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Tritium modeling in HCPB breeder blanket at a system level

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Tritium behavior in a DEMO reactor is a key design issue because of its self-sufficiency and impact on safety. Considering the difficulty in handling tritium, and that the transport, diffusion and permeation phenomena involve a large number of physical properties and parameters, it is intended to prepare a simulation tool to predict its behavior. A preliminary model for tritium transport at system level has been developed for the HCPB (Helium Cooled Pebble Bed) breeder concept (DEMO2014), focusing on the multi-physics of the release, diffusion, permeation, recombination phenomena. The numerical technique presented here is based on EcosimPro simulation tool, a program with an object-oriented nature which offers the possibility of mixing various disciplines by robust equation-solving algorithms. The study presents the results obtained in a reference case in which the most generic parameters provided by the HCPB designers have been used. Together with the breeder blanket concept, a tritium extraction system (TES) and a coolant purification system (CPS) have been included into the gases circuits. The results of tritium permeation to the coolant provide relatively low values (around 0.2 g/d), that will be improved in the future by a more detailed system description.

Keywords: Tritium, Model simulation, DEMO blanket, System level, HCPB.

1. Introduction

One of the main objectives in the Horizon 2020 roadmap is the safety of DEMO reactor and its self-sufficiency. Thus tritium generation inside the breeder material, the extraction process from the system and its permeation into the coolant are really important concerns. In this framework, the EUROFusion project has identified a working area included into the development of the breeder blankets, mainly focused into the development of tritium extraction system design and experiments together with a tritium control strategy, the whole supported by a model and simulation tool [1]. The final objective of this working package is to demonstrate the feasibility of tritium management, including extraction and control, for the four EU breeding blanket concepts.

The creation of a simulation tool for the design of a breeder blanket system results to be an essential part of this interlinked activity for DEMO project [2]. The main requirement is to include a general physics taking into account all the phenomena occurring in different part of the reactor, at different scale. Starting from it, specific tritium libraries have been developed in EcosimPro[3] containing different components which, through flow diagrams, can create sub-systems, for the final creation of a model at a system level.

In this frame a HCPB model has been developed. HCPB is one of the four Breeder Blanket concept proposed for future fusion reactors. This model is based on 5 main parts: lithium ceramics in a pebble bed as tritium breeder, a purge gas based on helium with hydrogen trace for tritium removal, a pebble beryllium bed as neutron multiplier and pure helium at high pressure as coolant of the system [4]. The generation, permeation, extraction and release of tritium are among the main issues to understand and implement for an optimization of the breeder blanket concept. Considering the interest of the scientific community [5], some general results are delivered in this work.

The model starts considering a BU and the main auxiliary components in order to simulate the inventory of the tritium generated in the breeder zone, extracted from the purge gas loop trough a TES (Tritium Extraction System), and finally the permeated one from the purge gas into the coolant system, considering that a small quantity is purified throughout a bypass connected to a CPS (Cooling Purification System). The main objective of the work is to observe tritium behavior in critical components and identify its weaknesses and strengths in terms of self-sufficiency and safety for the future Fusion reactor.

2. Model description

The model has been developed using the object oriented modelling software EcosimPro. This simulation tool requires input parameters related to design configuration and concerning tritium kinetic behaviour in the materials. The system is modelled using a process flow diagram joining different components contained in the Tritium_Balance library. Each component of the diagram computes a certain amount of dynamical equations related to all the physical processes that the user needs to consider. That way it is possible to create subsystems into the Tritium_Eurofusion library and finally generate a code from a system level perspective, adding all the phenomena occurring at a component level [6].

In this first model, the U of the breeder unit has been considered as the minimal geometric element of a 2014 DEMO HCPB model. The purge gas inside the BU flows from the central part of the BU towards two symmetrical branches, each one with a semi-U shape. Considering that the curved central zone is the one nearest to the first wall a geometrical discretization along the radial direction is proposed. In that way an exponential tritium generation profile, will automatically include a higher generation rate in this zone.

