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Tritium Transport Behavior and Parameter Sensitivity Analysis of the Tokamak Exhaust Processing System Based on the TSAP Code†

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Abstract

To quantify the influence of key parameters on the tritium inventory and losses in the Tokamak Exhaust Processing (TEP) system, this paper develops the TSAP numerical solver based on a detailed TEP model. By solving a system of multi-component mass balance differential equations, the tritium transport behavior is quantitatively characterized. Systematic sensitivity analyses are conducted on parameters such as palladium membrane thickness, temperature, and impurity buffer tank volume. The results can provide a reference for the optimized design of the TEP system.

Keywords: nuclear fusion; tritium plant; sensitivity analysis; Tokamak Exhaust Processing system

1. Introduction

The Tokamak Exhaust Processing (TEP) system is a core subsystem of the fusion reactor tritium plant fuel cycle. Its main functions are to purify the exhaust gas from the tokamak core and efficiently recover unburned deuterium-tritium fuel and deliver it to the downstream isotope separation system, while safely releasing the detritiated impurity gas. As shown in Figure 1, the tritium plant is divided into three major sections: the inner loop, the outer loop, and the safety confinement. The TEP is located at the front end of the inner loop and is the first large-scale tritium-related processing unit of the fuel cycle. In devices such as ITER and CFETR, the TEP usually adopts a three-stage treatment process based on palladium-silver alloy membrane separation, catalytic cracking, and the PERMCAT reactor (e.g., the CAPER process at KIT, Germany) to achieve a high decontamination factor and low fuel losses [1–3].

In recent years, numerical simulation studies on tritium transport behavior in the TEP have been carried out. Professor Abdou at UCLA proposed the mean residence time method [4]; NITEK (Canada) and KIT jointly developed the TRIMO code [5]; the University of Science and Technology of China and the Southwestern Institute of Physics established a CFETR tritium cycle model [6,7]. However, most of these models simplify the TEP into a few modules and fail to reflect the detailed transport mechanisms of key components such as palladium membrane permeators, catalytic beds, and PERMCAT reactors; they also lack systematic sensitivity analyses of geometric and process parameters. Studies

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have shown that the performance of palladium-silver alloy membranes is significantly affected by temperature, membrane thickness, and pressure exponent [8,9]; the impurity buffer tank volume directly affects the system's tritium inventory and decay losses [10]; and reflux ratio optimization is crucial for improving recovery efficiency [11]. Therefore, establishing a numerical model that finely characterizes the tritium transport behavior of each TEP component and conducting key parameter analyses are of great significance for the engineering design and operational optimization of the TEP.

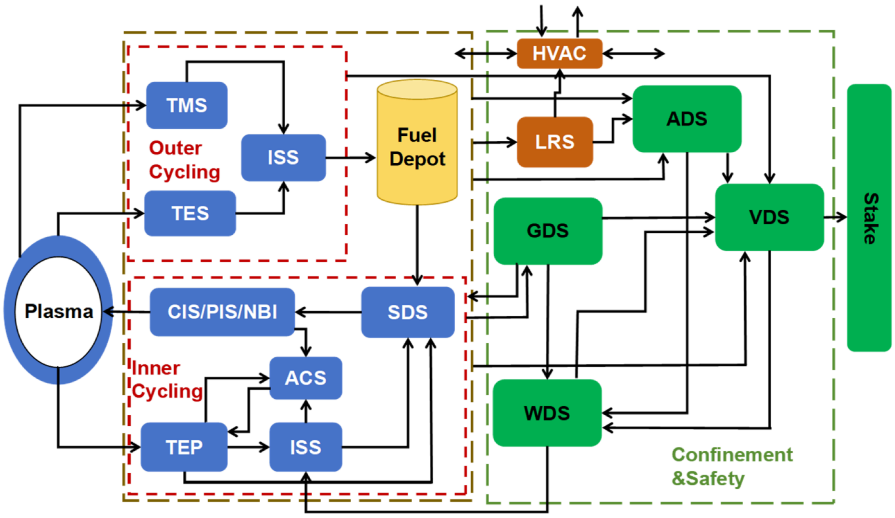


Figure 1. Simplified block diagram of the tritium plant model.

