GA-A21412

PERFORMANCE CHARACTERISTICS OF THE DIII-D ADVANCED DIVERTOR CRYOPUMP

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This is a preprint of a paper to be presented at the
15th IEEE/NPSS Symposium on Fusion Engineering,
October 11-15, 1993, in Hyannis, Massachusetts, and
to be printed in the *Proceedings*.

Work supported by
U.S. Department of Energy
Contract Nos. DE-AC03-89ER51114 and DE-AC05-84OR21400

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GENERAL ATOMICS PROJECT 3466
OCTOBER 1993

GENERAL ATOMICS

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ABSTRACT

A cryocondensation pump, cooled by forced flow of two-phase helium, has been installed for particle exhaust from the divertor region of the DIII-D tokamak. The Inconel pumping surface is of coaxial geometry, 25.4 mm in outer diameter and 11.65 m in length. Because of the tokamak environment, the pump is designed to perform under relatively high pulsed heat loads (300 W m^{-2}). Results of measurements made on the pumping characteristics for D_2 , H_2 , and Ar are discussed.

INTRODUCTION

The design considerations of a cryocondensation pump for particle exhaust in the advanced divertor configuration of the DIII-D tokamak are described elsewhere [1-3]. In this design, a liquid helium-cooled loop, located under the baffle chamber, serves as the cryopumping surface. In the original plan [1], the cryopumping loop was electrically open to avoid current flow through the loop by induction during plasma current ramps and during disruptions, since any such current will introduce significant heat loading as well as electromagnetic force on the pump. However, subsequent analysis [4] revealed that, in such an open loop configuration, potential differences of up to 300 V can develop between the electrically isolated cryopump and the DIII-D vacuum vessel during major disruptions and vertical instabilities of high current plasmas. To minimize the probability of arcing between the cryopump and its surroundings under these conditions, a closed loop pump design was selected. This change in configuration introduced two new design challenges: 1) increased heat loading to the He due to currents induced in the loop during plasma current start-ups, and, 2) increased electromechanical forces that would result during plasma disruptions.

The issue of increased heat loading on the pump was investigated experimentally [5]. These experiments revealed that, at a power loading of about 100 W (representative of power levels anticipated during DIII-D plasma start-up), the temperature on the surface of a 25.4 mm diam Inconel tube of 10 m length, cooled by liquid He flowing at a mass flow rate of about 5 g/s, rises from 4.2 K to about 8 K. Based on vapor pressure data, a temperature rise above 6 K will cause deterioration in cryopumping of D_2 gas. For H_2 , the pumping speed will begin to deteriorate at 4.5 K. Further experiments showed that increasing the flow velocity by inserting a thin walled flexible porous coaxial insert in the He line enabled the line

to absorb considerably more power (up to 300 W) while maintaining the temperature rise to less than 0.5 K. This latter scheme was adopted for the closed loop version of the pump. The mechanical stability of this new configuration was analyzed extensively and a spring loaded pump support scheme was designed, that minimizes displacement of the pump during plasma disruptions while permitting thermal contraction during cooldown [6].

CALCULATED PUMPING SPEED OF THE CRYOPUMP

Fig. 1 shows the pumping configuration as installed in the DIII-D tokamak. A pumping speed of 50,000 l/s was estimated [1] for D_2 at 0.5 mTorr using a Monte Carlo code, DEGAS. This calculation assumed the pumping surface, the liquid nitrogen shield, and the secondary shield to be toroidally continuous. Mechanical design of the pump is described elsewhere [3]. The cryo-condensation pumping surface is made of 0.89 mm wall Inconel tube of 25.4 mm diameter and 11.68 m length, cooled by forced flow of two-phase helium flowing at a rate of 5 g/s. Because of the need to withstand high mechanical loads, a large number of low heat leak spring supports are used between the He line and the surrounding liquid nitrogen-cooled line (one every 15°). Since each spring support has an axial length of 7.5 cm, the pumping area masked by the springs is about 18% of the total surface area. Further, the numerical calculations assumed a toroidally continuous opening through which the particles reach the pump, while structural considerations required the openings on the secondary shield and the inner radiation shield to be in the form of discrete slits. Also, about 10% of the pumping surface is masked off to prevent interference with certain diagnostics. The mechanical supports to the pump (24 in number) also reduced the conductance to the pump. An approximate estimate for the loss in pumping speed, from the combined effect of the geometrical factors described above, is about 30%. With this correction, the calculated value for the pumping speed for D_2 is about 35,000 l/s.

