect in channels and 3D effects near the bends and manifolds are observed. Fig. 7 displays the contour plots of the tritium concentrations showing lower values in the back channels and accumulation along the PbLi pathway. Interesting features of tritium concentration reflecting velocity profile effect are well described by Fig. 8 where the tritium concentration and the corresponding velocity profile are plotted as a function of the radial direction along the center line of the geometry at the front channel indicted by dotted arrow in Fig. 7. Tritium concentration is lower at the front wall (D) due to permeation, then it increases due to the high tritium generation rate and low velocity close to the front wall (C). At locations A and B, tritium concentration falls down again (associated with high-speed regions of the M-shape velocity profile).

Since high local tritium concentrations (for example, location C) are particularly undesirable near the solids walls, further design improvement and operation condition optimization are needed to keep more tritium in the PbLi bulk and reduces tritium permeation through the wall.

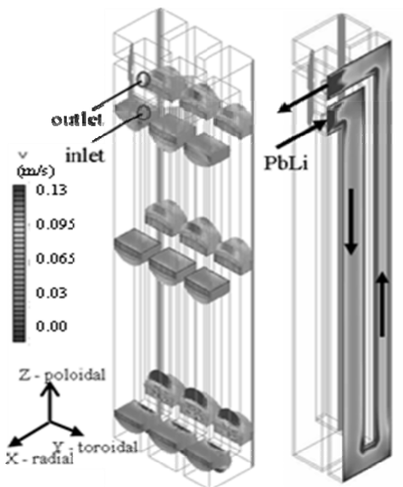

Fig. 6. Velocity profile in simplified DCLL TBM channels with toroidal magnetic field

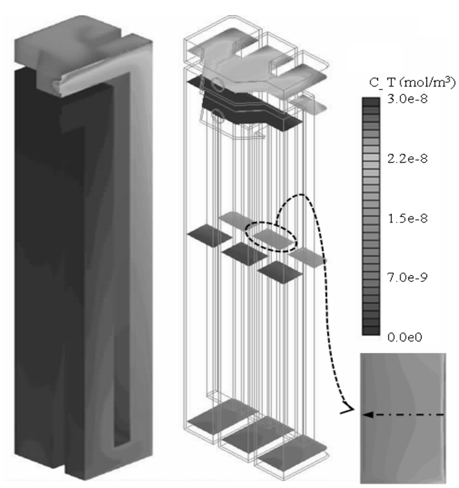

Fig. 7. Contour plots of the tritium concentrations (mol/m^3) in simplified DCLL TBM channels with toroidal magnetic field and radial distributed tritium production.

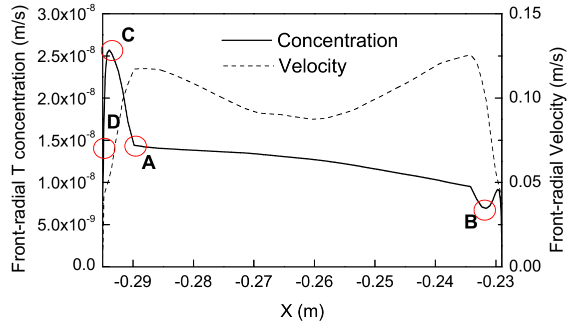

Fig. 8. The tritium concentration and the corresponding velocity profile are plotted as a function of the radial direction along the center line of the geometry at the front channel indicted by dotted arrow in Fig. 7

III.C. Simulation of the tritium concentration in a HCLL concept geometry

The current European HCLL blanket concept is a modular design, where a number of rectangular boxes, the breeder units (BU), is arranged in columns and combined to form a blanket module.

Computations of the tritium transport in the prototypic 3D geometry given by the HCLL concept have been performed in this paper. The geometry under study consists of two breeder units (BU) separated by stiffening plates. Each unit contains five cooling plates (Fig. 9). All the walls are electrically conducting. The liquid metal starts in the feeding distributing gap and it distributes among the cooling plates and flows into the second connected breeder unit by passing through an opening near the first wall. After distributing into the second BU the fluid is collected in the draining poloidal distributing gap. For more details on the complete HCLL-TBM geometry see G.R 2009 (Ref. 6).

