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REALIZATION OF DIRECT INTERNAL RECYCLING FOR DEMO FUEL CYCLE BASED ON A NOVEL CRYOPUMP CONCEPT

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Abstract

High fuel retention in the fuel processing system is a critical factor constraining the economic and safety performance of future fusion reactors. In order to solve this issue, a novel concept of fuel cycle named as the Direct Internal Recycling (DIR) was presented by EU-DEMO. In addition to the metal foil pump, the other promising solution of DIR is to using multi-stage cryopump, however, there is no detail design and R&D carried out. In the paper, a two-stage cryopump was successfully designed and developed, and its effects to reduce the tritium retention in the DEMO torus cryopump pumping system was analysed. Based on the analysis, the tritium inventory of the two-stage cryopump system can be reduced by 30% compared with the common design. In addition, the pumping and the hydrogen/helium separation performance of the two-stage cryopump was investigated based on the analysis and experiments. The pumping speeds of D_2 and He are ~40 m^3/s and 10 m^3/s respectively at at a pressure of 1×10^{-2} Pa. The measured deuterium/helium separation rate was about 86%, confirming its capability for deuterium/helium separation.

1. INTRODUCTION

Achieving steady-state particle control in the core plasma is a fundamental prerequisite for sustaining fusion reactions within a reactor. This requires the continuous injection of high-purity fuel, coupled with the efficient removal of unburned fuel particles and various impurities. Typically, only about 1% of the fuel undergoes fusion in a single pass [1], while the reaction also produces helium ash. To recover the substantial amount of unburned fuel from the exhaust stream and enable its reinjection into the plasma, it is essential to develop and implement an integrated fuel processing system. This system must be capable of evacuating, separating, purifying, concentrating, and storing hydrogen isotopes [2]. Serving as the critical interface between the fusion plasma and the tritium plant, the torus primary pumps initiate the fuel processing cycle. Cryogenic pumps, known for their excellent ultimate pressure, high pumping capacity for light gases, compatibility with tritium, and resilience to magnetic fields, have been selected as the torus primary pumping solution for the ITER tokamak. However, as periodic-operated devices, cryogenic pumps temporarily store pumped gases before regeneration. This cyclical operation leads to a significant accumulation of tritium within the pumps, posing potential challenges related to safety and tritium inventory management for future fusion power plants.

To address the tritium inventory challenges associated with the use of cryogenic pumps, a mercury-based diffusion pump has been extensively studied for EU-DEMO. However, concerns remain regarding the backflow of mercury into the core plasma and its toxic impact on noble metal catalysts [3]. Furthermore, to accelerate fuel processing and minimize tritium inventory within the tritium plant, a novel concept known as Direct Internal Recycling (DIR) has been proposed by KIT [4]. The core principle of DIR involves establishing a short-cut pathway between the exhaust gases from the torus and the tokamak fuelling system. A promising implementation of DIR involves deploying a Metal Foil Pump (MFP) upstream of the torus primary pump. The MFP enables partial separation of hydrogen isotopes from impurities via diffusion, with achieved hydrogen permeation fluxes as high as 6.7 $Pa\cdot m^3\cdot s^{-1}\cdot m^{-2}$ [5]. Despite its potential for rapid, in-line fuel separation—bypassing slower processing in the tritium plant—the MFP faces critical challenges. These include the mechanical stability of its large-area, thin-foil structure (thickness below 100 μm), and operational reliability under strong magnetic fields and ECR plasma conditions [6]. These issues require further investigation and resolution.

In addition to the MFP-based approach for implementing Direct Internal Recycling (DIR), another promising solution involves the use of a multi-stage cryopump [7]. This system offers inherent compatibility with magnetic

fields and exhibits a longer operational lifetime compared to the MFP. In principle, all plasma exhaust gases can be captured by cryopanels through condensation or cryosorption. The conceptual design involves arranging cryopanels in series and maintaining them at different temperatures. This configuration aims to selectively trap gas species based on their distinct physical properties, thereby achieving separation through a controlled, stepwise regeneration process. However, the practical implementation of this technology requires the development of a mechanically viable structure that can be integrated within the DEMO pumping port. Furthermore, the fuel separation efficiency and the resulting hydrogen isotope purity must be rigorously validated through experimental demonstration.

