Research Progress on Tritium Extraction Technology from Liquid Lithium-Lead Fusion Breeding Blankets

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Abstract

As fossil fuels are gradually depleted, the development of commercial fusion reactors has become one of the approaches to solving energy problems. To achieve tritium self-sufficiency in fusion reactors, the technology for extracting tritium from fusion reactor breeding blankets is of significant research importance. From the perspectives of economy and feasibility, liquid lithium-lead blankets possess considerable advantages and development prospects. This paper reviews the tritium extraction technologies in liquid lithium-lead blankets proposed for the International Thermonuclear Experimental Reactor (ITER) and the European Fusion Demonstration Reactor (DEMO), including three tritium extraction processes: Permeation Against Vacuum (PAV), Gas-Liquid Contact (GLC), and Vacuum Sieve Tray (VST). It summarizes the advantages and disadvantages of each process, required auxiliary systems, technical issues, etc., and performs a performance comparison among them, aiming to provide ideas and references for the design and research of tritium extraction systems in fusion reactors.

Full Text

Preamble

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Research Progress on Tritium Extraction Processes from Liquid Lithium-Lead Fusion Breeder Blankets

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Abstract

[**Background**] With the gradual depletion of fossil fuels, the development of commercial fusion reactors has emerged as a viable solution to the energy crisis. The technology for extracting tritium from the breeder blanket of fusion reactors is crucial for achieving tritium self-sufficiency and thus holds significant research importance. [**Purpose**] The objective of this study was to review and assess the advancements and methodologies for tritium extraction from liquid PbLi in fusion blankets. [**Methods**] This paper reviews the tritium extraction technologies from liquid LiPb blankets proposed for the International Thermonuclear Experimental Reactor (ITER) and the European Demonstration Fusion Reactor (DEMO). Three tritium extraction technologies are discussed: Permeation Against Vacuum (PAV), Gas-Liquid Contact (GLC), and Vacuum Sieve Tray (VST). The advantages and disadvantages, required auxiliary systems, technical issues, and performance comparisons of each process are summarized. [**Results**] The review provides ideas and references for future research and design of tritium extraction systems. [**Conclusions**] Although all three tritium extraction technologies show promise, given the urgency of ITER, the tritium extraction system composed of a bubble column after cascade design can be implemented first.

Keywords: Tritium extraction, Fusion reactor, Breeding blanket, Liquid LiPb

Fusion energy is regarded as the ultimate solution to humanity's energy problems due to its advantages of being clean, safe, efficient, and sustainable. Among various fusion reactions, the deuterium (D)-tritium (T) reaction exhibits the highest reaction rate and largest cross-section at equivalent temperatures, while requiring relatively lower temperatures and energy, making it easier to achieve and thus forming the design core of first-generation fusion power plants.

To sustain fusion reactions and ensure tritium self-sufficiency, fusion reactors are equipped with tritium breeding blanket modules (such as ITER TBM), with a tritium breeding ratio set no lower than 1.15 to compensate for tritium losses during actual operation [1]. Additionally, the Tritium Extraction and Recovery System (TERS) is designed to extract tritium from the blanket, which after separation, purification, and storage at the plant, is transported to the fusion core as fuel [2].

Compared with solid breeder blankets, liquid breeder blankets have a simpler structure and can be manufactured without complex processes. Except for FLiBe, liquid blankets can achieve efficient tritium breeding without expensive neutron multipliers. The circulating flow of liquid metal enables convenient online tritium extraction, reducing the frequency of blanket replacement and thereby improving the utilization efficiency of fusion reactors. Meanwhile, liquid blankets also demonstrate excellent load-bearing capacity and thermal conductivity, making them ideal candidate blankets for high thermal efficiency and high power density. Among liquid blankets, liquid lithium-lead (PbLi) has become the preferred breeding material for liquid blankets as it integrates multiple

functions including coolant, neutron multiplier, and tritium breeder [3].

However, tritium exhibits strong migration, dissolution, and permeation capabilities in materials, along with chemical and radiation corrosion characteristics that may lead to hydrogen embrittlement of materials and degrade their structural properties. To ensure the sustainability and safety of fusion energy, the tritium extraction system must efficiently recover tritium from the breeder blanket with recovery efficiency far exceeding 80% to reduce tritium inventory and rapidly transport extracted tritium to the fuel cycle system.