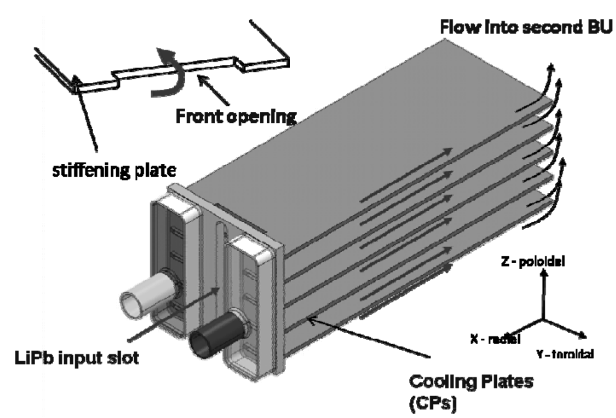

Fig. 9. HCLL breeder unit geometry.

Fig. 10 shows the tritium concentration and the corresponding velocity profile at the middle plane of the geometry. the velocity distributions show that stiffening plate has stronger influence on the velocity profile, which causes the larger flow rate at stiffening plate. In the duct cores a rough uniform velocity distribution is observed, with small increase in the side layers along the cooling plates. This kind of velocity distribution would be preferred due to its benefit on tritium permeation reduction. In the top and bottom channels of each breeder unit the two side layers merge and no uniform core region is present any more. The distribution of the tritium concentration in the breeder units shows lower values in the first breeder unit and accumulation along the PbLi pathway. Along the poloidal direction the tritium concentration varies as the channel aspect ratio changes and strongly affected by the velocity distribution. The top and bottom channels of the first breeder unit has the lower tritium concentration due to the relative high velocity at these places. In the duct cores, we can see a rough uniform tritium distribution, and there are no high local tritium concentrations near the structure walls. This kind of distribution would be good to preventing tritium permeation and reduce tritium loss to He coolant.

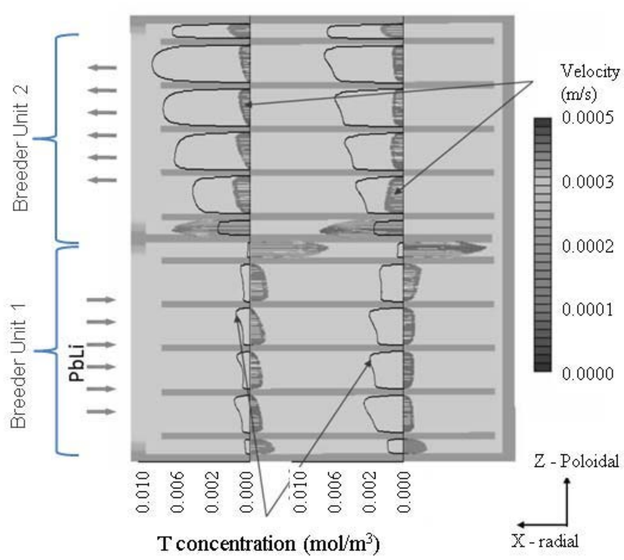

Fig. 10. The tritium concentration and the corresponding velocity profile at the middle plane of the geometry.

IV. CONCLUSIONS

In this paper, progress toward the development of a comprehensive 3D predictive capability of tritium transport in PbLi blanket is discussed and presented. The model simulates multi-step tritium transport processes, simultaneously taking into account of the effects of MHD velocity profile, and geometry complicity. Simulation in the DCLL/HCLL breeder units show that the velocity distribution close to the walls governs the tritium permeation and the transfer process. the M-shape side layer velocity profile or flat-shape Hartman layer velocity profile in the liquid metal flow has a significant benefit in preventing tritium permeation due to the higher convection effect near the wall. the simulation results also confirm that the MHD benefit on permeation reduction even for more complex 3D MHD flows. Since high percent of tritium escapes into the He coolant, very efficient blanket permeation barriers are needed to be developed for breeder blankets.

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