This paper presents the successful design and development of a two-stage cryogenic pump. The system's efficacy in reducing tritium retention within the DEMO torus cryopump system was analysed, and its function in separating hydrogen from helium was experimentally verified. This work provides a foundation for implementing the Direct Internal Recycling (DIR) concept in DEMO.

2. DEVELOPMENT STRATEGY AND STRUCTURE DESIGN OF THE TWO-STAGE CRYOPUMP

2.1. Development strategy

The development logic for the DEMO two-stage cryopump, outlined in Fig. 1, comprises four main stages. First, the required pumping speed for each cryopump is defined, forming the basis for the conceptual design. This design is then iteratively assessed and refined through molecular dynamics simulations to evaluate its pumping performance. Subsequently, safety considerations are integrated: the permissible number of pumps in regeneration is determined by calculating the system's staggering interval—based on safety deflagration limits and the reactor fuelling rate—and comparing it with the regeneration time per pump. Finally, the system-scale requirement is addressed by analysing the total pumping speed needed for DEMO from the divertor neutral pressure and fuelling rate; comparing this with the capacity of a single pump yields the number of units required to operate in parallel. The total number of the pump then can be obtained. While increasing the number of pumps can enhance the overall pumping speed or reduce the regeneration time required for each individual cryopump, it also leads to a significant increase in the total tritium inventory within the cryopump system. This has adverse effects on the economic performance and safety of the fusion reactor, in addition to occupying an excessive number of vacuum vessel ports. Therefore, priority should be given to improving the pumping speed of individual pumps and reducing their regeneration time.