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The tritium produced in atomic form inside the pebble bed via transmutation, diffuses through the grains to the ceramic surface where, from the chemical interaction with the hydrogen present in the purge gas and with the oxygen present in the ceramic structure, is purged away in the molecular forms of HT, HTO, T_2 following the possible reactions:

$$Li^+H^-Li^+ + T^+ = \mathbf{HT} + 2Li^+ \; ; \; OH^- + T^+ = \mathbf{HTO} + V_o \quad (1),$$

where V_o is an oxygen vacancy, one of the most typical defect for this kind of ceramic structures [7], [8]

As a consequence of the temperature range inside the breed pebble also the isotopic al exchange described by:

$$H_2 + HTO \leftrightarrow HT + H_2O \qquad (2),$$

will take place [9], [10], releasing some water molecules inside the purge gas. Also a small fraction of T_2O should be formed, but it will be neglected.

In the interface between the Eurofer and the coolant mainly tritium and hydrogen in atomic form will permeate. Consequently recombination and dissociation processes may occur in the interface between the purge gas and the coolant pipe material and between the Eurofer pipe and the coolant gas, as:

$$J_m\,(H_2) = -\,K_d\; p(H_2) + K_r\; c(H)^2 \qquad (3),$$

$$J_m\,(T_2) = -\,K_d\; p(T_2) + K_r\; c(T)^2 \qquad (4),$$

$$J_m\,(HT) = -\,K_d\; p(HT) + K_r\; c(H)\cdot c(T) \qquad (5).$$

Where J_m is the molecular flux, K_d is the dissociation constant, p(x) is the partial pressure, K_r is the recombination constant and c(x) is the concentration. The gas fluxes schematic direction can be better understand in Figure 1.

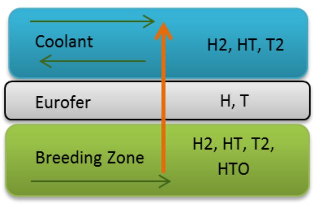

Figure 1: gas fluxes schematic direction inside each component (horizontal line) and tritium permeation flow (vertical line).

Finally the purge gas loop has been closed with a TES, so that the tritium in its molecular forms together with the hydrogen and the helium composing the purge gas are isotopically separated inside this component with certain efficiency.

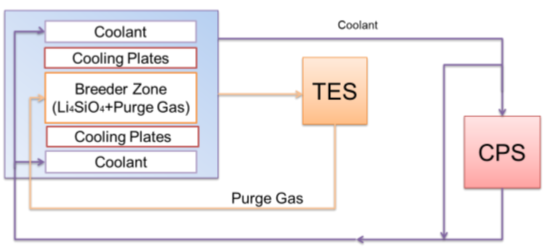

Figure 2: Process flow diagram of the HCPB model at system level.

It consists of the gas entry, coming from the BU, and one gas outlet relative to the swamped T_2. At the same time the coolant loop has been closed considering a CPS component bypassing the coolant loop and purifying from T about the 1% of the total He coolant present in the blanket system, with a determined efficiency η (see Figure 2), considering that

$$C_{out} = (1 - \eta)^* \, C_{in} \quad (6),$$

where $C_{out/in}$ are the concentrations of the molecules containing tritium.

In this model the physics of each component is considered together with the materials main characteristics. In this way the experimental campaign data and models at a BU level can be easily integrated in the upgrade of the model. Finally a node discretization of the components compels to consider the variation of mass concentrations, mass flow, variation of density with temperature, mass fraction and a discretized generation profile. The pulse function selected for the reactor consist of 9 diary pulses, each with a burn time of 2 hours and a dwell time of 40 minutes, with a consequent tritium generation corresponding to the 75% of the full power day generation (GFPD).

