Engineering Design of Cryocondensation Pumps for the DIII–D Radiative Divertor Program*

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ABSTRACT

A new double-null, slotted divertor configuration will be installed for the DIII–D Radiative Divertor Program at General Atomics in late 1996. Four cryocondensation pumps, three new and one existing, will be part of this new divertor. The purpose of the pumps is to provide plasma density control and to limit the impurities entering the plasma core by providing pumping at each divertor strike point.

The three new pumps are based on the design of the existing pump, installed in 1992 as part of the Advanced Divertor Program. The pump continues to operate successfully. The torodially continuous pumps vary in lengths from approximately 7 to 12 m depending upon their locations within the vessel. Each pump is independently operated and offers on average 0.7 m^2 of liquid helium-cooled pumping surface. The tubular pumping surface is surrounded concentrically by nitrogen shields and a particle shield of larger diameters. The nitrogen-cooled shields limit the heat flux on the helium surface. The particle shield limits energetic particles from impacting the helium and nitrogen cooled surfaces, preventing the condensed gases on the pump, primarily water, from being released.

The new pumps require geometry modifications to the original design. Therefore, extensive modal and dynamic analyses were performed to determine the behavior of these pumps and their helium and nitrogen feed lines during disruption events. Thermal and fluid analyses were also performed to characterize the helium two-phase flow regime in the pumps and their feedlines.

A flow testing program was completed to test the change in geometry of the pump feed lines with respect to helium flow stability. The results were compared to the helium thermal and fluid analyses to verify predicted flow regimes and flow stability.

INTRODUCTION

A divertor system was installed in the DIII–D tokamak in 1989-1992 under the Advanced Divertor Program (ADP) [1]. In phase 1 of the program, a torodially continuous gas baffle structure was installed on the tokamak floor and was used to collect particles and prevent them from recycling back into the plasma core. This gas baffle was used with a torodially continuous, biasable electrode ring. In the second phase of the ADP program, a torodially continuous cryocondensation pump was installed under the gas baffle structure (Fig. 1). The cryopump provided plasma density and impurities control and allowed for the decoupling of plasma current and density. This advanced divertor system continues to operate successfully with no two-phase flow instabilities observed. Deuterium pumping speeds of 32,000 l/s at 2 mTorr baffle pressure are achieved with pump heat loads of up to 300 W [4].

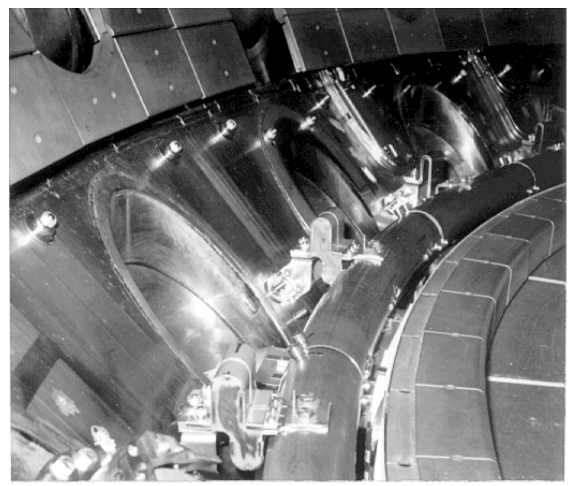

Fig. 1. Installation of ADP cryopump inside the DIII–D tokamak.

Since the ADP installation, experimentation has shown that gas puffing with deuterium and neon at the plasma strike point reduces the peak heat flux to the target plate by radiating the energy over a larger area [2]. Thus, under the Radiative Divertor Program (RDP), baffle plate and cryopump structures are being designed for installation to provide greater baffling capability during gas puffing as well as to provide low density target plasmas for electron cyclotron heating (ECH). To accommodate double-null plasma experiments, inner, central, and outer baffle structures will be installed on both the ceiling and floor of the DIII–D tokamak (Fig. 2). A cryopump will be located in each of the two center and two outer baffle plate structures. The total of four cryopumps (one existing) will provide plasma density and impurity control as well as particle exhaust at each of the four strike points.