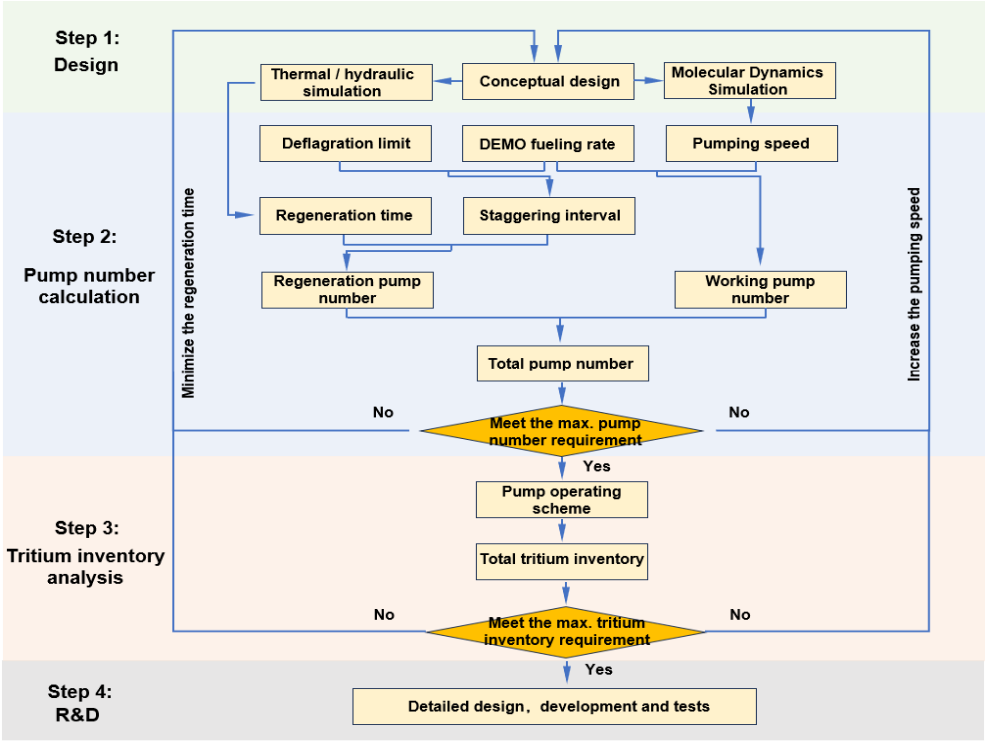

FIG. 1. Workflow diagram of the two-stage cryopump design

2.2. DEMO fuel cycle based on the two-stage cryopump application

As Fig.2 shows, the gas flowing through the divertor first enters the first stage of the two-stage cryopump, where the majority of hydrogen isotopes are captured by cryogenic condensation. A small fraction of hydrogen isotope gas, along with helium, then proceeds to the secondary stage, where it is trapped via cryosorption. Upon reaching the regeneration point, the two-stage cryopump is isolated from the vacuum vessel and between its two stages by specially designed valves, and regeneration is performed at relatively low temperature (less than 100 K). The regeneration products from the first stage are directly routed to the fuel injection system and reintroduced into the plasma for further fusion reactions (DIR). In contrast, the regeneration products from the secondary stage are discharged to the conventional tritium plant, where they undergo exhaust processing, isotope separation, fuel storage, and are eventually reinjected into the fusion plasma through fuel injection system.

In the event of accident, such as a LOCA, or due to contamination from excessive hydrocarbon adsorption that causes significant degradation in pumping performance, the two-stage cryopump should be regenerated at elevated temperatures (~470K). The frequency of this high-temperature regeneration is substantially lower compared to standard low temperature regeneration.

The most demanding operation scheme of DEMO is foreseen to be the steady-state operation. Compared with the current devices, the fuelling rate of the DEMO can reach to 350 Pa·m^3/s [8] and the neutral gas pressure at the divertor area is estimated to be around 1-10 Pa. There will be a pressure gradient generated between the divertor and the inlet of the cryopump, and the pressure of the pump inlet is in the rang of 0.1 Pa. Based on prior research experience, the pumping speed for a fusion-reactor-scale cryopump is validated to reach approximately 100 m^3/s at the specified inlet pressure. Accordingly, a configuration of four two-stage cryopumps operating in parallel is required to handle the particle exhaust during plasma operation. This arrangement also provides sufficient collective pumping capacity to achieve the required vessel pressure of 10^{-4} Pa [9]during the dwell time.

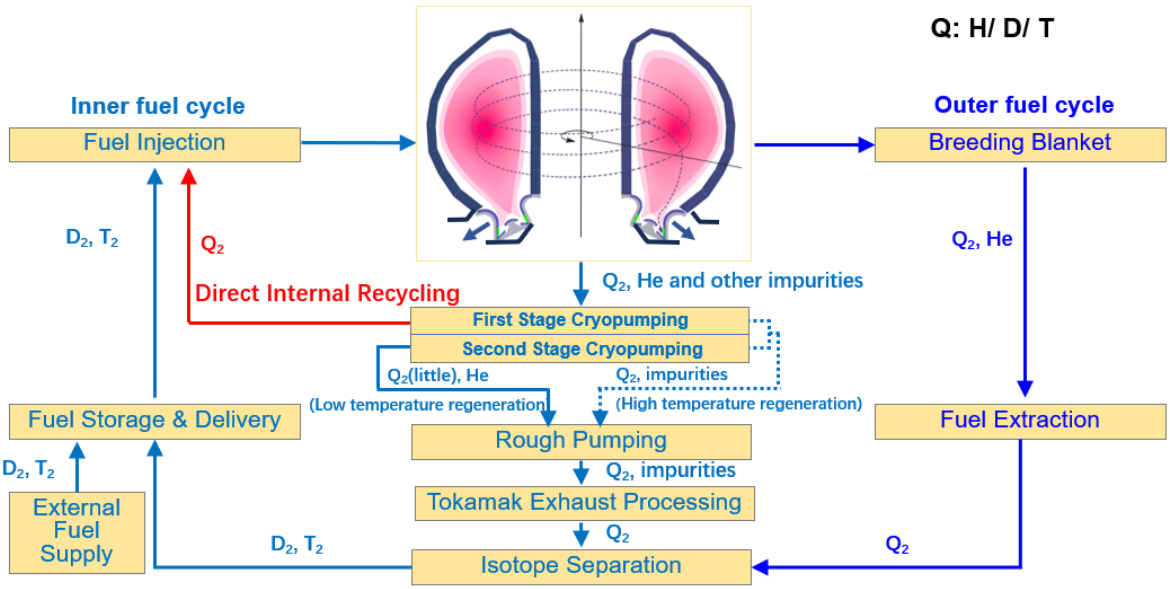

FIG. 2. Simplified scheme of the DEMO fuel cycle with two-stage cryopump application

