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Sensitivity study on tritium transport in water cooled solid blanket of China Fusion Engineering Test Reactor

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ABSTRACT

The Water Cooled Solid Blanket (WCSB) is selected as a basic choice of the CFETR blanket design, where the tritium would be bred by lithium and extracted subsequently in the tritium cycling loop. However, there always some inevitable losses exist during the tritium cycle due to the complexity of the system, which is considered as a big concern of the tritium self-consistency. In order to realize the tritium self-consistency of CFETR, a mathematical-physical model is developed to analyze the tritium transport in the WCSB. In the present work, the sensitivity study of some key parameters on tritium losses and inventories were conducted. It was found that the tritium transport in the WCSB is influenced by the (a) thickness of the tungsten which covers the first wall, (b) the concentration of the hydrogen in the coolant water and (c) the content of the water in the purge gas, etc.

1. Introduction

The preliminary concept design of CFETR (China Fusion Engineering Test Reactor) has been completed. The Water Cooled Solid Blanket (WCSB) is selected as a basic plan of the CFETR blanket design. Initially, about 30 g tritium is aimed to be burned for the daily operation of CFETR [1]. However, due to the rarity of tritium in the natural world and its short half-life, the tritium self-sufficiency is one of the key factors for the future fusion reactors operation [2,3]. In order to achieve the goal of tritium self-sufficiency in CFETR, the mechanism of the tritium transport in the WCSB needs to be understood. Here a mathematical-physical model is developed to analyze the behavior of the tritium transport in the breeder blanket.

The pebbles of lithium and beryllium fills up the breeder zone of the WCSB. In the fusion reactors, the role of the lithium-6 fuel is to generate tritium through the nuclear reaction with neutrons, meanwhile the beryllium is used to multiply the neutrons [4–8]. Then the tritium which is produced in the breeder zone would transport back into the fusion plasma through a complex process. The tritium will interact with the bred zone, cooling water and pipeline leading to the inevitable losses and permeation of the tritium.

The sensitivity study of the key parameters on the tritium transport can provide the guidance for the CFETR blanket design. The process of the tritium transport in a WCSB is different compared to the other types of blanket especially in tritium transportation, which have been studied [9–12]extensively for ITER or some other future fusion reactors, such as LiPb liquid blanket and helium cooled solid blanket. In the WCSB, the main forms of tritium in water are HT and HTO, and there is nearly no T_2 [9]. The concentration of the hydrogen in the coolant water and the content of the water in the purge gas will affect the permeation and leakage of tritium.

In this work, some other important parameters such as coating of the first wall, water concentration and hydrogen concentration are studied to improve the tritium containment in the WCSB. In this paper, the sensitivity study of tritium loss and storage combined with the radioactive decay of tritium is also conducted.

2. Model of the tritium transport in the WCSB

2.1. Overview of the tritium transport

Fig. 1 is a schematic diagram of the tritium transport model in the WCSB. The tritium is generated by two different sources in the blanket: one is the breeding zone; the other is the influx of the tritium through the first wall. The Tritium Extraction System (TES) extracts the tritium from the purge gas. The Coolant Purification System (CPS) extracts the tritium from the coolant water of the main loop. The loss rate of the tritium is a key factor for the tritium transport.

2.2. Model of tritium transport

The model of the tritium transport is described by the mass conservation. During the steady state operation of CFETR, the change of the total mass of the tritium in a system needs to be analyzed. In this paper,

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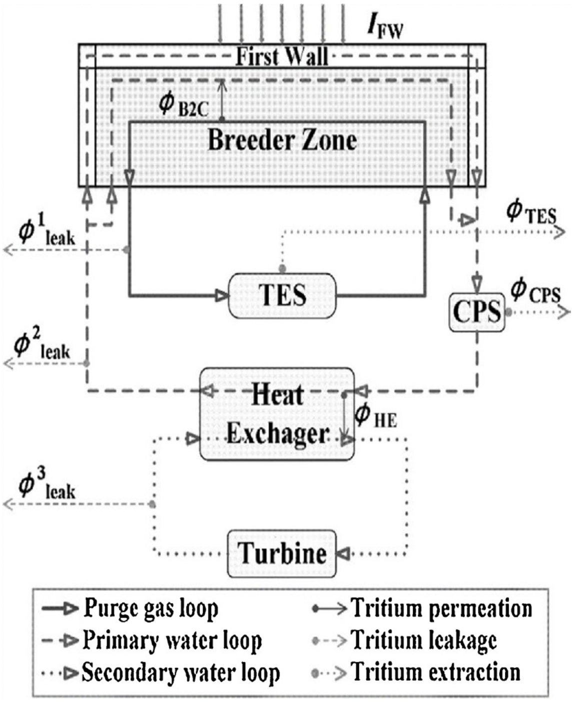

Fig. 1. Tritium transport in CFETR WCSB blanket.