Based on this background, this paper conducted an in-depth investigation of domestic and international literature on tritium extraction processes from liquid PbLi breeder blankets. The survey results show that the main PbLi-T separation processes applicable to fusion reactor tritium extraction systems include the vacuum permeation method, gas-liquid contact method, and vacuum sieve tray method.

1. Vacuum Permeation Against Vacuum Method

The core principle of Permeation Against Vacuum (PAV) technology lies in utilizing the permeation phenomenon of tritium through specific membranes to achieve efficient tritium extraction. The working principle of PAV is shown in [Figure 1: see original paper]. This technology employs a metal permeation membrane to separate PbLi from vacuum, thereby establishing a concentration gradient favorable for tritium extraction on both sides.

The operation process of PAV technology can be divided into several key steps [4]. First, tritium dissolved in PbLi diffuses within the alloy, which is the first step for tritium to move from the liquid alloy to the membrane surface. Next, tritium atoms are adsorbed by the metal membrane from the PbLi side and subsequently occupy the interstitial lattice sites of the metal membrane. Then, tritium atoms move between the membrane surface and interior through tiny channels within the membrane. Due to the concentration gradient on both sides, tritium diffuses between the interstitial sites of the membrane, gradually approaching the vacuum side. When tritium finally reaches the vacuum side of the membrane, it undergoes a recombination and desorption process, ultimately leaving the membrane in molecular form and completing the entire extraction process.

The hydrogen permeation flux equation through the membrane [5] is expressed as:

$$J = \frac{k}{t}(\sqrt{P_{H_2,ret}} - \sqrt{P_{H_2,per}})$$

where k is the hydrogen permeability, t is the metal membrane thickness, $P_{H_2,ret}$ is the equilibrium pressure of hydrogen in the liquid PbLi pipeline, and $P_{H_2,per}$ is the pressure of tritium in the vacuum pipeline.

The efficiency of PAV is defined as:

$$\eta_{PAV} = \frac{C_{in,PAV} - C_{out,PAV}}{C_{in,PAV}}$$

where $C_{in,PAV}$ is the hydrogen isotope concentration at the PAV model inlet, and $C_{out,PAV}$ is the hydrogen isotope concentration at the PAV model outlet.

PAV technology offers significant advantages compared with other tritium extraction technologies. The most prominent is that once tritium is extracted from PbLi, it does not need to be separated from the gas. This feature simplifies the operational process and reduces system complexity. Additionally, since the residence time of tritium in the system is minimized, this helps reduce tritium loss and potential safety risks.

The permeation membrane, as the core component of PAV technology, directly determines the extraction efficiency of the entire system. Researchers have developed various permeation materials, such as niobium (Nb), vanadium (V), palladium (Pd) alloys, α-Fe, and stainless steel [5, 7-9]. shows the different permeability characteristics exhibited by these materials.

Table 1 Hydrogen permeability of different materials at 823K

Materials	Permeability / $\mathrm{mol \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-0.5}}$
Nb	1.41$×10^{-7}$
V	8.72$×10^{-8}$
Pd	1.29$×10^{-8}$
α-Fe	1.48$×10^{-10}$
SS304	1.35$×10^{-11}$
SS316	1.09$×10^{-11}$

Spain's CIEMAT developed a novel vacuum permeator prototype called FUSKITE [10], as shown in [Figure 2: see original paper]. The FUSKITE design employs a set of cylindrical and concentric α-Fe double membranes while enclosing a vacuum space internally. This structure enables FUSKITE to maintain close contact with flowing PbLi eutectic in the pipeline, thereby achieving efficient tritium permeation. In experiments, the device operated under forced circulation conditions with a maximum temperature of 773K and a maximum PbLi flow velocity of 1 m/s. To further optimize the device's performance, researchers conducted simulation analysis using TMAP7 and COMSOL Multiphysics. The simulation results showed that FUSKITE's permeation efficiency is closely related to multiple factors. First, as the PAV length increases, tritium permeation efficiency also improves accordingly, because a longer PAV provides more permeation area, thereby increasing opportunities for tritium to pass through the membrane. Second, the thickness

of the lithium-lead eutectic channel and α-Fe membrane significantly affects permeation efficiency; when these thicknesses increase, the resistance for tritium to pass through the membrane also increases, leading to reduced permeation efficiency.