2.3. Two-stage cryopump design

As shown in *Fig.3*, the cryopump features a two-stage cryopanel structure. The two stages are independently opened and closed by a cylinder-driven two-stage valve, enabling independent regeneration between the two stages. The cryopanels of the first stage are made of bare stainless steel, while the second stage cryopanels are coated with activated charcoal using an inorganic adhesive. Both stages of the cryopanels are cooled by 4.5 K liquid helium. During the operation of the cryopump, the mixed gas exhausted from the plasma first enters the first stage pump body, where high-boiling-point impurities condense on the 80 K baffle, and the majority of hydrogen isotopes condense on the cryopanels of the first-stage. Since the first stage pump body has no condensation or adsorption capacity for helium, helium gas flows into the second stage pump body and is adsorbed

by the activated charcoal inside. When regeneration of the cryopump is required, the two-stage valve is actuated by the cylinder to isolate the two-stage cryopump. By warming up of the two stage cryopanels, the adsorbed/condensed gases are regenerated and evacuated through the mechanical pumping system. Even though a small amount of fuel can come into the second stage, this novel cryopump configuration is capable of achieving a remarkably significant separation of fuel from helium ash.

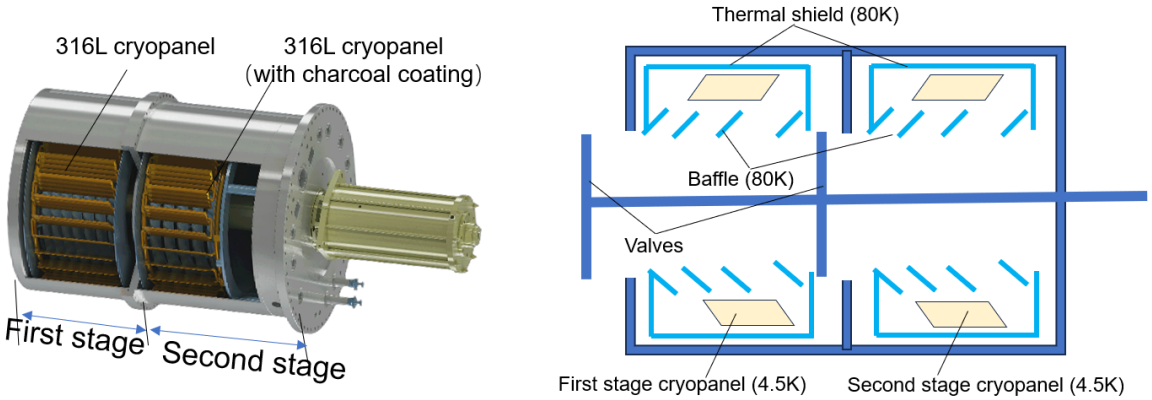

FIG. 1. (Left) 3D design of the two-stage cryopump, (Right) Schematic cross-section

3. PERFORMANCE ANALYSIS OF THE TWO-STAGE CRYOPUMP

3.1. Cooling and heating performance analysis

The heating and cooling rates are governing factors in determining the regeneration speed of a cryopump. Increasing these rates effectively shortens the regeneration time, which in turn reduces the number of pumps required to be in regeneration simultaneously. This reduction is critical for decreasing the tritium inventory within the cryopump system, minimizing the number of pumping ports on the fusion reactor, and thereby enhancing the overall tritium breeding ratio.

In traditional fusion reactor cryopumps, such as the ITER cryopump, complete desorption of hydrogen isotopes and helium from the cryopanels must be achieved at 100 K. To streamline this process, regeneration is performed by directly supplying 100 K cold helium gas into the cooling pipes of the cryopanels. Following the heating and holding phases, liquid helium at 4.5 K is reintroduced into the pipes to restore the pumping surface to its operating temperature. This cycle repeats as required.