the net loss and production of the tritium are formulated as follow:

$$\frac{d}{dt}C_T^{br}(t) = \dot{G}_V^{br} - \frac{C_T^{br}(t)}{\tau_{res}} - \lambda_T T_T^{br}(t)$$

$$\frac{d}{dt}C_T^{Be}(t) = (1 - f_r)\dot{G}_V^{Be} - \lambda_T C_T^{Be}(t)$$

$$\frac{d}{dt}C_{HTO}^{P}(t) = \frac{1}{m_{He}}[\dot{G}_{HTO}(t) - \dot{\Delta}_{HTO}^{p}(t) - \phi_{TES}^{HTO}(t) - \phi_{leak,HTO}^{p}(t)] - \lambda_T C_{HTO}^{p}(t)$$

$$\frac{d}{dt}C_{HT}^{P}(t) = \frac{1}{m_{He}}\left[\dot{\Delta}_{HTO}^{p}(t) - \phi_{TES}^{HT}(t) - \phi_{leak,HT}^{p}(t) - \phi_{prem}^{CP}(t) - \phi_{prem}^{out,p}(t)\right] - \lambda_T C_{HT}^{p}(t)$$

$$\frac{d}{dt}C_{HT}^{c}(t) = \frac{1}{m_{H_2O}}\left[\phi_{prem}^{CP}(t) + \phi_{imp}^{FE}(t) - \phi_{prem}^{SG}(t) - \phi_{prem}^{out,c}(t) - \phi_{leak,HT}^{c}(t) - \phi_{CPS}^{HT}(t) - \dot{\Delta}_{HT}^{c}(t)\right] - \lambda_T C_{HT}^{c}(t)$$

$$\frac{d}{dt}C_{HTO}^{c}(t) = \frac{1}{m_{H_2O}}[\dot{\Delta}_{HT}^{c}(t) - \phi_{leak,HTO}^{c}(t) - \phi_{CPS}^{HTO}(t)] - \lambda_T C_{HTO}^{c}(t)$$

$$C_i^j(0) = 0,\ i = HT,\ HTO,\ \text{j}= br,\ Be,\ p,\ c$$

The upper and lower subscripts, that are br, Be, p, c, CP, FW, SG and out, represent the lithium bed, the beryllium pebble bed, the purge gas circuit, the cooling water circuit, the heat exchanger, the first wall, the cooling water secondary circuit, and the loop outside of the blanket, respectively. The meaning of each terms in the equations are listed in the table below:

In the breeder zone, the tritium is produced at a steady rate of $\dot{G}_V^{br}$ in the pebble of lithium silicate, then it will be released into the blanket after an averaged residence time τ_{res}. Due to the surface water effect of the lithium silicate pebble, the tritium will be generated in the form of HTO [12], and then it will be released as purge gas.

The tritium is not only produced by the pebble bed of lithium silicate, but also by the beryllium pebbles. In the beryllium pebbles, the tritium is produced at a steady rate of $\dot{G}_V^{Be}$, then it will be released at a fixed rate of f_r. Considering the influence of the temperature and pressure, the diffusivity equation with boundary conditions [5] is used to describe the permeation of HT as below:

$$J_{perm} = \frac{1}{PRF}\frac{P}{\Delta x}(\sqrt{P_h} - \sqrt{P_1}) \tag{1}$$

Where, the *PRF* is the permeation reduction factor [9], P is the permeability of the tritium, Δx is the thickness, P_h, P_1 is the partial pressure of the tritium.

The tritium exists in the form of HT and HTO in the loop. The dynamically interconvert between HT and HTO can be realized by the isotopic exchange reaction,

$$\mathrm{HT{+}H_2\,O \rightleftarrows HTO{+}H_2} \tag{2}$$

And after achieving the equilibrium of the chemical reaction, the concentration of each molecules and the chemical equilibrium constant K_{eq} follow the relationship:

$$\mathrm{K_{eq}} = \frac{[\mathrm{H_2}][\mathrm{HTO}]}{[\mathrm{HT}][\mathrm{H_2O}]} \tag{3}$$

$\dot{\Delta}_{HTO}^{p}$ is the ratio of HTO interconverted into HT in the purge gas, and$\dot{\Delta}_{HT}^{c}$ is the ratio of HT interconverted into HTO in the coolant water.

2.3. Parameters of the WCSB

The designed power of CFETR is 200 MW with a tritium consumption of 30 g/d. To realize the tritium self-sufficiency in CFETR, TBR shall be larger than 1.2. The main parameters of the CFETR WCSB scenario are listed in Table 1, which are based on the design of helium as the purge gas working at the pressure of 0.1 MPa, water as the coolant working at the pressure of 15 MPa, Li_2TiO_3 pebble as the tritium breeder, $Be_{12}Ti$ pebble bed as the neutron multiplier, CLAM as the structure material and tungsten as the coating of the first wall [1].

Table 1
The notation of the mathematical symbol.

Mathematics symbol	unit	Notation
$\dot{G}_{HTO}$	mol/s	The total rate of HTO formation in breeder region
$\dot{G}_V^{br}$	mol/ m^3s	The tritium breeding rate in the breeder region
$\dot{G}_V^{Be}$	mol/ m^3s	The tritium bred rate in the neutrons multiplication region
$\phi_{TES}^{HTO}(t)$	mol/s	TES($i = HT, HTO$)
ϕ_{CPS}^{i}	mol/s	CPS($i = HT, HTO$)
$\phi_{leak,i}^{j}$	mol/s	Tritium leak rate in the loop ($i = HT, HTO, j = br, Be, p, c$)
ϕ_{prem}^{k}	mol/s	HT permeation rate in the loop($K = CP, SG, outp$)
ϕ_{imp}^{FW}	mol/s	the tritium injection rate through the first wall
$\dot{\Delta}_{HT}^{p}$	mol/s	Isotope exchange reaction rate forming HTO
$\dot{\Delta}_{HT}^{c}$	mol/s	Isotope exchange reaction rate forming HT
$\phi_{leak,\mathrm{i}}^{j}$	mol/s	Tritium leak rate in the loop ($i = HT, HTO$)
$\dot{\Delta}_{HTO}^{p}$	mol/s	Isotope exchange leads to HTO reaction rate