Based on the TEP conceptual design of the China Academy of Engineering Physics [12], this paper establishes a detailed tritium transport model covering the front-end permeation, impurity processing, and end-stage cleaning units, and develops the TSAP (TEP Simulation and Analysis Program) numerical solver. The code uses the mean residence time method to describe common components such as buffer tanks and pumps. For the palladium membrane permeator and PERMCAT reactor, nonlinear flow relationships are derived based on the micro-element analysis method and Sieverts' law, and a system of multi-component mass balance differential equations is constructed. The steady-state tritium inventory of each component is obtained through time-domain solution, and sensitivity analyses of key parameters are carried out to quantify their influence on tritium transport behavior, providing a theoretical basis for the low-inventory, low-loss design of the TEP.

2. Model and Numerical Calculation Method for the TEP

2.1. Tritium Transport Model of the TEP System

As shown in Figure 2, the TEP system is divided into three units. Front-End Permeation (FEP) unit: The exhaust gas is buffered by the inlet buffer tank and then sent by a pump to the palladium membrane permeator bank. Under the action of the palladium-silver alloy membrane, hydrogen isotopes permeate to the permeate side and are sent to the D-T buffer tank, while the non-permeated impurity gas proceeds to the next unit. Impurity Processing unit: The impurity gas containing hydrogen isotopes passes through a catalytic reactor (cracking catalyst) to release tritium from tritiated compounds in elemental form, and then undergoes further hydrogen isotope separation in an impurity processing palladium membrane separator. End-Stage Cleaning unit: The residual gas enters the PERMCAT reactor for further tritium removal through catalytic exchange, improving recovery efficiency. The resulting pure hydrogen isotope gas is sent to the downstream isotope separation system; the detritiated impurity gas is safely discharged after treatment in a decay tank.

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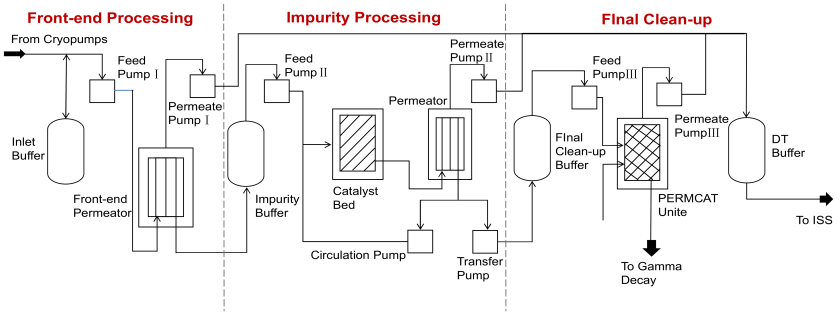


Figure 2. Model of the Tokamak Exhaust Processing System.

2.2. Tritium Transport Calculation Method for the TEP System

Based on the above model, the TSAP numerical solver is developed. The mean residence time method is used to describe the hydrogen isotope transport in common components such as buffer tanks and pumps, while a Diffusion-limited model is used to describe permeation losses. For the core component, the palladium membrane permeator, a micro-element analysis method is applied. Based on the diffusion behavior of hydrogen isotopes in the palladium membrane and Sieverts' law, the differential equation for tritium flow rate is obtained:

$$df^T = -\frac{P(p_{high}^{T\ n} - p_{low}^{T\ n})dA}{l} - \lambda dI^T \quad (1)$$

Here, df^T is the differential change in tritium flow rate, and dA represents a differential area element on the palladium membrane. P is the permeability constant of hydrogen in the membrane, n is the pressure exponent, and l is the membrane thickness. p_{high}^T is the partial pressure of tritium in the impurity gas stream, which can be expressed as $p_{high}^T = \frac{p^{inflow}}{f^{inflow}} f^T$, where p^{inflow} and f^{inflow} are the inlet pressure and flow rate. p_{low}^T is the partial pressure of tritium on the permeate side, given by $p_{low}^T = k_{low}^T p_{low}^{total}$, where k_{low}^T is the tritium concentration on the permeate side.