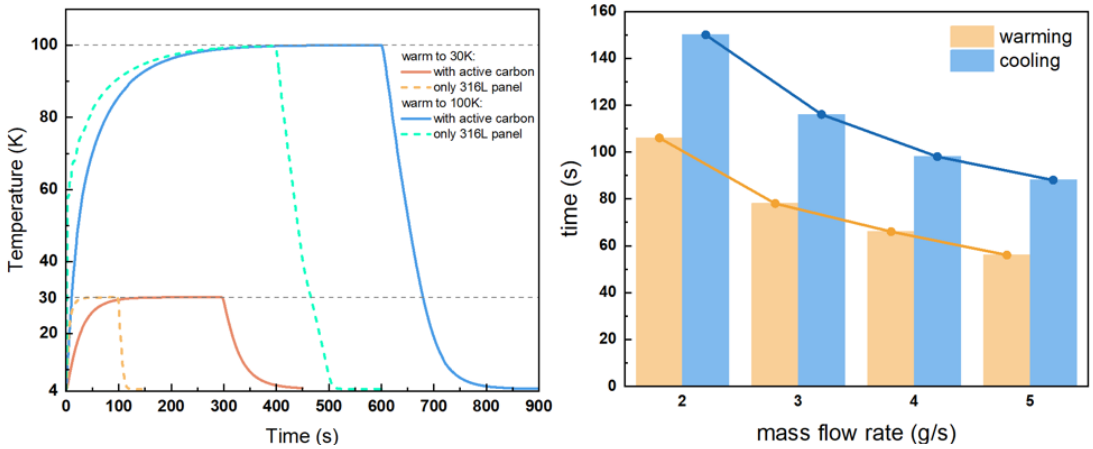

FIG. 4. (Left) Analysis results of the cryopanel's heating and cooling process, (Right) cooling/heating Rate vs. helium mass flow rate

As shown in Fig. 4, with a helium mass flow rate of 2 g/s, the time required to heat the stainless steel cryopanels and the stainless steel cryopanels coated with activated charcoal from 4.5 K to 100 K is 400 seconds and 600 seconds, respectively.

In the two-stage cryopump, the first stage consists of stainless steel panels responsible for condensing hydrogen isotopes, while the second stage uses stainless steel panels bonded with activated charcoal, primarily for adsorbing helium. Depending on operational requirements, a simultaneous regeneration mode for both stages can be adopted. In this mode, the cooling circuits of the first- and second-stage cryopanels can be connected in parallel, sharing common inlets and outlets, thereby simplifying the pipeline layout of the cryopump. According to the gas species adsorbed/condensed on each stage, 30 K cold helium gas can be supplied simultaneously to both the first- and second-stage cryopanels, enabling the release of hydrogen isotopes from the first stage and helium from the second stage.

Due to the presence of activated charcoal, the heating and cooling times of the second-stage cryopanels are approximately 100 seconds longer than those of the first-stage stainless steel cryopanels. To investigate the influence of increasing helium mass flow rate on the heating and cooling rates of the cryopanels, the time required for the activated charcoal cryopanels to heat from 4.5 K to 30 K and cool from 30 K to 4.5 K was analyzed within a mass flow rate range of 2 g/s to 5 g/s. The shortest cooling and heating time is 90s and 50s respectively. Compared to conventional cryopumps, the two-stage cryopump achieves a several-fold increase in regeneration rate. This enhancement helps reduce the number of pumps required and lowers the tritium inventory.

3.2. Pumping and fuel separation performance analysis

Based on COMSOL simulations, this study investigates the pumping speeds for deuterium and helium under molecular flow conditions, along with the deuterium/helium separation efficiency, in a designed two-stage cryopump with an outer diameter of 1200 mm and a valve aperture of 580 mm. The results indicate that the deuterium pumping speed increases with its sticking probability on the first-stage cryopanel (Fig.5). At 4.5 K, where the sticking coefficients of deuterium and tritium on stainless steel approach unity, the maximum achievable pumping speed reaches 35 m^3/s.

It should be noted that the simulations assume molecular flow, neglecting intermolecular collisions. At higher pumping-port pressures, however, such collisions become non-negligible. The resulting increase in molecular transmission probability is expected to significantly enhance the pumping speed.