Sandra Dulla [11] et al. from Politecnico di Torino designed a Permeation Against Vacuum model for low-speed tritium extraction from PbLi. As shown in [Figure 3: see original paper], the core of the model consists of parallel spiral vanadium tubes inserted into a vacuum container, with a special design that allows tritium to permeate smoothly from PbLi. The researchers conducted detailed formula design and finite element method structural analysis, as well as fluid dynamics analysis, and calculated the tritium extraction efficiency through simulation software, achieving a tritium extraction efficiency of 81.6%.

Songjiang Deng [12] et al. from the Institute of Materials, China Academy of Engineering Physics conducted in-depth numerical simulation studies on tritium extraction from PbLi using a vacuum permeator. As shown in [Figure 4: see original paper], the model geometry was simplified to a permeation tube with an α-Fe membrane. First, they established a 1D model using Matlab specifically for numerical calculation of tritium transport. Additionally, to more comprehensively consider the effects of flow and mass transfer, the researchers also established a 3D model using COMSOL Multiphysics. Through comparative analysis of simulation data, they found that reducing flow rate and tube diameter, as well as increasing tube length, could effectively improve the extraction efficiency of the permeator. Meanwhile, the researchers also noted that due to concentration polarization effects, the permeation efficiency calculated by the 3D model showed certain differences from the 1D model. This study not only provides an effective numerical simulation method but also offers a theoretical basis for deeply understanding tritium permeation behavior in PbLi.

F. Papa [4] et al. from Italy designed a vacuum permeator model, as shown in [Figure 5: see original paper]. The core structure of this device consists of several niobium permeation membrane U-shaped tubes welded onto P22 alloy steel plates and located within a vacuum chamber. Through optimization of the overall structure, the welding area, component volume, and membrane thickness were successfully reduced, which not only improved the structural efficiency of the device but also enhanced its stability and durability. The design process paid special attention to the overall equipment size and pressure loss thresholds. To limit the velocity of PbLi in the pipeline, optimization was performed, ultimately obtaining the optimal PbLi velocity of 0.5 m/s for hydrogen isotope permeation. In theoretical calculations, the maximum extraction efficiency of this model at 500°C was expected to reach 40%, demonstrating its potential for hydrogen isotope extraction.

To verify the actual performance of this design, F. Papa [13] et al. manufactured the model and conducted experimental characterization on the TRIEX-II facility at the ENEA Brasimone Research Center. During the experiments, the PbLi temperature was controlled at approximately 450°C, the flow velocity was

1.2 kg/s, and the hydrogen partial pressure varied within the range of 170-360 Pa. In three trials at around 450°C, the maximum hydrogen permeation flux reached 4.67$×10^{-8}$ mol/s. In addition to permeation flux measurement, the existence of permeation flux was further confirmed through pressure increase tests. This series of experimental results not only represents the first experimental evaluation of PAV technology performance but also validates the feasibility of using PAV technology to extract hydrogen isotopes from flowing PbLi.

PAV technology demonstrates high development potential as an important technology in the tritium extraction field due to its unique advantages such as fast tritium processing speed, short extraction time, simple structure, and passive operation. The significant advantage of PAV technology is that once tritium is successfully extracted from PbLi, it does not need to be separated from the stripping gas, which significantly shortens the residence time of tritium within the system, thereby improving extraction efficiency and safety. However, the development of PAV technology also faces some challenges. Among them, the development of permeation membranes with high permeability, high mechanical performance, and high corrosion resistance [5] is a key technical challenge. The research and development of these high-performance permeation membranes require substantial effort and resources, including material selection, preparation processes, performance testing, and other aspects. The recent first experimental evaluation of PAV technology performance undoubtedly lays an engineering foundation for this technology's development. To further improve the safety, reliability, and extraction efficiency of vacuum permeators, substantial research work is still needed. Among these, using permeators with different structures and testing different permeation membrane materials are important research directions. By comparing the performance of different structures and materials, optimal design solutions can be identified to promote further development of this technology.