By solving this equation, the tritium flow rate at the outlet of the palladium membrane permeator can be obtained:

$$f^T = C_1 f^{inflow} + (f_{inflow}^T - C_1 f^{inflow}) e^{\frac{p^{inflow\,n}}{f^{inflow}}(\frac{PA}{l} + \frac{\lambda V}{RT})} \quad (2)$$

where $C_1 = \frac{2RTPk_{low}^T}{RTP + \lambda(r_s - l)l}(\frac{p_{low}^{total}}{p^{inflow}})^n$.

For the PERMCAT reactor, in addition to membrane permeation, outward permeation leakage losses must also be considered. The differential equation is:

$$df^T = -\frac{dA\ P(p_{high}^{T\ n} - p_{low}^{T\ n})}{l} - \lambda dI^T - \frac{dA'\ Pe\ p_{high}^{T\ n}}{PRF\ th} \quad (3)$$

where dA' is the outward permeable area of hydrogen isotopes in the differential volume, and th is the reactor tube wall thickness.

By solving the above system of differential equations, the steady-state tritium inventory and losses in each component can be obtained.

3. Sensitivity Analysis

Based on the TSAP code, a steady-state solution of the TEP system is obtained, and the distribution of hydrogen isotope inventory among key components is analyzed. The results show that the inventories in the palladium membrane permeator and the PERMCAT reactor are extremely low, while the impurity buffer tank, due to its buffering function, becomes the main accumulation site for tritium. This forms the core pattern of "low

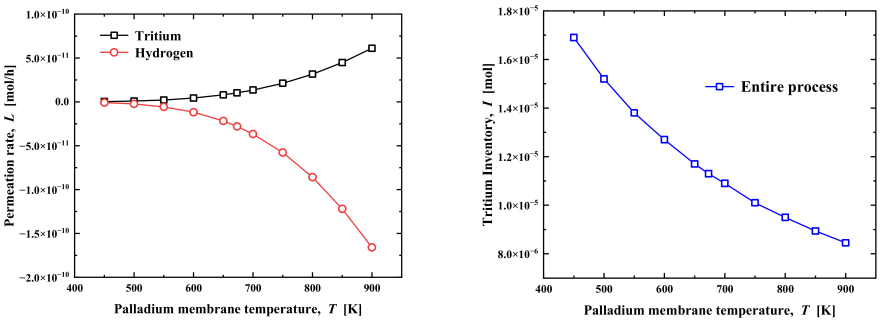
inventory in palladium membranes, high inventory in buffer tank." Under this pattern, the thickness and temperature of the palladium membrane directly determine the separation efficiency and permeation flux of hydrogen isotopes, serving as key factors for regulating the system's tritium recovery capability. Meanwhile, the impurity buffer tank volume dominates the accumulation degree and decay losses of tritium in the system, becoming the core design variable for controlling total inventory. To deeply explore the influence of key parameters, three parameters—palladium membrane thickness, temperature, and impurity buffer tank volume—are selected to systematically analyze their effects on the TEP tritium inventory characteristics from three dimensions: permeation driving force, transport rate, and residence time.

The main conclusions are as follows:

(1) Palladium membrane temperature has a significant effect on the permeation rate and tritium inventory: As shown in Figure 3, when the temperature increases from 450 K to 900 K, the tritium permeation rate increases by approximately 200 times, and the tritium inventory decreases by about 50%. The increase in temperature, through the synergistic effect of increasing the diffusion coefficient and slightly decreasing the solubility, causes the permeation rate to increase exponentially, accelerating tritium transport through the membrane and thus reducing the system inventory. It is recommended to control the palladium membrane operating temperature in the range of 673–773 K to achieve high permeation efficiency, low inventory, and long-term material stability.