Furthermore, the probability of hydrogen isotope molecules reaching the second stage is inversely correlated with the sticking coefficient on the first-stage cryopanel. This probability stabilizes when the sticking coefficient exceeds 0.6, enabling a consistently high fuel/helium ash separation efficiency, with a maximum value of 98%.

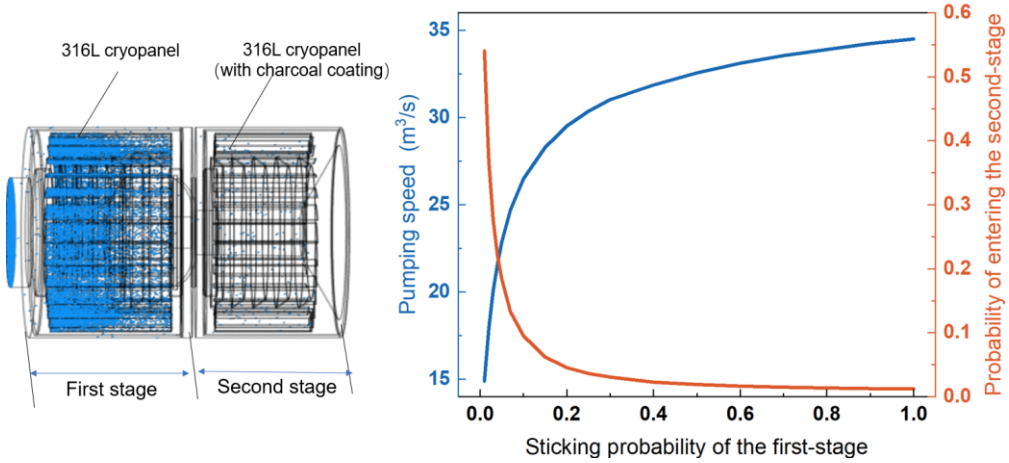

FIG. 5. (Left) D_2 particle distribution in the two-stage cryopump, (right) simulation results of pumping speed and separation rate of D_2.

3.4. Tritium inventory analysis

In addition to simulating the pumping performance of the designed cryopump, it is also necessary to study its operational safety. As an entrapment pump, the cryopump will form a high hydrogen concentration inside during operation. In order to prevent the hydrogen isotope deflagration caused by air leakage from generating a pressure exceeding 0.2 MPa inside the device, the hydrogen isotope concentration in the cryopump is limited to 4.5 g/m^3. Under the maximum fueling rate of DEMO, the maximum operating time of each pump without exceeding the

limited concentration is 325 s. At the same time, according to the design requirement of 4 pumps operating simultaneously obtained from the above text, the start-up interval (ΔT) of each pump can be set to 80 s.

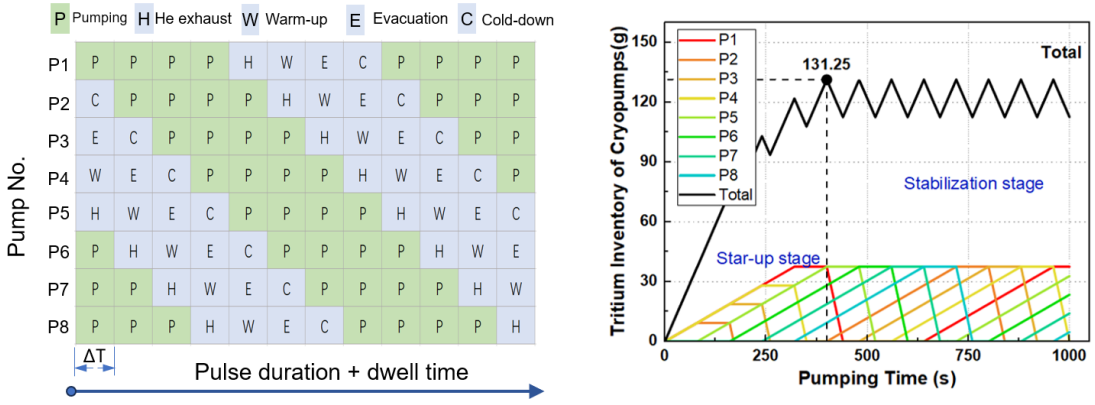

FIG. 6. (Left) Pumping and regeneration schedule for DEMO, (Right) The tritium inventory on the 8 cryopumps for the operating schedule.

