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Optimizing tritium extraction from a Permeator Against Vacuum (PAV) by dimensional design using different tritium transport modeling tools

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ABSTRACT

The Permeator Against Vacuum (PAV) has been conceived as the simplest, cost effective and reliable technology system dedicated to tritium extraction from breeding liquid metals.

An optimal design of a PAV requires a detailed hydraulic design optimization for established operational ranges (HCLL at low velocities of ~1 mm/s or DCLL in the ranges of tens of cm/s). The present work analyses the PAV extraction efficiency dependency on the design parameters as optimum on-line Tritium Extraction System (TES). Three different models have been built for that purpose: one through physically refined 1D tritium transport computation using TMAP7 (unique simulation tool with QA for ITER); and two further detailed models on 2D/3D FEM tool (COMSOL Multi-physics 4.0). The geometry used in this work is a simplification of Fuskite® conceptual design developed at CIEMAT, consisting of a set of cylindrical and concentric α-Fe double membranes enclosing a vacuumed space and in contact with in-pipe flowing LiPb eutectic.

The aim of this paper is to give the first steps to establish the optimal design parameters of a PAV and evaluate the state-of-the-art of these models.

1. Introduction

The demonstration of tritium self-sufficiency as a fuel for the first generation of fusion reactors or DEMOnstration Power Plant (DEMO) is one of the key issues to be tested by the Test Blanket Modules (TBM) and its auxiliary Tritium Breeding Systems (TBS) in ITER. Tritium self-sufficiency is strongly dependent on plasma burn-up, tritium residence times at Plant Systems (PS), the blanket Tritium Breeding Ratio and on tritium residence time at the Tritium Extraction System (TES).

The TES will be dedicated in bred tritium extraction from the LiPb eutectic in a HCLL or DCLL reactor and then the tritiated forms will be redirected to the different tritium processing systems, after which the fuelling systems will prepare T to be re-injected into the Vacuum Vessel (VV).

Fuel self-sufficiency requires quick tritium processing and high extraction efficiencies. Precise tritium accountancy is needed also for optimal reactor operation and for safety issues.

The PAV is a promising solution for both questions, as it presents the following advantages among the available concepts of TES [11]:

(i) short extraction times (t_{TES} ~ minutes),
(ii) runs as single-step process for pure atomic T recovery (quick transfer to fuelling systems avoiding PS processing times, case of Fig. 1),
(iii) ease to manufacture (to be experimentally demonstrated for complex designs),
(iv) compact component that can be in-pipe integrated directly at the Breeding Blanket outlet,
(v) works passively (only pumping is needed),
(vi) can be thermally governed, and
(vii) high performances attained for optimal designs.

1.1. Aim of the work

CIEMAT is developing a new prototype of Permeator Against Vacuum (PAV) named FUSKITE® (Fig. 2a and b). The major goals of this work are to obtain the design parameters optimizing PAV efficiency through physically refined 1D Tritium Transport (TT) computation using TMAP7 [8] simulation tool and using 3D FEM COMSOL Multiphysics v0.4 [9]; and to compare different models to improve quality and develop 3D reliability models for component modeling. FUSKITE geometry complexity has been simplified for these first assessments, consisting of a set of cylindrical concentric channels (Fig. 2c and d). Data inputs used are taken from a conceptual DEMO HCLL/DCLL design [2,3] and TT parameters are derived from those given by hydrogen/deuterium in the materials involved: Lead Lithium Eutectic (LLe) [6] and α-Fe [7].

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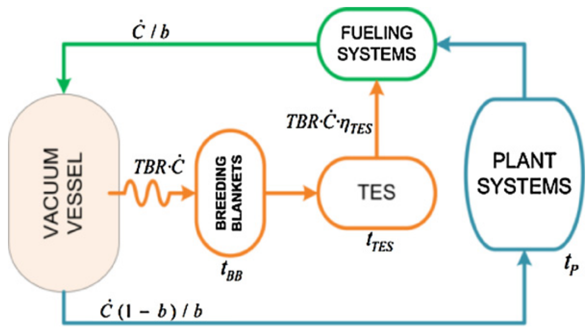

Fig. 1. Simplified lay-out for tritium reactor processing systems and characteristic times [1].

2. PAV model geometry

FUSKITE® concept, consisting of a spirally rolled double Permeation Membrane (Fig. 2a and b), is complex for design because a 3D complete hydraulic model is required. The necessity of general and malleable models in forecast of design changes is a desirable challenge, and thus simple models are preferred. Also available tritium transport tools have several limitations, e.g. TMAP7 is 1D, and simulation can encounter multiple difficulties at meshing or to acquire convergence. Therefore, geometry has been simplified into a set of cylindrical and concentric in-vacuumed double membranes leaving the LLe flow between them (Fig. 2c and d). The dimensional data used in the model as standards can be visualized in (Table 1).