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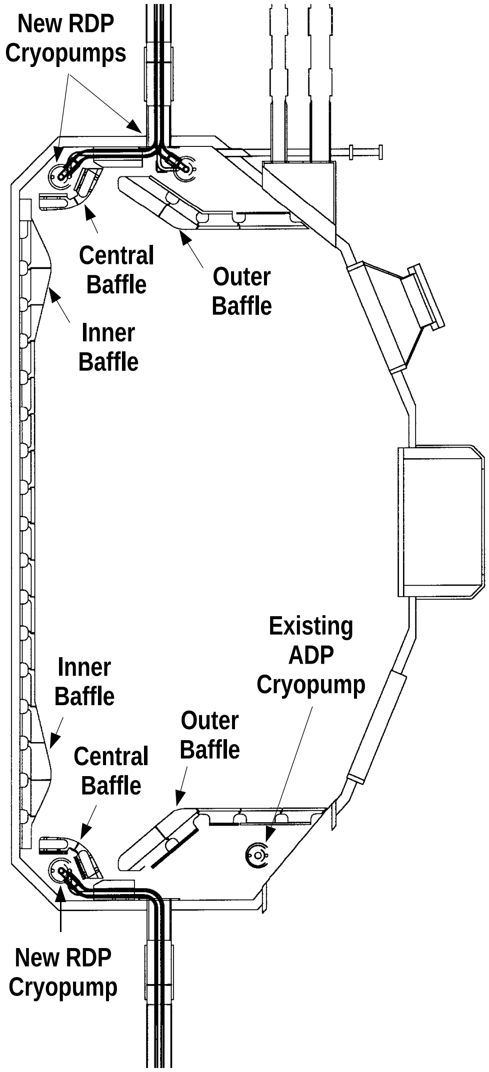

Fig. 2. Radiative Divertor baffles and cryopumps in the DIII–D tokamak

GENERAL DESIGN

The torodially continuous liquid helium and nitrogen-cooled cryopumps vary in circumference from approximately 7 to 12 m depending upon their locations within the vessel. Each pump offers on average 0.7 m^2 of liquid helium-cooled pumping surface made of 2.5 cm diameter Inconel tubing. This provides a total pumping speed greater than 100,000 l/s if all four pumps are operated simultaneously [3]. The liquid helium-cooled pumping surface is surrounded by concentric liquid nitrogen-cooled shields, then covered by a radiation particle shield for an overall pump cross section outer diameter of 9.5 cm (Fig. 3). The nitrogen-cooled shields limit the heat flux on the helium surface. The radiation particle shield limits incoming particles from impacting the nitrogen-cooled surfaces, preventing the condensed vapor on the pump from desorption.

The cryopumps are supplied with a steady flow of liquid helium and nitrogen through feed line tubes entering the tokamak floor and ceiling vertical ports. Due to the tokamak ports having an 8 cm inside diameter, a concentric tube configuration was chosen for the feed lines as a space-saving measure (Fig. 4). The concentric helium tubes are surrounded by a nitrogen-cooled shield. The inlet liquid helium flows through the inner tube, and the outlet helium flowsbetween the inner and outer concentric tubes. This return helium provides subcooling to the helium supplied to the pump due to the outlet flow being at a lower pressure, thus a lower temperature under non-heat load conditions. The nitrogen inlet and outlet tubes are plug welded to the nitrogen shield. This helps to cool the nitrogen shield and limit the heat load to the helium.

Each cryopump and its feed lines are mounted to the vessel walls by a series of support brackets. Twelve supports are used for the inner pumps and 24 for the outer. The supports are made up of two brackets: one bracket attaches to the vessel and another, called a hoop bracket, that attaches from the vessel bracket to the cryopump's outer nitrogen shield (Fig. 3). The hoop bracket is used for all three of the new RDP pumps, whereas the vessel brackets differ between the inner and outer cryopump supports. The hoop bracket geometry is critical to the cryopump support system for two reasons: (1) it allows for radial motion during cooldown and operation of the cryopumps, and (2) it acts as a stiff vertical spring limiting the pump’s deflection from loads caused by vertical disruption events (VDEs).

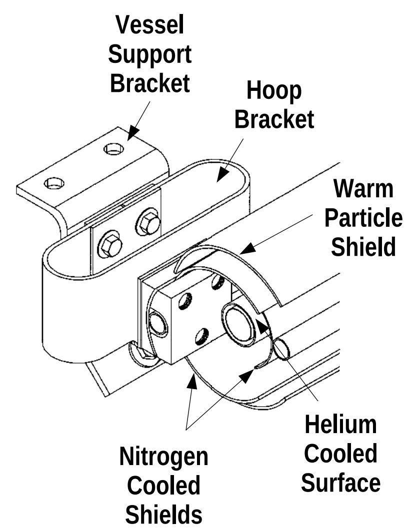

Fig. 3. Cryopump cross section and support structure

STRESS ANALYSIS

Although the general configuration is a replication of the ADP cryopump, the support structure and feed line design for the three new RDP cryopumps are different. Due to the design changes, dynamic and thermal analysis is required. The support system and feed lines in the ADP cryopump are flexible compared to the design of the RDP feed lines, shown

