Pumping characteristics of a cryopump with Ar sorbent in He and in D$_2$/He mixture

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The He ash generated as a result of D/T burn in a fusion reactor must be exhausted from the plasma to avoid fuel dilution effects. In view of this, transport and exhaust studies of He in fusion plasmas are getting increasing attention in recent years. In fusion plasmas, the exhaust gas will be a combination of D$_2$ and He, with He forming only a small fraction (about 10%). We have investigated the cryosorption pumping characteristics of pure He and a mixture of D$_2$ and He (90% D$_2$) using a cryosorption pump with condensed layers of Ar as sorbent. A cryocondensation pump cooled by liquid He at 4.3 K, and located in the outboard divertor region of the DIII-D tokamak, was used for the experiment. The investigation was conducted in a pressure regime that is relevant for particle exhaust from fusion plasmas. The experiment revealed that: 1) cryosorption pumping speed of pure He drops precipitously if the Ar/He ratio falls below about 20, 2) the pumping speed for He in a D$_2$/He mixture decreases in an exponential manner with the amount of D$_2$ pumped, 3) increasing the thickness of Ar in the range of 1 - 12 μm had little effect on the pumping speed for He in a D$_2$/He mixture, and 4) for a pumping surface coated with a thick (>2 μm) layer of Ar, surrounded by a radiation shield having a transparency factor of about 6, a He pumping speed in the range of 15-25 m$^3$s$^{-1}$m$^{-2}$, in the millitorr pressure range for pulse duration of about 5 s can be obtained after pumping about 80 torr l of D$_2$.

I. INTRODUCTION

A fusion reactor based on deuterium/tritium fuel will generate significant amounts of helium as a by-product of the fusion reaction. The mass energy balance equation of DT fusion shows that 15.8 torr l/s of He will be produced for each GW of fusion reactor output. This helium must be exhausted from the plasma or else the buildup of He ash will eventually lead to quenching of the thermonuclear burn. Understanding the transport and exhaust characteristics of He using present-day fusion devices is important to the design of fusion reactors. Cryosorption pumping of He, using charcoal, molecular sieves, and condensed layers of certain gases such as Ar, CO$_2$, SF$_6$, and N$_2$, as sorbents, has been demonstrated. Most He pumping investigations in recent years were aimed at He neutral beam injection into fusion plasmas. Use of condensed gases as sorbents for cryosorption pumping of He is convenient when a cryocondensation pump is readily available. Such is the case

with the DIII-D tokamak, as it is equipped with a liquid He cooled cryocondensation pump,\textsuperscript{15,16} internal to the torus, near the divertor region for plasma density control. The experiments were performed using this divertor cryopump. Because of its inert nature, Ar was the sorbent used in the DIII-D experiments. However, it has been reported\textsuperscript{9} that the cryosorption pumping capacity of He on CO\textsubscript{2} frost is about a factor of 5 higher than that on Ar. Thus, CO\textsubscript{2} frosted cryopumps appear favorable for He pumping applications. However, special schemes to overcome the problem of CO\textsubscript{2} condensing on liquid N\textsubscript{2} cooled surfaces need to be adopted. Also, the poisoning effect of D\textsubscript{2} condensation on CO\textsubscript{2} frosted cryosorption pumps has not been investigated.

A literature survey of cryosorption pumping characteristics of frozen gases\textsuperscript{7-14, 17} reveals some general features of He pumping on Ar frost. These are: 1) the pumping speed deteriorates with increase in concentration of He in the frost and practically vanishes when the He/Ar concentration exceeds about 1/20, 2) with increase in frost thickness, the temperature at the frost surface is increased, thereby affecting the pumping speed, and, 3) condensable gases like H\textsubscript{2} and D\textsubscript{2} have a deleterious effect on He pumping\textsuperscript{6,14} (although a systematic study on this poisoning effect could not be found). The aim of our investigation was to quantify the pumping characteristics of He on Ar frost, in a regime that is important for fusion applications. In fusion devices the exhaust gas will be a mixture of He and isotopes of hydrogen, with He forming only a small fraction (about 10%). The pumping characteristics of pure He and of a mixture of D\textsubscript{2} and He (90\% D\textsubscript{2}, and 10\% He) were studied.