2. Gas-Liquid Contact Method

The working principle diagram of the gas-liquid contactor is shown in [Figure 6: see original paper], where the packed column is a vertical tower containing packing material. In the Gas-Liquid Contact (GLC) method, contact between gaseous tritium and liquid PbLi is established for diffusive exchange between them, providing a larger contact interface for solute exchange in co-current and counter-current flows of liquid and gas phases. In GLC, there are three mechanisms [14] for tritium transfer from liquid to gas: (a) diffusion of tritium through the liquid boundary layer; (b) recombination/dissociation reactions at the liquid-gas interface; and (c) diffusion of tritium through the gas boundary layer.

Given the excellent performance of packed columns in gas-liquid contact, they have been widely applied in the chemical industry and gradually introduced into tritium extraction from liquid breeders. Among various gas-liquid contactors, packed columns stand out for their maturity and reliability, becoming the

preferred choice for many researchers.

N. Alpy [15] et al. from CEA France built a dedicated experimental facility called the Melodie loop to evaluate the technical performance of gas-liquid contactors. The facility uses hydrogen as a counter-current sweep gas to simulate tritium extraction from liquid PbLi and conducted a series of tests on packed column performance. The schematic diagram of the Melodie loop is shown in [Figure 7: see original paper]. Through clever design, it can accurately simulate the gas-liquid contact process under actual working conditions. At a temperature of 673 K, researchers studied both submerged and non-submerged configurations of an 800 mm high packed contactor, not only verifying the applicability of mass transfer through liquid distribution via packing but also providing valuable experimental data for optimizing packed column design and operation. When calculating hydrogen exchange between liquid and gas, researchers used two flux formulas:

(1) The hydrogen flux extracted from Pb–17Li (eutectic lithium composition of 0.70 ± 0.02 wt%) is:

$$F_{LH} = L(C_H - K_S\sqrt{P_{IE}})$$

(2) The atomic hydrogen flux in the gas at the extractor outlet is:

$$F_{GH} = \frac{G \cdot Y_{H_2}}{0.0224}$$

where F_{LH} is the atomic hydrogen flux leaving the extractor in Pb–17Li; L is the Pb–17Li flow rate; C_H is the atomic hydrogen concentration in Pb-17Li; K_S is Sievert's constant; P_{IE} is the hydrogen pressure at the extractor inlet; P_{OE} is the hydrogen pressure at the extractor outlet; F_{GH} is the atomic hydrogen flux in the sweep gas; G is the sweep gas flow rate; and Y_{H_2} is the hydrogen content in the sweep gas at the extractor outlet.

The extractor efficiency can be expressed as:

$$\eta = \frac{F_{GH}}{F_{LH} + F_{GH}}$$

Table 2 shows the experimental data from this study. By reducing the liquid load, the best efficiency of 30% was achieved at 673 K when the inlet hydrogen pressure in Pb–17Li was 1000 Pa. This efficiency can be improved by further reducing the liquid flow velocity.

M. Utili [16] et al. from ENEA Italy designed and built a dedicated tritium extraction facility called TRIEX. The schematic diagram of the TRIEX loop is shown in [Figure 8: see original paper]. Experiments using gas-liquid contactors for tritium extraction research used hydrogen instead of tritium and argon as the sweep gas. Three experiments were conducted under different gas flow

rates G and liquid metal flow rates L, with tritium extraction values between 10%-30%. To more accurately evaluate the efficiency of gas-liquid contactors in tritium extraction, the research team developed the following extraction efficiency model:

$$\eta = 1 - \exp\left(-\frac{K_D \cdot S}{L_{vol}}\right)$$

where K_D is the mass transfer coefficient calculated in MELODIE; L_{vol} is the liquid metal volume; S is the contact area between liquid metal and sweep gas; and $G_{molM.V.}$ is the molar volume of the sweep gas.

Experimental results showed that to improve tritium extraction efficiency, uniform gas-liquid distribution inside the contactor must be ensured, and the contact area between gas and liquid should be maximized as much as possible. Through this approach, tritium transfer from liquid metal to sweep gas can be more effectively achieved. The measured experimental data are shown in **Table 3**.

Based on the TRIEX facility, the ENEA Brasimone Research Center, in collaboration with Politecnico di Torino and Sapienza University of Rome, designed and installed a dedicated facility called TRIEX-II [17]. This facility can test gas-liquid contactor (GLC), vacuum permeator (PAV), and liquid vacuum contactor (LVC) technologies under different temperatures, lithium-lead mass flow rates, and hydrogen isotope concentrations. The DACS main window of TRIEX-II is shown in [Figure 9: see original paper]. The GLC model uses deuterium instead of tritium and pure helium or a mixture of helium and hydrogen as sweep gas, equipped with MellapakPlus 452Y structured packing. The device can operate stably in the temperature range of 300 to 500°C.