3. Experimental data

The input values used are the ones relative to 2014 DEMO for HCPB breeder blanket system [10, 11], plus the data of DEMO Fusion power plant PRD and reports on T flow [13], summarized in the Table1. The total number or Breeder Unit (BU) here considered has been calculated considering the total number of boxes contained in the stiffening grid, presented in the equatorial IB and OB modules (48 and 63 respectively), multiplied for all the modules of the 16 sectors composing the entire breeder blanket. The geometry has been calculated starting from the CAD files of an equatorial IB and OB HCPB blanket module with the design status of 2014 [14] and scaled to our components [15]. The recombination and dissociation coefficients such as the solubility and all the main parameters used are derived by hydrogen isotopes experiments [15, 16].

Table 1: Input values used in the simulation, derived from DEMO 2014 design.

Data	UNITS	Value
Fusion Power (DEMO2014)	MW	1572
T breeding ratio TBR	a.u.	1.05
pulses	#/day	9
Full generation time	s	7200
Dwell time	s	2400
T gen. rate/full power day	g/d	252
T generation profile	g/(d cm^3 cm)	G(r) = 3.8929E-07$e^{-0.03866r}$
Tritium Residence Time in Pebble	s	τ=1.28*10^{-5}exp(9729/T) [18]

Pebble Bed Packed factor	a.u.	64%
HT/HTO release factor	a.u.	97/3
Structural Material	n.a.	EUROFER
Purge Gas pressure	MPa	0.15
Purge Gas flow rate	kg/s	0.4
Purge Gas inlet Temperature	°C	500
Purge Gas outlet Temperature	°C	600
Tritium Extraction eff.	a.u.	80 %
Coolant Pressure	MPa	8
Coolant Flow rate	kg/s	2400
Coolant Temperature	°C	300 (In) 500 (Out)
Cooling Purification System eff.	a.u.	90%
Total U – BU in the reactor	a.u.	54720

4. Results

The reference case considers a pulsed generation scenario calculated in 10 days of reactor operation (see Figure 3), which makes the system oscillate around a stationary state.

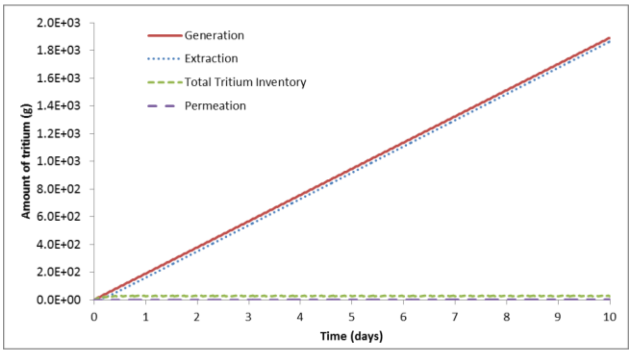

Figure 3: Reference case results calculated in 10 days of simulation, in which it is possible to distinguish the generation (continuous line), the extraction (point-dot line), the total inventory inside all the components of the system (medium-dot line), and finally the permeation (large-dot line).

Considering a DEMO power plant of 1572 MW and a TBR (Tritium Breeding Ratio) of 1.05, the generation rate per day is of 189g to which corresponds an extraction of 162 g, a total tritium inventory in the system of almost 28 g and a permeation to the coolant of 0.21 grams of tritium.

The total tritium inventory (27-28 grams on average) is distributed along the different parts of the blankets. Almost the 99% of tritium is still trapped into the lithium ceramic pebble bed, where it is generated by transmutation and not totally extracted. A small quantity (almost the 0.17%) is circulating in the purge gas and not totally extracted by the TES, while after 10 days 0.25 mg are trapped into the Eurofer cooling plates, and only 0.011 mg are located in the coolant.