II. EXPERIMENTAL PROCEDURE

The advanced divertor cryopump is in the form of a loop, located on the lower outboard divertor region under a baffled chamber (Fig. 1). Plasma particles are thrust into the baffled chamber through an toroidally continuous opening (30 mm in height) under the bias ring. The pumping surface is formed by an Inconel tube (11.65 m long, 25.4 mm OD, and 0.89 mm wall), with an internal coaxial insert for increasing the flow velocity of the liquid He coolant. The bare area of the pumping surface is approximately 1 m\textsuperscript{2}. Known quantities of Ar were condensed on the liquid He cooled surfaces. The pumping speed for He was measured as a function of He loading, by pulsing known quantities of He and measuring the time constant for pressure decay. If $\tau$ denotes the e-folding time of the pressure decay after abruptly turning off the gas flow, and $V$ is the volume of the torus, the effective pumping speed $S_{\text{eff}}$ is given by:

$$ S_{\text{eff}} = \frac{V}{\tau} \quad (1) $$

If the baffle chamber conductance from the torus to the pump is denoted by $C$, the pumping speed of the cryopump $S$ is then given by:

$$ S = S_{\text{eff}} \cdot \frac{C}{(S_{\text{eff}} \sim C)} \quad (2) $$

He gas was pulsed into the torus using calibrated piezoelectric gas flow valves with fast (~ ms) response times (multiple valves were used to obtain the high flow levels
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required). Pressure measurements were made using capacitance manometers (Baratrons). The response time for these Baratrons was about 50 ms, small in comparison with the large time constant for the pressure decay resulting from the large torus volume (35,000 l). The Ar frost was regenerated by warming the pump and exhausting the desorbed gases from the torus using a turbo pump. In experiments involving D2/He mixture, we attempted to use a special gauge for measuring the partial pressure of He in the presence of D2 (based on spectroscopic analysis of the light emanating from a penning discharge). However, the nonlinear response of the gauge to the background light from D2, made it unsuitable for separating the partial pressure components of He and D2 when the gas composition was changing exponentially with time. The pumping speed for He at any given condition was obtained by puffing a short pulse of He (50 ms duration at a flow rate of 40 torr l/s) and measuring the characteristic time for pressure decay. The experiments were performed at particle strike rates corresponding to pressures typically observed under the baffle chamber (~ millitorr). The effect of Ar layer thickness on the pumping characteristics of He was also studied.

IV. EXPERIMENTAL RESULTS

1. Pumping of Pure Helium

Fig. 2 shows the pumping speed for He as a function of He loading using an Ar frost layer of about 1 µm thickness. The frost thickness was estimated assuming a density of 1.77 g.cm⁻³ for the Ar frost. The frost density depends on the temperature of the condensing surface and the rate at which the frost is formed, but is generally above the liquid density, which for Ar is 1.44 g.cm⁻³. In agreement with other published results, the pumping speed shown in Fig. 2 drops with He loading and becomes vanishing when the He/Ar concentration exceeds about 10%. The geometry of the pump was severely conductance limited and the pumping was not uniformly distributed around the surface of the tube. Nevertheless, a sticking coefficient for He could be obtained by normalizing the measurements made in He with those made in D2 (since the sticking coefficient for D2 at 4.3 K is 1). This procedure yields an initial sticking coefficient for He on Ar frost of about 0.8. Based on published results, increasing the frost thickness should proportionately increase the He capacity. In our experiments though, doubling the frost thickness did not double the He capacity. This difference may be because of the significantly higher He strike rate used in our experiment, compared to those described in the literature. It appears that, at this high strike rate, the He atoms do not have time to migrate to the inner sorbent layers. The diffusion coefficient for He in Ar frost at 4.3 K could not be found in the literature, but a characteristic diffusion controlled velocity on the order of 10⁻⁸ cm/s has been estimated for H₂ in Ar frost at 20 K. If we assume that the He atoms diffuse in a similar time scale, the time for He to migrate through a distance of 1 µm in the frost is ~ 10⁴ s. Thus it appears that the 180 s time interval between He pulses was not enough for the He atoms to diffuse to the deep inner layers of the frost.
2. Pumping Characteristics for D₂/He Mixture

The pumping characteristics for a mixture of D₂/He (90/10) were investigated as a function of D₂/He loading. The pumping speed for He was measured by puffing a short pulse of He after the pump has pumped a known quantity of the mixture. Fig. 3 shows the results. The pumping speed decreases with increase in D₂/He loading. Although deuterium pumping by the Ar frost has a deleterious effect on the pumping speed for He, it does not appear to be due to the commonly conceived notion of site competition. Since D₂ condenses on the Ar frost, the deuterium atom is immobile. A monolayer on the pumping surface translates to about 0.1 torr of D₂. Therefore, the pumping surface must be covered with D₂ immediately after the first pulse. Thus, the effect of D₂ condensation on the top of Ar frost appears to be simply a gradual weakening of the attractive forces between the Ar and He atoms. The results of Fig. 3 also include the effect of He loading on He pumping speed, as about 2 torr of additional He is pumped corresponding to each He puff used to measure the pumping speed.