MEASURED CHARACTERISTICS OF THE CRYOPUMP

A. Cooldown and Regeneration Features

The cryogenic system is a closed loop system, with cryostat located near the tokamak [7,8]. The cryostat can be

*Manuscript received October 11, 1993. This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114 with General Atomics and DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Fig. 1. Cross section of the DIII-D tokamak (left) and the cross section of the advanced divertor components including the pump (right).

independently cooled by bypassing the pump. Starting from a cold cryostat, cooldown of the pump from room temperature takes approximately an hour. In the DIII-D tokamak, He glow discharge wall conditioning is routinely applied after each plasma discharge. To initiate the glow requires a He pressure surge of about 50 mTorr. Once the glow discharge strikes, the He gas flow is reduced and the pressure is maintained at about 2 mTorr. The liquid He flow is cut off just before the glow discharge cleaning is initiated. The He gas pressure surge during the glow initiation period regenerates all the D₂ frost on the cryopump. During the discharge cleaning, which typically lasts about 5 minutes, the liquid He flow is valved off and, by the end of the 5 minute glow, the cryopump outlet temperature warms up to about 30 K. The liquid nitrogen flow is continuously maintained. Cooldown at the end of the glow is accomplished by reopening the liquid He flow control valve. During a typical cycle with 5 minutes of glow, liquid He flow is reestablished in less than three minutes after opening the flow control valve. In this mode of operation, a fresh pumping surface is maintained at the beginning of each plasma discharge, without compromising the discharge duty cycle, and accumulation of D₂ frost to explosive levels from prolonged plasma operation is eliminated.

B. Pumping Speed

Two capacitance manometers, one located in the main torus and the other in the baffle chamber, were used to measure the pressure. Controlled amounts of gas were introduced using feedback controlled piezo electric valves. These flow control valves were calibrated by measuring the pressure rise after puffing a pulse of gas of known duration into the tokamak of known volume (35,000 l), isolated from all pumps. Denoting the gas flow rate by Q (Torr l/s), the pumping speed by S_p (l/s), the conductance between the torus and the baffle

chamber by C_b (l/s), the torus pressure by p_t (Torr), and the baffle pressure by p_b (Torr),

$$Q = C_b (p_t - p_b) = S_p \times p_b \quad (1)$$

These measurements were checked by determining the decay rate of pressure after abruptly cutting off the gas flow, since the effective pumping speed is given by:

$$S_{\text{eff}} = (S_p \times C_b) / (S_p + C_b) = V / \tau \quad (2)$$

where V is the tokamak volume and τ is the e-folding time for the torus pressure decay.

The pumping speed is a function of gas species, pressure, and the temperature of the pumping surface. Although the temperature of the coolant is constant, the temperature of the pumping surface can be affected by the power flux incident on the pump. For H₂ gas, because of its relatively high vapor pressure near the boiling point of He, a small increase in the surface temperature can cause a significant decrease in pumping speed. The pumping speed was measured for three different gases, H₂, D₂, and Ar. Measurements were done in a wide range of pressure, but the primary interest was in the millitorr range, since the pressure measured under the baffle chamber during diverted plasmas are typically in the millitorr range. The results of pumping speed measurements for D₂ are shown in Fig. 2. The apparent pumping speed increased with increase in pressure in the entire range studied. The data at the low pressure end has a higher margin of error since the capacitance manometers are not accurate at very low pressures. At pressures in the millitorr range, the mean free path is comparable with the entrance aperture dimensions of the cryopump, and therefore, the flow regime is in transition from molecular to the viscous. In this transition regime, the conductance to the pump is proportional to the pressure, which

explains the results shown in Fig. 2. The geometry of the pump and its surroundings is not easily amenable for a quantitative estimate of the effect of pressure on conductance, but an approximate linear dependence of conductance on pressure is observed in simpler geometries.

The pumping speeds measured for hydrogen at different pressures are shown in Fig. 3. The pumping speeds for H_2 and D_2 do not agree with the theoretically expected $M^{-0.5}$ relationship, M being the atomic mass number. The correction factor arising from the molecular to viscous transition regime depends on the mean-free-path, which is inversely proportional to the square of molecular diameter. Also, at the operating temperature of 4.35 K (the boiling point of He corrected for the 33 kbar), the sticking coefficient for hydrogen may be less than unity. If the conductance effects are ignored, the measurements suggest a sticking coefficient of about 0.8 at 4.35 K. The pumping speed was also measured for Ar gas, in the pressure range of 1–2 mTorr (see Table I). However, because of the lower pumping speed and consequently higher time constant for the pressure rise for Ar, equilibrium pressures could not be reached during the 9 s gas pulse. The pumping speed for Ar was estimated by using the measured conductance and the decay rate of the pressure trace. These measurements were also checked by extrapolating the measured baffle pressures to obtain the equilibrium values [$P_b(\infty)$] using the expression:

$$P_b(t) = P_b(\infty) [1 - \exp(-S \times t/V)] \quad (3)$$

As indicated before, power is dissipated in the pump during plasma current ramp-up since the cryopump forms a closed loop. The maximum estimated power is about 80 W, lasting for about 1.5 s. Power is also incident on the pump in the form of energetic particles reflected off the diverted plasma strike region. The estimated contribution from the energetic particles and radiation is about 20 W, but because of the uncertainty on the reflection coefficients in the energy range of interest, there is considerable uncertainty on this figure. Experiments with prototypical geometry suggested a safety margin of about 3 for the allowed heat loading on the pump, but these experiments also revealed that the temperature increases on the pumping loop is strongly affected by the details of the flow loop configuration. Therefore, the power handling ability in the actual configuration of the pump was

Fig. 2. Pumping speed versus pressure in D_2 .

Fig. 3. Pumping speed versus pressure in H_2 .

Table I
Pumping Speed for Argon

Baffle Pressure (mTorr)	Pumping Speed [Using Eq. (1)] (l/s)	Pumping Speed [Using Eq. (3)] (l/s)
1.19	8240	8190
2.02	8170	8140
2.37	8470	9560
2.42	8350	9530

determined experimentally by inducing a current in the pumping loop by means of the tokamak ohmic heating coil. Because of maximum current limitations of the ohmic heating supply for long pulse duration (10 s), a triangular current waveform was used to excite the coil to induce a square wave voltage on the cryopump loop. The magnitude of the induced voltage is decided by the slope of the current waveform. The period of the induced waveform was selected to minimize the shielding effect of the torus. Numerical calculations suggested a frequency of 3 Hz. The current, voltage and power waveforms for a pulse of 100 W are shown in Fig. 4. The experiment was done using D_2 , the gas commonly used to fuel DIII-D plasmas. Fig. 5 shows that there was no noticeable effect with application of power on pumping speed for D_2 , for power levels up to 330 W (the maximum value tested). This experiment demonstrated that the pumping speed in deuterium will not be affected by plasma operations.

C. Exhaust Throughput

The maximum operating pressure is dependent on the pulse duration. At a mass flow rate of 5 g/s, a pulse duration greater than 50 s may be regarded as steady state since the time taken by the helium coolant to travel the entire length of the pump is about 50 s. Because of limitations on the gas flow system and on the computerized data acquisition system we were unable to use long pulses at high flow rates. However, a pressure of 9 mTorr of H_2 for a pulse duration of 7 s was maintained by the pump, with no indication of any instability. Since the pumping speed for hydrogen at this pressure exceeds 45,000 l/s, the throughput of the pump exceeded 325 Torr l/s or about 300 Torr·l/s⁻¹·m⁻².

Fig. 4. Traces showing, from top to bottom: 1) ohmic heating coil current, 2) voltage induced in the cryopump loop, 3) power dissipated in the pump, 4) gas throughput into torus, 5) pressure in the baffle chamber.

Fig. 5. Effect of power on pumping speed.

Similarly, a pressure of 9 mTorr of D_2 for a pulse duration of 9 swas also successfully handled by the pump. In a separate experimental observation, 11 mTorr of He pressure was maintained for at least 15 s, but the pump became unstable at some pulse duration (undetermined) that was greater than 15 s.

PARTICLE EXHAUST IN THE DIVERTOR CONFIGURATION

The pump is located under the baffle (Fig. 1), where the pressure is sensitively affected by the position of the plasma strike region relative to the entrance aperture of the baffle chamber [9,10]. By controlling the position of the strike region, the baffle pressure and hence the particle exhaust from the plasma can be carefully controlled. Fig. 6 shows the results obtained for a scan of the divertor X-point during a plasma discharge. A four-fold increase in particle exhaust is seen as the diverted plasma strikes close to the mouth of the baffle chamber. In experiments with heavy gas puffing, a maximum particle exhaust of about 400 Torr l/s has already been achieved [11]. This particle exhaust rate is a factor of 20 higher than the initial design goal.

Fig. 6. Exhaust rate versus separatrix-ring gap.

CONCLUSIONS

A cryocondensation pump for particle exhaust from the lower outside divertor region of the DIII-D tokamak has been installed and operated. The pump provides high pumping speeds (30,000–40,000 l/s in the 1–4 mTorr range of D_2 pressure), in agreement with numerical predictions. Other noteworthy features of the cryopump are: 1) ability to handle high power dissipation (about 350 W m^{-2}) without exhibiting any deterioration in D_2 pumping speed, and, 2) high D_2 throughput ($>400 \text{ Torr l/s}$) for pulsed applications.

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