Following the plan of the ITER cryopump, the pumping/regeneration stage of the cryopump can be subdivided into the He exhaust and Warm-up, Evacuation, and Cold-down stage. According to the simulation results of the cryopanel with activated charcoal above, the time required for the Warm-up stage is approximately 80 s, and the Cold-down stage is approximately 120 s. Additionally, considering the time required for the evacuation stage, the overall regeneration stage takes about 300s. Therefore, to achieve the cyclic operation of the pump group, a total of 8 cryopumps will be arranged for operation, with 4 pumps working and 4 pumps regenerating at the same time (Fig. 6 left). Therefore, the maximum of tritium inventory in the cryopump is 131.25 g (Fig. 6 right).

As shown in the figure above, the tritium inventory in a single pump complies with safety requirements. If each cryopump can evacuate its trapped gases in a shorter time after the pumping phase, the total tritium inventory in the system can be reduced, thereby decreasing the initial tritium input and operational costs. Benefiting from the unique bare plate design of the two-stage cryopump, when independent regeneration is applied, the total time required for the warm-up and cold-down stages of the bare plate is more than halved compared to a plate coated with activated charcoal. Additionally, using a fore pump with higher pumping speed can shorten the evacuation stage duration, further reducing the total tritium inventory (Fig. 7, left). Analysis shows that reducing evacuation time beyond a threshold value ΔT has no further impact on the total tritium inventory. Only by continuously shortening the helium exhaust and warm-up times can the inventory be effectively reduced. Meanwhile, the shortened total regeneration time allows for a modified operational plan: four units working simultaneously while two are regenerated. This configuration reduces the number of cryopumps required, decreases the number of vacuum ports occupied, and cuts the tritium inventory by 10% (Fig. 7, right).

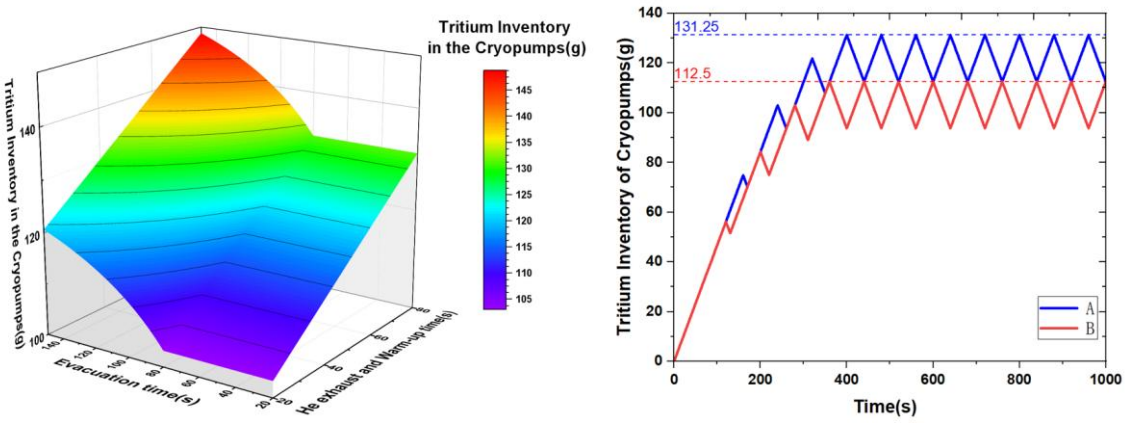

FIG. 7. (Left) The total tritium inventory changes with time in the regeneration stage, (Right) Tritium inventory change curves of two options (80 s and 4+4 pumps(A), 40 s and 4+2 pumps(B)).

