Tritium Transport Modelling: first achievements on ITER Test Blanket Systems simulation and perspectives for DEMO Breeding Blanket

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ABSTRACT Beyond other objectives, the European TBM Programme is expected to generate experimental data for development and validation of tritium transport simulation tools, whose full availability is essential for predicting tritium processing performance of a breeding blanket in DEMO/power reactor. This will be implemented by designing, constructing, installing and testing in ITER the HCLL (Helium Cooled Lithium Lead) and HCPB (Helium Cooled Pebble Bed)-TBS (Test Blanket Systems).

In this ambit, a tritium transport simulation tool has been developed through a collaboration between Fusion for Energy (F4E, European Domestic Agency for Fusion Development and ITER) and CIEMAT/Emperarios Agrupados (Spain), based on the customization of the EcosimPro simulation platform. In the current version the code implements a 1D dynamic mathematical model, without including multi-physics coupling effects (e.g. MHD, thermal-hydraulics of Pb-16Li, etc.).

First results of a parametric analysis on HCLL-TBS tritium migrations are here presented and discussed. This preliminary analysis has allowed to successfully verify the model consistency and to better understand the impact of some operating conditions on the tritium inventory in the most relevant HCLL-TBS sub-systems.

1. Introduction

The tritium migration path in HCLL-TBS begins from the location where tritium is generated, the HCLL-TBM, and develops through the TBS ancillary systems, shown in the block diagram of fig. 1. There it is possible to identify: i) HCLL-TBM, with the box made of reduced activation ferritic-martensitic steel Eurofer-97, cooled by pressurized He at 8 MPa, and containing slowly flowing Pb-16Li alloy that acts as tritium breeder and neutron multiplier [1]; ii) the Pb-16Li loop, for recirculation of Pb-16Li alloy externally to the TBM and vacuum vessel; iii) HCS (Helium Cooling System), the primary cooling circuit with high pressure He (8 MPa) for the extraction of the thermal power from the TBM; iv) CPS, for the extraction and recovery of tritium permeated into the primary cooling circuit and to control the TBM coolant chemistry; v) TES (also called TRS), for the tritium extraction from Pb-616Li and further tritium concentration in gas phase (He); vi) TAS, for the tritium accountancy prior being routed to the ITER Tritium Systems [2].

Fig. 1 Block diagram of HCLL-TBS ancillary systems [2]

Developing and validating a tritium transport simulation tool for TBS is requested by: i) the obligation to provide the ITER licensing authorities with a sound assessment of the tritium inventory in the different TBS sub-systems as well as tritium leaks, mainly by permeation, into the working areas; ii) the need to design the TBS experiments in ITER in the most comprehensive way; iii) the need of having a validated tool to support of a DEMO breeder blanket design.
The tritium transport simulation tool here presented has been developed through a formal collaboration between F4E and CIEMAT/Empresarios Agrupados (Spain). The code, based on the customization of the EcosimPro simulation platform, implements a 1D dynamic mathematical model, without including multi-physics coupling effects (e.g. MHD, thermal-hydraulics of Pb-16Li, etc.).

For a large set of pre-selected ITER irradiation scenarios specified as input, the tool gives the following outputs: i) the amount of tritium permeated from the TBM into HCS through the cooling and stiffening plates; ii) the amount of tritium solubilized in the functional and structural materials of the TBM and in all TBS ancillary systems; iii) the tritium permeation rate through the piping of each ancillary system into the relevant ITER operational rooms; iv) the percentage of tritium reaching TAS over the tritium generated in the TBM per unit time.

The paper describes first the main characteristics of the simulation tool. Then, it presents the preliminary simulation results which cover a selected interval of HCLL-TBS operating conditions for Pb-16Li mass flow-rate, tritium generation rate, tritium transport parameters, tritium extraction efficiency, under the most demanding plasma scenario, consisting of inductive back to back pulses lasting 24 hours (duty cycle 25%, 1800 seconds repetition time, 48 pulses per day). The paper recalls also the main lines of development of tritium transport modelling from this preliminary phase up to the final one when the predictive capabilities have to be exploited at the maximum extent in support of the DEMO breeding blanket design.

2. Description of the model

HCLL-TBM model basically foresees three channels, delimited by two cooling plates (CPs) and first wall, where Pb-16Li flows performing a U-shaped path, as shown in fig. 2. Globally 8 units (then corresponding to the 16 breeding units in HCLL-TBM), each consisting of the three channels, are considered in the model. While flowing in the TBM, Pb-16Li is irradiated by neutrons and generates tritium, with an exponential generation rate profile in the radial direction. Tritium generated in atomic form is transported by flowing Pb-16Li through the TBM while, through a set of embedded cooling and stiffening plates, a part of it also permeates into the HCS. Temperature profile for the liquid metal and Eurofer-97 steel in the TBM is shown in fig. 3.

