Fusion Engineering and Design 87 (2012) 299–302

Contents lists available at SciVerse ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

A model for tritium transport in fusion reactor components: The FUS-TPC code

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ARTICLE INFO

Article history:
Received 14 September 2011
Accepted 3 January 2012
Available online 20 February 2012

Keywords:
Tritium
Permeation
DEMO
HCLL
Blanket
Lithium–lead

ABSTRACT

Hydrogen dissolves in and permeates through most materials, thus it is important to understand the permeation, diffusion and dissolution phenomena of atomic hydrogen in materials in which hydrogen and its isotopes are present. In this work the problem of tritium transport from lead–lithium breeder through different heat transfer surfaces to the environment has been studied and analyzed by means of a computational code. The code (FUS-TPC) is a new fusion-devoted version of the fast-fission one called Sodium-Cooled Fast Reactor Tritium Permeation Code (SFR-TPC). The main features of the model inside the code are described. A simulation, using the code, was performed by adopting the configuration of the European configuration of the Helium Cooled Lead Lithium (HCLL) blanket for DEMO.

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1. Introduction

The management of tritium and the related transport analysis in the overall tritium cycle are key issues for DEMO and future fusion reactors. The most efficient way to provide tritium in steady state is to produce it directly inside the fusion reactor and to recover it. In order to achieve this goal, specific breeding blankets are used.

Tritium production occurs following, e.g., the reactions: $^{6}Li + {}^{1}n \rightarrow {}^{3}T + {}^{4}He + 4.8\,MeV$ [1] and $^{7}Li + {}^{1}n \rightarrow {}^{3}T + {}^{4}He + {}^{1}n - 2.5\,MeV$ [1].

A tritium permeation analysis code (FUS-TPC) was developed to analyze tritium transport in the European configuration of the HCLL blanket for DEMO. The code (FUS-TPC) is a new fusion-devoted version of the fast-fission one called SFR-TPC [2], developed to study tritium inventories and losses from Sodium-Cooled Fast Reactors (SFRs). The MATLAB software was used to develop this code. The FUS-TPC code is based on mass balance equation for various chemical forms of tritium (i.e. T^{-}, HT, HTO), coupled with a variety of tritium sources, sinks, and permeation models.

The objective of this work is to evaluate tritium inventories inside several components of the tritium cycle (i.e., inside the breeder loop, the coolant loop, and the steels) and tritium losses to the environment. In this code, a simplified diffusion-limited and time dependent model was adopted, with a series of simplifying and conservative assumptions. Although more sophisticated models are required (i.e. some models able to treat tritium and helium generation distribution from neutronic data, Helium state of solution in Pb–15.7Li under design conditions and MHD Pb15.7Li velocity profiles), the model here proposed can provide a reliable first order picture of the tritium related blanket performance.

2. Description of FUS-TPC code

In this section it is firstly provided a description of the main components of HCLL DEMO blanket. Consequently to this qualitative description, the mathematical structure of the code will be illustrated, analyzing and highlighting the main differences with respect to SFR-TPC, from which FUS-TPC is derived. The code relies on a simpler structure, especially from the computational point of view.

2.1. Description of DEMO blanket

A detailed description of DEMO blanket design specifications is reported in Ref. [3]. DEMO vacuum vessel is covered by blanket modules. They are constituted by a box structure architecture ($2\,m \times 2\,m \times 0.8\,m$) including first wall, stiffening grid, and back collector [4].

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0920-3796/$ – see front matter © 2012 Published by Elsevier B.V.
doi:10.1016/j.fusengdes.2012.01.002