(2) Palladium membrane thickness is inversely proportional to the hydrogen isotope permeation rate: As shown in Figure 4, when the membrane thickness increases from 0.003 m to 0.010 m, the tritium permeation rate decreases from 1.03×10^{-11} mol/h to 3.08×10^{-12} mol/h, a reduction of about 70%; however, the system tritium inventory remains stable, indicating that the permeation process is mainly controlled by bulk diffusion, and the effect of membrane thickness on the steady-state inventory is negligible. For engineering applications, it is recommended to preferentially use a thin membrane of 0.003–0.005 m, provided that mechanical strength requirements are met, to increase permeation flux.

(3) The impurity buffer tank volume is significantly positively correlated with the total system tritium inventory: As shown in Figure 5, when the buffer tank volume increases from 0.5 m^3 to 4 m^3, the total tritium inventory increases from 26.5 mol to 125.0 mol, and the buffer tank's own inventory share increases from 53.2% to 90.0%, making it the core component dominating the total system inventory. This phenomenon is determined by the mean residence time mechanism: inventory is proportional to volume, and increasing the volume prolongs the tritium residence time. In design, it is recommended to preferentially use a small-volume scheme of 0.5–1 m^3 if buffer requirements permit, or to offset the inventory increase by optimizing the internal flow field of the tank or increasing the reflux ratio of the upstream palladium membrane.



(**a**) Permeation rate (**b**) Tritium inventory

Figure 3. Effect of temperature on hydrogen isotope permeation rate and tritium inventory in the palladium membrane separator.

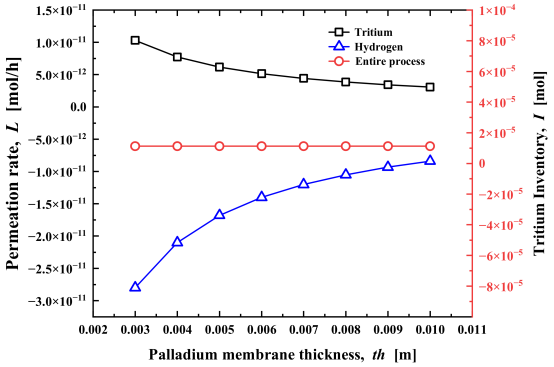


Figure 4. Sensitivity analysis of palladium membrane thickness.

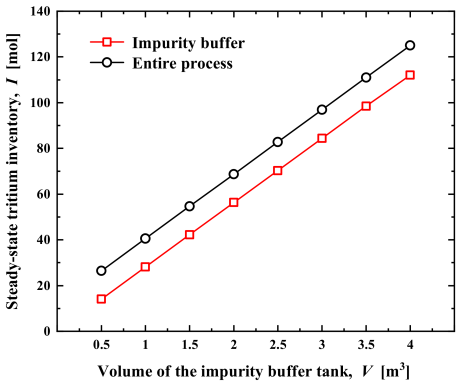


Figure 5. Sensitivity Analysis of Impurity Buffer Tank Volume.

4. Conclusions

In this paper, a detailed tritium transport model is established for the Tokamak Exhaust Processing system of a fusion reactor, and the TSAP numerical solver is developed. The solver combines the mean residence time method and the micro-element analysis method. By solving a system of multi-component mass balance differential equations, it achieves quantitative characterization of tritium transport behavior in key components such as the palladium membrane permeator, PERMCAT reactor, and buffer tank. Based on this code, the influence of three key parameters—palladium membrane thickness, temperature, and impurity buffer tank volume—on the TEP tritium inventory and loss is systematically analyzed.

The results show that the impurity buffer tank volume is significantly positively correlated with the total system tritium inventory: when the buffer tank volume increases from 0.5 m^3 to 4 m^3, the total system tritium inventory increases from 26.5 mol to 125.0 mol, making the buffer tank the core design variable controlling total inventory. The palladium membrane thickness is inversely proportional to the hydrogen isotope permeation rate: when the membrane thickness increases from 0.003 m to 0.010 m, the permeation rate decreases by about 70%, but its effect on the steady-state inventory is negligible. In the temperature range from 450 K to 900 K, the permeation rate can be increased by about 200 times, and the inventory can be reduced by about 50%, showing an exponential regulation effect. The TSAP code can quantitatively characterize tritium transport behavior, providing an important reference for the low-inventory, low-loss design and parameter optimization of the TEP system.

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