In fig. 4 all transport resistances to tritium permeation in a channel are represented. Form the liquid metal side, one can recognize: i) a liquid boundary layer; ii) the interface between the liquid metal and the steel; iii) the bulk steel where tritium moves by pure diffusion; iv) the interface between steel and gas phase, where phenomena of dissociation and recombination take place; v) the gas phase.
As announced in the introduction, the domain of the simulation model is the full HCLL-TBS, formed by the HCLL-TBM and the four ancillary systems, linked as shown in fig. 5. The Pb-Li loop process flow diagram is shown in fig. 6.

It essentially consists of the following main components:

- a recirculation/storage vessel, hosting the mechanical recirculation pump that assures a liquid metal flow-rate in the range of 0.2–1 kg/s. It is treated as an Eurofer-97 tank with 30 mm thickness.
- a detritiation unit (TEU) to extract tritium from the liquid metal into a gas phase, treated as an Eurofer-97 cylinder of 8 mm diameter 3 mm thickness
- a cold trap to control the level of impurities and corrosion products in the liquid metal, treated as an Eurofer-97 tank of diameter of 400 mm and thickness of 10 mm
- Pb-Li loop pipes: they are modeled with an internal diameter of 35 mm and wall thickness of 3.56 mm. Total length is 27 m.

3. Test Matrix and main assumptions

The test matrix, reported in Tab. 1, has been arranged for a check of the internal consistency of the code and, at the same time, for a preliminary performance prediction in terms of tritium recovery capability and inventory distribution. Therefore, it has been organized to implement a preliminary parametric analysis involving tritium generation rate, recombination coefficient at the He side of the TBM cooling plates, TEU efficiency and Pb-16Li flow-rate.
TABLE 1. Test matrix for the simulation runs on tritium migration in HCLL-TBS

<table>
<thead>
<tr>
<th>n. run</th>
<th>Tritium generation rate (mg/d)</th>
<th>Recombination factor (-)</th>
<th>TEU efficiency (%)</th>
<th>Pb-16Li flow-rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>1</td>
<td>40</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>1</td>
<td>40</td>
<td>0.4</td>
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<tr>
<td>3</td>
<td>13</td>
<td>1</td>
<td>40</td>
<td>0.6</td>
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<tr>
<td>4</td>
<td>13</td>
<td>1</td>
<td>60</td>
<td>0.2</td>
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<tr>
<td>5</td>
<td>11</td>
<td>1</td>
<td>80</td>
<td>0.2</td>
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<tr>
<td>6</td>
<td>13</td>
<td>1</td>
<td>40</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>1</td>
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<td>0.2</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>10</td>
<td>40</td>
<td>0.2</td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>100</td>
<td>40</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>13</td>
<td>10000</td>
<td>40</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The parametric analysis is carried out assuming:
- constant hydrogen partial pressure in HCS He coolant: 1000 Pa.
- tritium partial pressure at the time zero in the He coolant (HCS) equal to 0 Pa and then increasing due tritium permeation
- Tritium/Pb-16Li Sieverts’ constant: $1.3\times10^{-3} \cdot \exp(-1350/RT)$ (mol m$^{-3}$ Pa$^{-0.5}$) [3]
- Tritium/Eurofer 97 solubility and diffusivity as in [4]
- reference recombination coefficient (rrc) at the He-side of the cooling plates, on which the recombination factor is applied is: $K_r = 4.713 \times 10^{-31} \exp(28769/kT)$, as in [5]. Recombination factors used in this analysis are just the multiplication factors multiplied by rrc.
- minimum (at the cold trap location) and maximum (at the TEU location) temperature in the Pb-Li loop: 270 °C, 450 °C
- TEU and cold trap are treated as simple pipes of the relevant dimensions, without internals.

4. Simulation Results

In the following figures the results of the simulation runs, according to the test matrix, are reported.