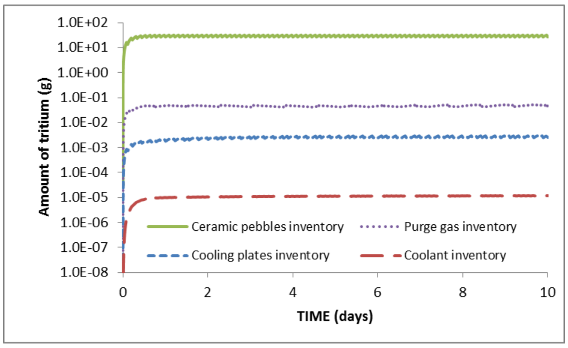

Figure 4: Tritium inventory in each part of the breeder blanket system where it can get trapped: the Li-ceramics pebble bed (continuous line), the purge gas (point-dot line), the Eurofer cooling plates (small-dot line), and the He coolant (large-dot line).

Regarding the permeation of tritium from the purge gas to the coolant, it is important to remember that a cooling purification system, purging with a 90% efficiency the 1% of the total He circulating into the coolant loop, has been considered (see Figure 5).

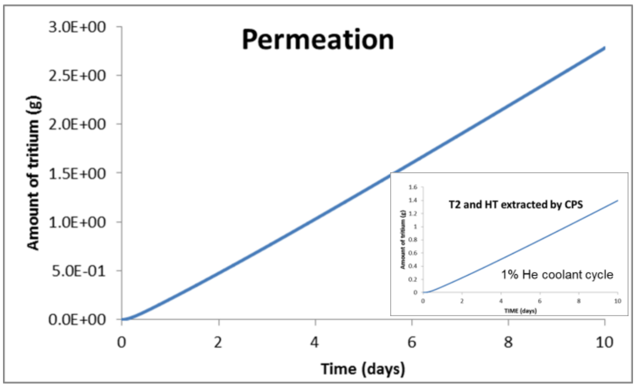

Figure 5: Tritium permeation into the coolant during 10 days of pulsed generation. In the small insert, the tritium (as T2 and HT) extracted by the CPS is represented.

After 10 days of operation, almost 2.7 grams of tritium are permeated into the helium coolant, corresponding to the 0.14% of the total tritium generated.

5. Summary and outlook

A preliminary study of the tritium modelling in an HCPB breeder blanket at a system level has been proposed in this study. The model has been created through a dynamic simulation tool where different disciplines (e.g. transport, hydraulics, control) can be mixed and solved by robust equation-solving algorithms. The code has been developed to compare on the same level of details and in a homogeneous approach different blanket options (HCPB, DCLL, HCLL, WCLL) for the early DEMO. The level of detail reached by this code is really interesting considering that almost all the physics describing tritium behavior inside the materials and in the interfaces can be included. Numerical and parametrical approach for all four before mentioned blanket has been developed to explore the possible workable scenario of important operational points which satisfy the limits in term of tritium release and permeation. According to a starting scenario the main results have been presented where tritium systems (TES and CPS) have been included.

The tritium extraction results to be strictly related to the TES efficiency (here established in the 80%), here considered as a black box system. A future step should include a more detailed component for this kind of system together with all the extraction steps. Regarding the inventory, we have find that almost the 99% of the tritium trapped in the system after 10 days of operation is located inside the lithium-based ceramic pebbles. It confirms the urgent need to identify some solution for increasing the extraction of tritium from the breeder zone (such as H_2O in the purge gas, different microstructure for the ceramic breeder, new technologies for the tritium extraction system..). Finally, there is the permeation of tritium in the purge gas, which is one of the most interesting data in terms of safety and tritium self-sufficient. From this first analysis at a system level, where a quite detailed component description has been added, we have find a permeation percentage of 0.14% after 10 days of simulation. This value is quite low if compared to other BB models at a system level performed with the same tool [19], but also when compared with the values find by another HCPB model at system level [20]. We suppose that a more detailed model, including pipe loops length, the neutron multiplier and a steam generator will finally provide a really complete and useful tool to reach a broader point of view of the reactor and thus help in improve HCPB performances.

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