Realization of direct internal recycling for DEMO fuel cycle based on a novel cryopump configuration

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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 KIT [1]. In addition to the metal foil pump [2], the other promising solution of DIR is to using multi-stage cryopump [3], however, there is no detail design and R&D carried out. In this work, 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 analyzed. Based on the analysis and experiments, its function in hydrogen/helium separation was proved.

As shown in Fig. 1(a), 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 Fig. 1(b). 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, 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.

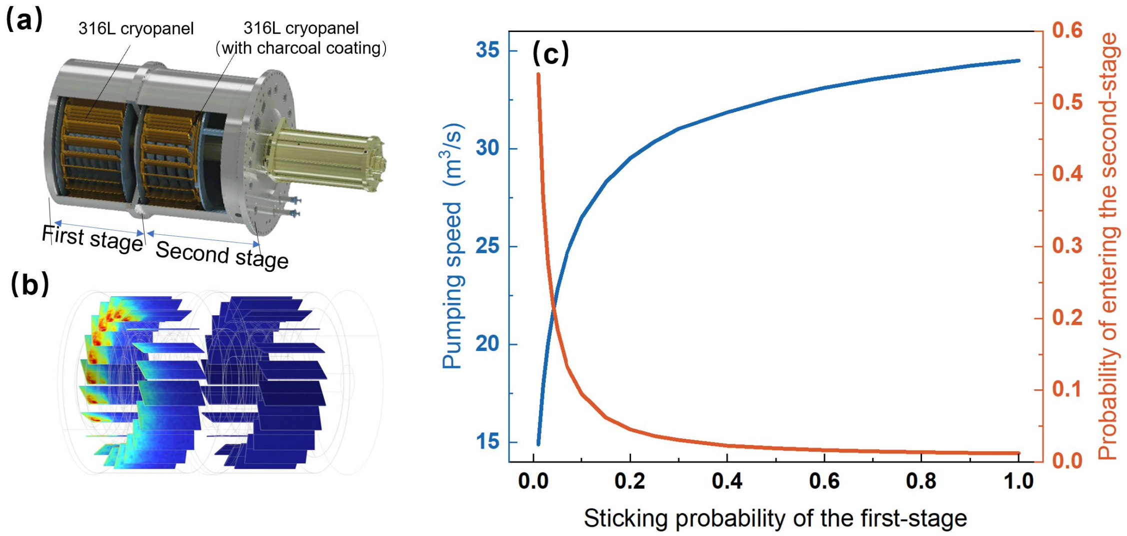

Fig.1. Design of simulation of the two-stage cryopump: (a). structure design, (b). D_2 particle distribution, (c). simulation results of pumping speed and separation rate of D_2.

Based on COMSOL simulation, the pumping speed of deuterium and helium under molecular flow conditions, as well as the deuterium/helium separation efficiency were studied. It was found that the pumping speed of deuterium in the designed two-stage cryopump (outer diameter: 1200 mm, valve aperture: 580 mm) increases with the sticking probability of deuterium on the first-stage cryopanel, reaching a maximum value of 35 m^3/s. At the same condition, the deuterium/helium separation rate is approximately 98%.

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. With a He coolant inlet temperature of 5.2 K, the measured deuterium/helium separation rate was about 70%, confirming its capability for deuterium/helium separation.

Fig.2. Prototype of the two-stage cryopump

The research results indicate that the two-stage cryopump is an effective technical approach for achieving DIR. This work provides valuable insights for the development of new fuel cycle systems in fusion reactors.

References:

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