3. Trapping of He by D₂

It has been shown that He does not get cryosorbed by D₂ frost.¹⁸ No evidence was found of pumping of He by trapping when a mixture of D₂ and He was introduced at the concentrations anticipated in a fusion exhaust mixture. A mixture of 90% D₂ with 10% He was puffed in to the torus with the cryocondensation pump (with no Ar frost) at liquid He temperature. The pumping action was observed only for D₂. The background pressure remained at a level corresponding to zero pumping for He atoms. Thus, without Ar frost, there is no noticeable co-pumping of He atoms even when accompanied by 9 times more D₂ molecules. However, a complex pumping pattern was observed when Ar frost was present. After loading with large quantities of D₂/He mixture, a short puff of He showed that the Ar frosted cryopump was saturated with He producing zero pumping as evidenced by the steady He pressure at the end of the pulse (see Fig. 4(a)). A mixture of D₂/He was then puffed into the chamber. The total amount of He in this puff was the same as the puff with pure He. The cryopump, however, pumped away not only the D₂, but also the He (see Fig. 4(b)). A third pulse of D₂/He mixture confirmed the pumping behavior. In fact, the background He pressure at the end of the third pulse was even less than the background before the beginning of the second pulse. The results suggest some form of mysterious co-pumping of He on an Ar frosted cryosorption pump. It could be that the presence of Ar layer might increase the residence time of He atoms on the surface to a level high enough to facilitate trapping by incoming D₂ molecules. When accompanied by predominantly D₂, a small residual pumping speed for He (approximately 1000 1 s⁻¹ m⁻²) was always present on an Ar frosted pump.

4. Pumping speed for He in D₂/He as a Function of Frost Thickness

This investigation was conducted specifically for He exhaust experiments from fusion plasma discharges. Helium was puffed into a deuterium plasma to study the transport characteristics of He in the plasma. Before the He atoms are introduced into the plasma, the Ar frosted cryopump was exposed to a significant amount of D₂. In one
such experiment, about 80 torr of D$_2$ was estimated to be pumped before the introduction of He. It was not clear if there is an optimum Ar frost thickness for maximum He pumping in this situation. We have examined the pumping speed for He with and without D$_2$ on widely varying thicknesses of Ar frost. Fig. 5 shows the results. No definite effect on pumping speed with frost thickness could be observed and there was considerable scatter among the data. However, in all cases, the pumping speed after condensing D$_2$ was significantly less than the pumping speed before condensing D$_2$. These results agree with the observations made earlier and the data shown in Fig. 3. The scatter in the data appears to be due to differences in the microstructure of the frost, even though we made every attempt to keep the gas feed rate and the pump temperature constant.

V. CONCLUSIONS

1. The pumping speed for pure He, using layers of Ar condensed at 4.3 K as the sorbent, is a function of the amount of He pumped. The measurements are done in pulsed mode at high He strike rates (pressures in the millitorr range). The initial pumping speed corresponds to a sticking coefficient of about 0.8, but the pumping speed almost vanishes as the Ar/He concentration in the frost exceeds about 20. Doubling the frost thickness did not double the He capacity.

2. There was no pumping by trapping of He on 4.3 K surface with no Ar frost, when 90/10 mixture of D$_2$/He was used.

3. Condensation of D$_2$ on Ar reduces the pumping speed for He, the degree of reduction appears to be roughly exponential with D$_2$ loading.

4. Varying the thickness of the Ar frost from about 1 μm to about 20 μm did not show any statistically significant improvement in the pumping speed. There was a large scatter in results when the frost thickness was varied, but at all thicknesses, the same amount of D$_2$ loading produced a significant reduction (50 -100 %) in the pumping speed for He.

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Fig.1 Pumping Configuration

Fig.2 Pumping Characteristics in Pure Helium

Fig.3 Pumping characteristics in a mixture of D2/He

Fig.4 a) zero pumping for He by trapping by D2 in a 90/10 mixture of D2/He with no Ar frost, b) small pumping of He for the same mixture when the pump is frosted by Ar

Fig.5 Pumping Capacity vs. Ar frost thickness
### Cryopump Design Parameters

**Helium Pump**
- Surface area: 1 m²
- Length: 10 m
- Tube diameter: 25 mm
- Tube wall thickness: 0.9 mm
- Static heat load to pump: 10 W
- Particle load: 20 W
- Resistive heating: 220 J
- LHe mass flow: 5 g/s

**Nitrogen Shield**
- Static heat load: 1000 W
- LN₂ mass flow: ~10 g/s
Argon Frost = 2000 torr l (=2 μm thick)
Bare Surface Area of Pump = 1 m²

Additional 2 torr l of He used for each data point.
The graph shows the behavior of the torus pressure and gas pulses over time. The pressure spikes indicate the occurrence of gas pulses at specific time intervals. The x-axis represents time in milliseconds (msec), and the y-axis represents pressure and gas pulses.
Before Condensing $D_2$

After Condensing 80 torr l of $D_2$