The research team analyzed the effects of PbLi mass flow rate and extraction gas mass flow rate on extractor pressure drop. Results showed that the extraction gas mass flow rate has a more significant impact on extractor pressure drop. Two GLC efficiency calculation models were provided:

(1) Using the partial pressure method to calculate tritium extraction efficiency:

$$\eta = 1 - \frac{p_{out,eq}}{p_{in,eq}}$$

where K_S is Sievert's constant; $p_{in,eq}$ and $p_{out,eq}$ are the partial pressures of hydrogen isotopes at the extractor inlet and outlet, respectively. This method shows good applicability for each technology tested in TRIEX, providing researchers with an effective evaluation tool.

(2) Using the mass spectrometry method to calculate tritium extraction efficiency:

$$\eta = \frac{K_S(p_{in,eq} - p_{out,eq})M_{PbLi}}{\rho_{PbLi}L(y_{out} - y_{in})}$$

where ρ_{PbLi} is the density of PbLi; M_{PbLi} is the molecular mass of PbLi; L and G are the molar flow rates of liquid metal and gas, respectively; and y_{in} and y_{out} are the molar fractions of hydrogen isotopes in the extraction gas at the extractor inlet and outlet, respectively. This method can be used for comparison and verification with the previous efficiency calculation method to ensure the reliability of calculation results.

Bo Xie [18] et al. from the Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, conducted experiments on hydrogen extraction from liquid lithium-lead alloy using the gas-liquid contact method on a self-designed and built liquid lithium-lead alloy bubbler experimental system. The experimental system is shown in [Figure 10: see original paper]. During the experiments, the team compared two different experimental conditions: (1) using argon as protective gas and helium as carrier gas; (2) argon serving as both protective and carrier gas. Through comparative analysis, they found that helium is more suitable than argon as the carrier gas for packed columns. Additionally, experimental results showed that as the column temperature increases, the hydrogen content at the column outlet also increases. However, the effect of carrier gas flow rate on outlet hydrogen content did not show an obvious pattern. It is worth noting that tritium extraction efficiency is closely related to the residence time of liquid lithium-lead in the packed column. As residence time increases, tritium extraction efficiency also increases.

In addition to experimental research, numerous researchers have extensively studied tritium extraction from liquid PbLi using the gas-liquid contact method through numerical simulation. Among them, Kecheng Jiang [19] et al. from the Institute of Plasma Physics, Chinese Academy of Sciences, used COMSOL Multiphysics finite element software to simulate the gas-liquid two-phase flow and mass transfer characteristics in a bubble column. They adopted a level set method coupled with dilute species transport model and conducted numerical analysis of the entire GLC model through gradually evolving numerical model design. According to simulation results, the tritium extraction efficiency of a single device was 20.8%. Although this value is not high, when 13 units work in series, the total efficiency can be significantly improved to 95%. This result provides a reference for equipment configuration and layout in practical engineering applications. Based on this, a schematic diagram of the fusion blanket tritium extraction system was proposed, as shown in [Figure 11: see original paper].

Gas-liquid contactor technology has high maturity, simple structural design, and is easy to manufacture and install, with excellent reliability and stability. Additionally, its good thermal conductivity is also one of the key factors ensuring efficient operation of fusion reactors. Therefore, the gas-liquid contact method is expected to be the first tritium extraction system technology applied in the International Thermonuclear Experimental Reactor (ITER). However, due to the presence of sweep gas, subsequent separation of sweep gas and hydrogen isotopes is required, which significantly increases the operating cost of

the tritium extraction system. Given the tritium self-sufficiency characteristic of fusion reactors, the demand for higher tritium extraction efficiency has become particularly urgent. Therefore, current research focuses on improving the tritium extraction efficiency of gas-liquid contactors and further optimizing gas-liquid mass transfer characteristics and two-phase flow design within bubble columns.