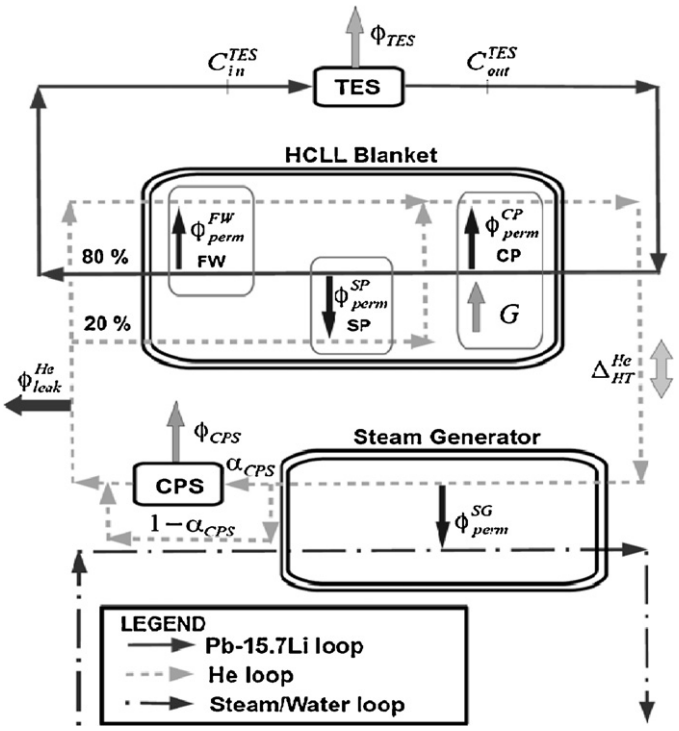

Fig. 1. Loop Descritpion. TES = Tritium Extraction System. CPS = Cooling Purification System.

2.2. Description of the adopted studied reference configuration

Fig. 1 presents the main components and the tritium transfer locations in HCLL blanket (tritium fluxes are defined by ϕ character).

In fusion reactors tritium is observed to come mostly from neutron – lithium breeding reactions. [3]. The different locations of tritium transfer are the hot metallic surfaces that is to say, the walls between Pb–Li and helium of first wall (FW), stiffening plates (SP) and cooling plates (CP) and the walls of steam generator (SG) tubes between helium and water.

Tritium transfer in these facilities occurs via permeation, and permeation fluxes ϕ^i_{perm} [mol/s] (i = FW, SP, CP) and $\phi^{\text{SG}}_{\text{perm}}$ [mol/s] take place.

2.3. Description of the code

Unlike SFR-TPC, FUS-TPC does not take into account any spatial tritium distribution and considers the tritium concentration inside the SG water negligible, because of its large dilution [4]. Thus, the mass balance equations are established for Pb–15.7Li and He loops, considering the average tritium concentrations for both. A brief description of main tritium fluxes appearing in Fig. 1 is reported in Table 1.

Table 1
Description of tritium fluxes in Pb–Li and He loops.

Flux	Description
G [mol/s]	Tritium generation rate
ϕ^i_{perm} [mol/s]	Flux through i walls (i = FW, CP, SP)
$\phi^{\text{SG}}_{\text{perm}}$ [mol/s]	Flux through SG tubes
ϕ_{TES} [mol/s]	Flux extracted by TES
ϕ_{CPS} [mol/s]	Flux extracted by CPS
$\phi^{\text{He}}_{\text{leak}}$ [mol/s]	T losses with He leakages
$\Delta^{\text{He}}_{\text{HT}}$ [mol/s]	Isotope HT exchange rate

2.3.1. Tritium mass balance equation in Pb–Li loop.

The mass balance equation for atomic tritium T^- inside Pb–Li loop is defined as:

$$\frac{dC_{\text{T}}^{\text{Pb-Li}}}{dt} = -\lambda C_{\text{T}}^{\text{Pb-Li}} + \frac{G - \phi_{\text{TES}} - \sum_i \phi^i_{\text{perm}}}{V_{\text{Pb-Li}}} \quad (1)$$

where $C_{\text{T}}^{\text{Pb-Li}}$ [mol/m^3] is the average Pb–Li tritium concentration, $V_{\text{Pb-Li}}$ [m^3] is the Pb–Li loop volume, λ [s^{-1}] is the decay constant and others fluxes appearing in Eq. (1) are listed in Table 1. It has to be pointed out that in this work the contribution of unburnt tritium coming from plasma is not considered and the source term in Eq. (1) is characterized only by the generation rate G [mol/s].