4.1: varying the tritium generation rate, results in fig. 7.1, 7.2, 7.3

- Tritium inventory in the TBM box

![Tritium Inventory in TBM Structural Material](image)
- Tritium inventory in Pb-16Li contained in the HCLL-TBM

FIG. 7.2 Tritium inventory in Pb-16Li as a function of the tritium generation rates (runs 1, 6, 7)

- Tritium permeation rate from HCLL-TBM into HCS

FIG. 7.3 Tritium permeation rate into HCS as a function of the tritium generation rates (runs 1, 6, 7)

4.2: varying the Pb-16Li flow-rate, results in fig. 8.1, 8.2, 8.3

- Tritium inventory in the TBM box

FIG. 8.1 Tritium inventory in the TBM box as a function of Pb-16Li flow-rate (runs 1, 2, 3)
- Tritium inventory in Pb-16Li contained in the HCLL-TBM

![Tritium Inventory in TBM box PbLi](image)

**FIG. 8.2** Tritium inventory in Pb-16Li as a function of Pb-16Li flow-rate (runs 1, 2, 3)

- Tritium permeation rate from HCLL-TBM into HCS

![TBM Tritium permeated to coolant](image)

**FIG. 8.3** Tritium permeation rate into HCS as a function of Pb-16Li flow-rate (runs 1, 2, 3)

**4.3:** varying the TEU efficiency, results in fig. 9.1, 9.2, 9.3

- Tritium inventory in the TBM box

![Tritium Inventory in TBM Structural Material](image)

**FIG. 9.1** Tritium inventory in the TBM box as a function of the TEU efficiency (runs 1, 4, 5)
- Tritium inventory in Pb-16Li contained in the HCLL-TBM

![Tritium Inventory in TBM box PbLi](image)

FIG. 9.2 Tritium inventory in Pb-16Li as a function of the TEU efficiency (runs 1, 4, 5)

- Tritium permeation rate from HCLL-TBM into HCS

![TBM Tritium permeated to coolant](image)

FIG. 9.3 Tritium permeation rate into HCS as a function of the TEU efficiency (runs 1, 4, 5)

4.4: varying the recombination coefficient, fig. 10

![TBM Tritium permeated to coolant](image)

FIG. 10 Tritium permeation rate into HCS as a function of the recombination factor (runs 1, 8, 9, 10)
5. Discussion and Conclusions

The main outcomes from this parametric analysis can be summarized as follows:

- **Results from 4.1:** as expected, increasing the tritium generation rate leads to an increase of the tritium inventory in the TBM box, in the Pb-16Li and in the tritium permeation rate into HCS. Tritium inventory steady state is not achieved (to be recalled that simulations in 4.1 refers to 0.2 kg/s of Pb-16Li flow-rate). Tritium inventory on the TBM box is always below 1 mg.

- **Results from 4.2:** increasing the Pb-16Li mass flow-rate leads to an evident decrease on the tritium inventory inside the TBM box and Pb-16Li and, at the same time, to a significant reduction of the tritium permeation rate into the coolant. The two effects are, of course correlated. As the Pb-16Li flow-rate increases towards the upper range limit (1.0 kg/s), the steady state inventory is almost reached in less than 24 hours, differently from what happens at 0.2 kg/s.

- **Results from 4.3:** TEU efficiency is heavily impacting both tritium inventory and permeation. Doubling the TEU efficiency from 40 to 80 % leads to a reduction of the tritium inventory in the TBM box of around 35% because of the lower tritium concentration in the liquid metal. This lower concentration drives the decrease of the tritium permeation rate into HCS.

- **Results from 4.4:** the tritium recombination coefficient at the interface gas-steel has a strong impact on the tritium permeation rate into HCS. Tritium permeation rate from HCLL-TBM into the primary cooling circuit is rather small at low recombination factor due to the strong transport resistance in addition to the one from the liquid metal boundary layer and steel bulk diffusion. However, for the highest value of the recombination factor, the tritium permeation cumulated in 24 hours is around 1 mg, a value which starts to be close to the one calculated in pure diffusion limited regime (instantaneous recombination at the gas-steel interface).

As a general remark, the parametric analysis results follow an expected and consistent trend. Moreover, even if not shown here because of lack of space, other two important arguments are in favor of the internal consistency of the model implementation in the code: i) the tritium mass balance perfectly closes in all simulation runs; ii) increasing the hydrogen-tritium recombination coefficient at the gas-steel interface leads to results closer to the case of pure tritium transport diffusion regime.

Further developments are foreseen in the next future: the first one will deal with a comprehensive modelling of the main TBS ancillary systems components, like TEU and cold trap in the Pb-Li loop, but also getter beds, molecular sieve systems, etc., in CPS and TES. Integration of MHD effects and thermal-hydraulics into the model will be a further important step to develop a valuable design tool.

Extensive experimental campaigns have been launched by F4E in the last years or are currently under preparation. They are aimed at achieving performance data on components relevant to HCLL-TBS to support design and modelling activities and, at the same time, to consolidate values of physical parameters, like the hydrogen-tritium transport parameters in solid and liquid TBS relevant materials which are of basic importance to construct accurate modelling capabilities.

References


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