3. Vacuum Sieve Tray Method

The Vacuum Sieve Tray (VST) method is an efficient tritium extraction method that utilizes nozzles on sieve trays to form droplet jets, thereby achieving effective separation of tritium from liquid lead-lithium alloy. As shown in [Figure 12: see original paper] and [Figure 13: see original paper], the lead-lithium alloy flows from the upper chamber through the sieve tray, forming unstable droplet jets. During the flow process, tritium atoms inside the droplets are transported to the droplet outer surface; at the droplet outer surface, tritium atoms recombine to form T_2 molecules, which then leave the liquid metal and are collected by a vacuum pump [5].

Early researchers [22-25] generally believed that the tritium transport process inside droplets was mainly controlled by the diffusion coefficient of hydrogen isotopes in liquid PbLi, leading to the conclusion that this method had low extraction efficiency. However, recent studies from Kyoto University [20, 21, 26] have shown that PbLi droplets falling in vacuum are excited by high-frequency oscillatory motion, which is believed to promote tritium mass transport in droplets, thereby improving extraction efficiency. To more accurately describe this process, researchers introduced a measured quasi-dispersion coefficient as the mass transfer coefficient for deuterium in PbLi droplets falling in vacuum.

Fumito Okino [26] et al. from Kyoto University conducted a conceptual design of a vacuum sieve tray tritium collection device and studied the PbLi droplet formation process in detail through experimental apparatus. The experimental apparatus is shown in [Figure 14: see original paper]. PbLi was ejected from a nozzle with a 1 mm diameter hole at a temperature of 400°C and pressure of 2.5$×10^{4}$ Pa, forming droplets with a radius of about 0.9 mm at a distance of 8-12 cm from the nozzle. The measured droplet radius and transition length from jet to droplet agreed well with theoretical values. Based on this data, researchers estimated that at 500°C, a single-stage sieve tray could achieve 45% tritium collection efficiency at a height of 1 meter. If higher recovery rates are required, they proposed that using 5-stage sieve trays (about 6 m height) could achieve over 90% recovery rate.

To eliminate solubility effects, Okino [20] et al. designed another set of experiments. The experimental apparatus is shown in [Figure 15: see original paper], using 4 nozzles with diameters ranging from 0.4 mm to 1.0 mm. Under conditions of initial velocity of 3.0 m/s and temperature of 375°C-450°C, they measured the amount of deuterium dissolved in Pb-17Li and the amount released

from droplets in vacuum. The resulting mass transport, expressed as a quasi-dispersion coefficient, was 3.4$×10^{-7}$ m^2/s, approximately two orders of magnitude higher than previous studies under static conditions. The obtained results showed less temperature dependence compared with previous studies. Additionally, they observed cyclic deformation of droplet shapes, which further confirmed the existence of convective mass transfer mechanisms for deuterium release from liquid Pb-17Li droplets falling in vacuum, thereby improving mass transport and transfer efficiency. These results comprehensively demonstrate the feasibility of tritium recovery using liquid Pb-17Li breeder blankets and VST devices.

To verify the applicability of this technology to the Japanese Helium Cooled Lithium Lead Test Blanket Module (HCLL TBS), Okino [21] et al. further analyzed the effectiveness of the VST method for tritium extraction from PbLi droplets in vacuum. They used experimental model nozzle diameters between 0.4-0.6 mm, droplet falling height of 0.5 m, and flow rates between 0.2-1.0 kg/s, ultimately obtaining extraction efficiencies of 0.77-0.96. The experimental apparatus had a height of 1.6 m and a chamber diameter of 200 mm, which not only meets the external dimension requirements of the HCLL Test Blanket Module (TBM) but also requires no additional pumping power. The analysis results indicate that this technology is not only suitable for ITER-TBS but can also be applied as a candidate tritium extraction system for the European Demonstration Fusion Reactor (DEMO).

Researchers in European countries, particularly Germany and Belgium, have also conducted extensive studies on VST technology. R. Antunes [27] et al. from the Karlsruhe Institute of Technology conducted experiments on deuterium extraction with a single nozzle and measured extraction efficiencies at different nozzle diameters. The mass transfer coefficient used in the experiments was the aforementioned quasi-dispersion coefficient for PbLi droplets in vacuum. The equation describing deuterium extraction efficiency is expressed as:

$$\frac{M(t)}{M_\infty} = 1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{D\pi^2 n^2 t}{r_0^2}\right)$$

where $M(t)/M_\infty$ is the ratio of extracted amount at time t to that at infinite time; D is the quasi-dispersion coefficient; t is the falling time; and r_0 is the droplet radius.