2.3.2. Tritium mass balance equation in He loop

Since it is foreseen to add H_2 and H_2O in the He coolant [5], both HT and HTO tritium species are present, to which are related HT and HTO average concentrations ($C^{\text{He}}_{\text{HT}}$ [mol/m^3] and $C^{\text{He}}_{\text{HTO}}$ [mol/m^3] respectively). The mass balance equations for these two species inside helium loop are given by:

$$\frac{dC^{\text{He}}_{\text{HT}}}{dt} = -\lambda C^{\text{He}}_{\text{HT}} + \frac{\sum_i \phi^i_{\text{perm}} - \phi_{\text{perm,SG}} - \phi^{\text{HT}}_{\text{CPS}} - \dot{\Delta}^{\text{He}}_{\text{HT}} - \phi^{\text{HT}}_{\text{leak}}}{V_{\text{He}}} \quad (2)$$

$$\frac{dC^{\text{He}}_{\text{HTO}}}{dt} = -\lambda C^{\text{He}}_{\text{HTO}} + \frac{\dot{\Delta}^{\text{He}}_{\text{HT}} - \phi^{\text{HTO}}_{\text{CPS}} - \phi^{\text{HTO}}_{\text{leak}}}{V_{\text{He}}} \quad (3)$$

All fluxes appearing in Eqs. (2) and (3) are described in Table 1.

2.3.3. Modeling of tritium fluxes

As reported in Eqs. (1)–(3), we are dealing with a system of Ordinary Differential Equations (ODEs) whose unknowns are $C_{\text{T}}^{\text{Pb-Li}}$ (t), $C^{\text{He}}_{\text{HT}}$ (t) and $C^{\text{He}}_{\text{HTO}}$ (t) and whose initial conditions are supposed to be all equal to zero. The objective now becomes to express all tritium fluxes reported in the above equations in function of these three unknowns, in order to implement the ODEs in a suitable solver (MATLAB ODEs solvers) which integrates and solves numerically the set of differential equations [6].

2.3.3.1. Tritium permeation fluxes through blanket. Due to the low hydrogen Sievert's constant [7,8] in Pb–Li and the consequent high tritium partial pressure foreseen in the liquid metal, a diffusion-limited model was adopted to estimate permeation fluxes through FW, SPs and CPs cooling channels walls. The tritium permeation flux through i cooling channel walls (i = FW, SP, CP) with a specified area A^i_{perm} [m^2], a wall thickness t^i_{wall} [m], a tritium permeability P_i [mol/m/s/$\sqrt{\text{Pa}}$] (defined at the i wall average temperature $T^i_{\text{av,wall}}$ [K]), a permeation reduction factor (PRF) PRF$_i$, the Pb–Li loop tritium partial pressure $p^{\text{Pb-Li}}_{\text{T}_2}$ [Pa] and an He loop tritium partial pressure $p^{\text{He}}_{\text{HT}}$ [Pa] is given by:

$$\phi^i_{\text{perm}}\ [\text{mol/s}] = \frac{P_i(T^i_{\text{av,wall}}) \cdot A^i_{\text{perm}}}{PRF_i \cdot t^i_{\text{wall}}} \cdot \left(\sqrt{p^{\text{Pb-Li}}_{\text{T}_2}} - \sqrt{p^{\text{He}}_{\text{HT}}} \right) \quad (4)$$

$p^{\text{Pb-Li}}_{\text{T}}$ and $p^{\text{He}}_{\text{HT}}$ are related to $C_{\text{T}}^{\text{Pb-Li}}$ and $C^{\text{He}}_{\text{HT}}$ by means of Sievert's law and Dalton's law respectively, defined as:

$$C_{\text{T}}^{\text{Pb-Li}}\ [\text{mol/m}^3] = K_S^{\text{Pb-Li}}(T_{\text{av}}^{\text{Pb-Li}}) \cdot \sqrt{p_T^{\text{Pb-Li}}} \quad (5)$$

$$C^{\text{He}}_{\text{HT}}\ [\text{mol/m}^3] = \frac{p^{\text{He}}_{\text{HT}}}{RT^{\text{He}}_{\text{av}}} \quad (6)$$

where R = 8.31 J/mol/K, $T^{\text{Pb-Li}}_{\text{av}}$ [K] and $T^{\text{He}}_{\text{av}}$ [K] are the gas constant, the Pb–Li average temperatures and the He average temperature respectively. Eq. (6) is derived considering that the molar fraction $\chi^{\text{He}}_{\text{HT}}$ [mol$_{\text{HT}}$/mol$_{\text{He}}$] (then also the concentration) of a gaseous

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