4. PROTOTYPE DEVELOPMENT AND EXPERIMENTS

4.3. Pumping speed test

To thoroughly validate the technical effectiveness of the two-stage cryopump, a full-scale prototype of the two-stage cryopump was developed and its testing platform was established. Through experiments, the pumping speeds of deuterium and helium were investigated under different valve openings and pressure conditions. The pump achieved a deuterium pumping speed of up to 40 m^3/s and a helium pumping speed of approximately 10 m^3/s at a pressure of 1×10^{-2} Pa. When the inlet pressure of the cryopump was increased to 0.1 Pa, its pumping speed for deuterium and helium increased significantly.

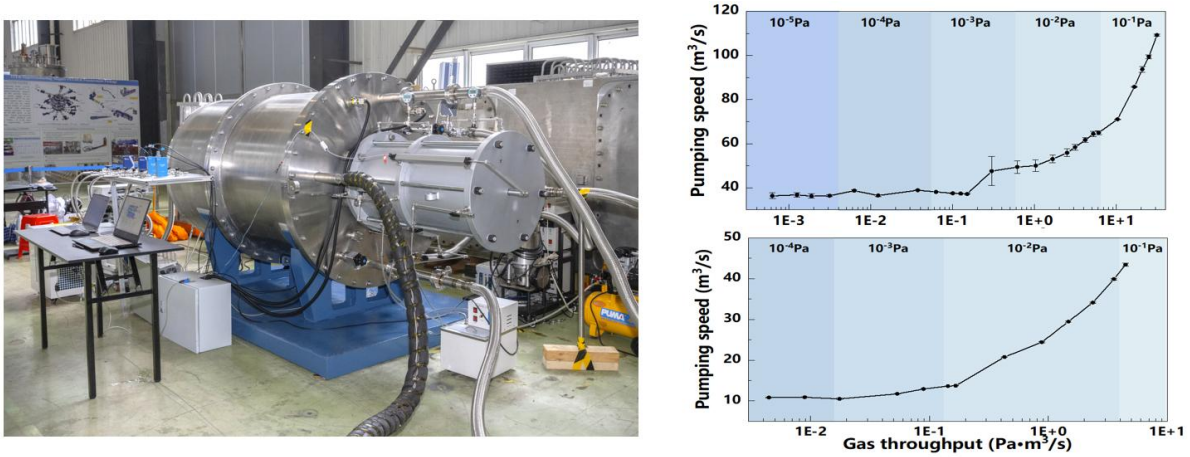

FIG. 8. (Left) prototype of the two-stage cryopump, (Right) pumping speed measurement results.

4.4. D_2/He separation test

To simulate the pumping and separation capabilities of a two-stage cryopump for fusion fuel and helium ash, two independent, high-precision gas flow controllers were used to simultaneously inject D_2 and He gases into the test chamber. To replicate the proportion of fusion helium ash, the D_2/He concentration ratio in the injected gas mixture for this experiment was set at 97.7:2.3. The total amount of test gas entering the cryopump was collected by a PLC.

By measuring the amount of D_2 that penetrated into the second-stage pump cavity and comparing it with the total injected D_2, the separation efficiency parameter of the first-stage pump body for deuterium fuel was determined. The optimal separation coefficient achieved in the experiment was 86%.

The primary reason for the discrepancy between the experimental results and the simulations was that the helium outlet temperature of the cryogenic refrigeration system used for testing the cryopump prototype was approximately 5.2 K other than 4.5 K. This temperature led to a decrease in the sticking coefficient of deuterium on the first-stage cryopump, thereby increasing its likelihood of diffusing into the second-stage pump cavity. Despite this, the experimental results showed good agreement with the simulation results under the same temperature conditions, which confirming the two-stage cryopump's capability for deuterium/helium separation.

5. CONCLUSION

Cryopumps, with their significant technical advantages of high pumping speed and cleanliness, serve as the primary torus pumping system for the fusion reactor. Moreover, multi-stage cryopumps represent one of the promising solutions for realizing the fuel's Direct Internal Recycling in a fusion reactor.

In this work, a double stage cryopump was successfully designed and developed, and its effects to reduce the tritium retention in the DEMO torus cryopump pumping system was analyzed. Based on the analysis and experiments, its function in hydrogen/helium separation was proved. This work laid a solid foundation for the application of DIR on DEMO.

ACKNOWLEDGEMENTS

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