The falling time is expressed as:

$$t = \frac{v_0 - \sqrt{v_0^2 + 2gh}}{g}$$

where g is gravitational acceleration; v_0 is the initial velocity of the falling droplet; and h is the falling height.

[Figure 16: see original paper] shows that within the nozzle diameter range of 0.4-1 mm, there is an obvious variation pattern between extraction efficiency and quasi-dispersion coefficient. Particularly noteworthy is that under conditions of falling time of 0.1 s and nozzle diameter of 0.4 mm, the extraction efficiency calculated using the traditional diffusion coefficient was only 12%. However, when using the quasi-dispersion coefficient measured by Kyoto University, the extraction efficiency reached as high as 95%. This significant difference indicates that the quasi-dispersion coefficient has higher accuracy in describing deuterium transport processes in vacuum, thereby more realistically reflecting the extraction efficiency of VST technology.

The extraction efficiency of vacuum sieve trays depends not only on droplet velocity and falling time but also on engineering design details such as nozzle diameter, length, and quantity. To understand the fluid dynamics process of tritium extraction from liquid PbLi in VST devices and the influence of engineering design details on extraction efficiency, M. A. J. Mertens [28] et al. from Ghent University conducted detailed modeling and simulation studies. The simulation device is shown in [Figure 17: see original paper]. Simulation results showed that when nozzle diameter is smaller, the mass flow rate variation over time is lower, but under the same conditions, smaller nozzles have higher extraction efficiency. This indicates that when pursuing high efficiency, certain mass flow rate may need to be sacrificed. However, for applications requiring both high efficiency and large mass flow rate, extremely small nozzle diameters may not be the optimal choice. Under design conditions of nozzle diameter of 1 mm, number of nozzles of 2.1$\times 10^{\{6\}, sievetrayheightof10m, diameterof16.7m, andvolumeof2200m}\{3\}$, the device's tritium extraction efficiency reached 99.2%.

To optimize the VST experimental scheme, Ester Diaz-Alvarez [29] et al. from the Karlsruhe Tritium Laboratory predicted through numerical simulation the effects of upper chamber equilibrium pressure, Pb-16Li temperature (eutectic lithium composition of 0.59$\pm 0.04 wt_\{2\}$ equilibrium pressure; as Pb-16Li temperature increases, the collected gas amount slightly increases; under the same conditions, extraction efficiency and D_2 collection amount are independent of nozzle number, but since nozzle number affects friction loss, the collected deuterium amount differs slightly. The theoretical extraction efficiency calculated using a mass transfer coefficient of 3.4$\times 10\hat{}\{-7\}$ m^2/s was greater than 85% in all simulated cases.

The advantages of the VST method are smaller tritium extraction system size, fewer chemical processes, and significantly enhanced tritium safety management due to its high extraction efficiency. However, in the face of potential maintenance issues such as corrosion and solidification, detailed and complete descriptions need to be established for in-depth study. Therefore, the VST method is feasible as an alternative method for TES. Nozzle design parameters play a crucial role in the VST method as they directly affect tritium extraction efficiency. Therefore, in the design of array nozzle vacuum sieve trays, factors such as nozzle spacing, nozzle quantity, chamber wall clearance, and exhaust port

design need to be thoroughly investigated [30]. These design parameters not only determine the overall performance of the VST system but also relate to system stability and safety. Currently, researchers from various countries are conducting a series of experimental plans targeting the VST method, aiming to further reveal the influence mechanism of nozzle design parameters on tritium extraction efficiency and explore optimal design solutions. The implementation of these experimental plans will help comprehensively understand the performance characteristics of the VST method and provide strong technical support for its application.

4. Performance Comparison of Three Methods

Table 4 lists the performance comparison of three candidate tritium extraction technologies—PAV, GLC, and VST—designed based on liquid PbLi loop tritium extraction modules.