3. Physical description and characteristics

The permeator efficiency is measured by the ratio between extracted tritium (difference between inlet and the outlet tritium content) and the inlet content at steady-state. Previous studies show immersed PAV extraction performance is dependent on one hand on operational parameters, such as temperature or in-tube liquid metal hydrodynamics, the last referring to fluid regime and velocity field (see data in Table 2). And on the other hand, depends on PAV conceptual design, such as geometry, involving flowing LiPb channels shape and size and wall thicknesses; and on material properties, especially on tritium transport parameters (i.e. mass transport within the lead lithium, LLe solubility and diffusivity, and solubility in the metal membrane) [2,4].

Operation and design parameters are resumed in the equation of a cylindrical permeator:

$$\eta(L) = 1 - \exp[A^*(v, R, h_m, \varepsilon) \cdot L] \tag{1}$$

where L is permeator length, ε the α-Fe wall thickness, v the liquid metal average velocity, R the PAV radius and h_m is the mass transfer coefficient. Experimental value used is given by Harriot and Hamilton [5]:

$$h_m = 0.0096 \cdot Re^{0.913} Sc^{0.346} \cdot \frac{D_{LL}}{d} \tag{2}$$

Table 1
Matrix of PAV model standard geometry parameters.

Size/parameters	Symbol	Value
PAV radio	R_{PAV} (mm)	85
PAV length	L (m)	0.5
Inner vacuum radio	a_1 (mm)	6.5
Vacuum thickness	$a_3 - b_2$ (mm)	6.5
Membrane thickness ($i = 1$)	ε (mm) = $b_{i+1} - a_i$	0.5 (1.5)
LLe channel	Δx (mm) = $a_{2i} - b_{2i-1}$	6.5
# channels	N_t	6

Table 2
Operational parameters given for EU-HCLL and US-DCLL TBM design concepts [1–3].

TBM Concept	T_{OUT} (K)	Q_M (kg/s)	$\bar{V}_{PAV}$ (m/s)	Re
HCLL	823	0.29	∼10^{-3} [a]	∼60
DCLL	973	–	∼0.1 [a]	>3×10^4

[a] Calculations performed for PAV radio (=85 mm).

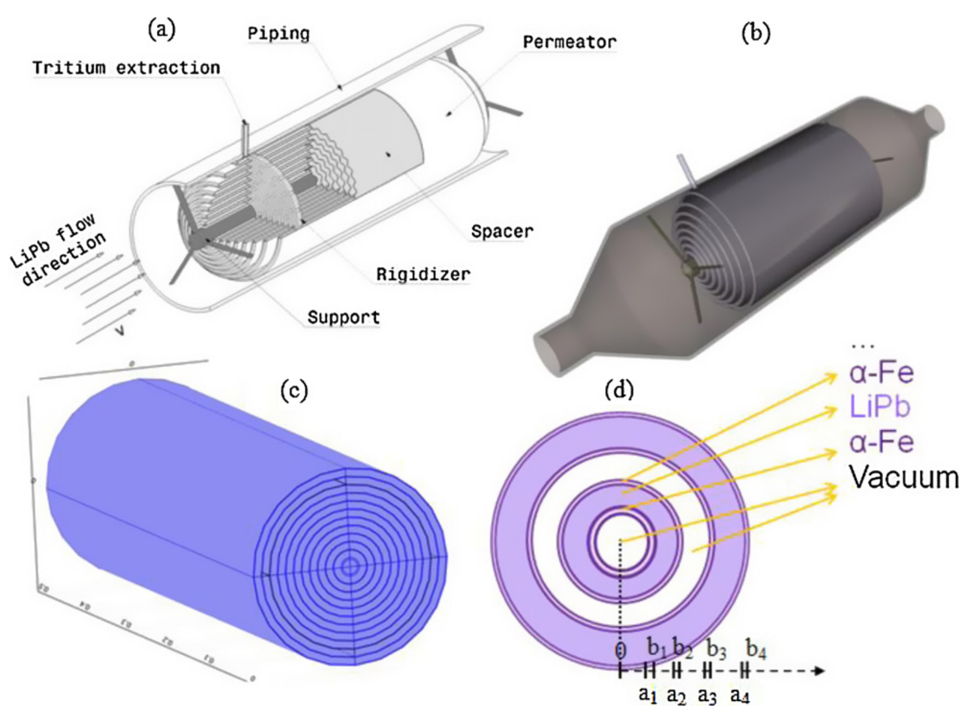

Fig. 2. CATIA (a) technical sketch and (b) drawing of FUSKITE® concept design, (c) COMSOL Multiphysics design of a cylindrical and concentric multi-channel PAV and (d) sketch showing layers of different regions of this PAV [1].