As can be seen from the table, compared with PAV and VST systems, the tritium extraction system integrated with GLC is relatively large in scale and urgently needs optimization of its design to meet ITER's strict standards. However, GLC technology has the highest maturity with no significant manufacturing technical difficulties, providing strong guarantees for system stability and reliability. The PAV system has advantages of compact system and low maintenance cost, but its numerous and compact vacuum permeation tubes undoubtedly increase system complexity, particularly in the welding of tube ends to tube sheets, which requires sophisticated process treatment to ensure system sealing and long-term operational stability. During tritium extraction, the GLC system relies on auxiliary systems to remove tritium from the extraction gas, which introduces an additional hydrogen content of 0.1-0.5% mol. In contrast, PAV and VST systems adopt different strategies, requiring a vacuum system to efficiently extract tritium from PbLi and equipped with pumping systems to manage tritium inventory and transport it to the tritium plant. Notably, the permeation membranes of the PAV system have extremely high material requirements, increasing manufacturing difficulty and cost. The millimeter-scale nozzles of the VST system have material corrosion issues, and its array nozzle and chamber design are still in continuous improvement. Despite these technical maturity challenges, the expected efficiencies of PAV and VST systems remain considerable, giving them certain competitive advantages.

Table 4 Loop performance comparison based on GLC, PAV and VST

Argument	GLC	PAV	VST
Advantages	• High maturity technology • Simple structure • Easy manufacturing and installation • Good thermal conductivity	• Compact system • High extraction efficiency • Continuous operation • No separation of extraction gas required • Low pumping head	• Simple method • High expected efficiency • High flexibility (PbLi mass flow) • Low maintenance cost • Continuous operation mode
Drawbacks	• Huge system • High capital cost • High energy consumption • Low extraction efficiency at low temperature	• High technical uncertainty and risk • Manufacturing complexity • Low flexibility (PbLi mass flow) • Materials with high permeability to tritium, high corrosion resistance and mechanical properties are required	• High technical uncertainty and risk • Nozzle corrosion issues • Array nozzle and chamber design still under development
Auxiliary system	Helium line and helium tritium separation system	Vacuum system and getter system	Vacuum system and getter system

Argument	GLC	PAV	VST
Technology issues	Helium tritium extraction system	Penetrant tube manufacturing, tube shape optimization and design of PbLi distribution system, connection with tube end	Surface optimization
Application	HCLL/WCLL/DCLL BBs	ITER HCLL-TBS	HCLL/WCLL BBs

5. Conclusion

In the design of ITER tritium extraction systems, the processes for extracting tritium from liquid lithium-lead mainly encompass the vacuum permeation method, gas-liquid contact method, and vacuum sieve tray method.

The vacuum permeation method is simple and efficient, serving as a candidate process in ITER-TES design. The main advantages of PAV are its compact system, low maintenance cost, and no need for extraction gas separation, with tritium extraction completed through auxiliary vacuum pumping systems. Permeation membrane material selection should consider materials with high permeability and high diffusion coefficients, with candidate materials including niobium, vanadium, and α-iron. For the PAV method, future research priorities include cost reduction and enhancing the structural strength of permeation membranes while ensuring extraction efficiency.

The gas-liquid contact method is mature and reliable, serving as a candidate solution in ITER-TES design. It mainly achieves tritium extraction through counter-current contact between extraction gas and lithium-lead, but GLC has low single-unit extraction efficiency, integrated system bulkiness, high energy consumption, and requires auxiliary helium-tritium separation systems for operation. Future research priorities include gas-liquid two-phase flow mass transfer characteristics within bubble columns and optimizing system structure and energy consumption.

The vacuum sieve tray method, as an efficient tritium extraction process, has been shown in recent studies to be not only applicable to ITER-TBS but also usable as a candidate tritium extraction system for the European Demonstration Fusion Reactor (DEMO). Its advantages lie in simple method and high extraction efficiency, but it also has technical uncertainties and high risks. To apply this technology in practice, more experimental verification is needed.

Comprehensive investigation and analysis show that the vacuum permeation method, gas-liquid contact method, and vacuum sieve tray method are all considered important development directions for tritium extraction processes from liquid lithium-lead in fusion reactor breeder blankets, all demonstrating good development prospects. Given the urgency of fusion experimental reactor development, the gas-liquid contact method, with its maturity and reliability, can serve as the preferred technology for tritium extraction systems. Through reasonable design of cascade bubble columns, limiting overall equipment height, and improving internal gas-liquid contact to enhance tritium extraction efficiency, it is expected to be well applied in the first lithium-lead blanket fusion experimental reactor in the future.

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Note: Figure translations are in progress. See original paper for figures.