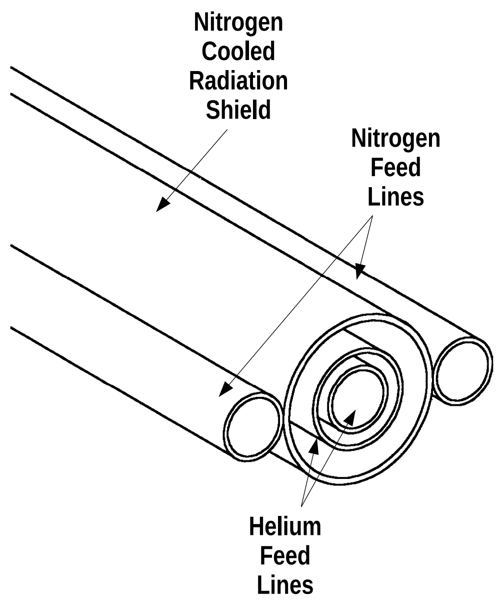

Fig. 4. Helium and nitrogen cryopump feedline configuration

partly in Fig. 2. The deflections and stresses experienced during pump operation and vessel bakeout at 350°C must be analyzed.

The baffle plate structures protect the cryopumps from halo currents during plasma VDEs. However, the torodially continuous cryopumps are subject to toroidal currents from the changing magnetic fields during a disruption. These currents result in impulse loads which are considered in the modal and dynamic analysis for hardware design.

First, a simplified spring-mass transient model was developed. This analysis gave a dynamic load factor (DLF) of 2.2, representing the cryopump's behavior during dynamic loading compared to the same loads statically applied. Taking the maximum load in the transient and increasing it by the DLF is the loading force used for each pump support when static stress analyses are performed to size components.

Next, a beam model was developed to analyze the mode shapes of the cryopump and its feed lines. The frequencies of these modes were compared to the vacuum vessel fundamental vertical frequency of 21 hertz. The feed lines had the lowest frequencies of 14.1, 14.8, and 25.1 hertz.

The beam model was also used to analyze the deflections and maximum stresses. Due to the feed lines having unacceptable deflections during a 21 hertz vessel excitation, an additional support for the feedlines was designed. Each support will be attached between the vessel ceiling or floor and the nitrogen-cooled shield of the feed lines for each of the two inner cryopumps to limit the vertical deflections. The interface of the feed lines to the pump also underwent slight modification to minimize stresses at the welded joint due to this location being a pivot point for feed line movement.

A static finite element analysis (FEA) was performed on the hoop bracket support (Fig. 2). The loads used included the DLF applied to the maximum load of each pump. The FEA analysis confirmed that the hoop bracket geometry satisfied design requirements.

THERMAL ANALYSIS AND TESTING

The issue was raised concerning two-phase flow stability of the liquid helium in the RDP cryopump feed lines. The ports proposed for use with the feed lines are a minimum of 1.2 m in vertical length, thereby creating vertical columns of two-phase flow. A cryogenic flow stability test was conducted modeling the lower inboard cryopump and its feed lines (Fig. 5). This pump configuration was chosen for the test because the highest elevation in its flow system is the cryopump, where the cryogen vaporization occurs during experiments and helium glow discharge which might cause flow instabilities upstream in the vertical supply tubes. The cryogenic flow stability test modeled the tubing lengths to be installed in the DIII–D vessel as well as any flow restrictions or added heat leaks. Testing was performed for 5 g/s, 7.5 g/s, and 10 g/s of liquid helium. The ADP pump currently operates at 5 g/s. It was important to know that the new pumps would also operate at 5 g/s so that no major ex-vessel cryogenic system upgrades, i.e. compressor, liquefier, and dewar, would need upgrading for additional capacity.

The heat load inputs for the cryogenic flow stability test were calculated to represent the steady-state, particle, and inductive heat loads during a typical experiment (E-coil ramp, breakdown, plasma current ramp, and plasma current flat top operation) [4]. Heat loads were applied to the test apparatus by having a power supply lead attached to one end of the helium tube. The current was increased incrementally to represent various power levels. To simulate the steady-state heat leak to the cryopump, 10 W of power was applied through the power supply at all times during testing. Additional power was added in 30 s increments until the test setup pressure, temperature, and vapor pressure bulb sensors showed definite signs of helium boil off.

At a dewar pressure and helium flow rate of approximately 41.3 kPa (6 psig) and 5.5 g/s, respectively, the test showed that about 230 W of power could be applied for 30 s while maintaining a pressure and temperature increase of only 20.7 kPa (3 psig) and 3 K, respectively. This is within the helium surface temperature limit of 6.3 K to provide baffle pumping capability during deuterium experiment. The calculated average heat load was 100 W for the 13 s experiment cycle (15 W steady-state plus 35 W particle load plus 50 W inductive heating) leaving nearly a factor of two margin for pump operation.

A thermal analysis effort was launched in parallel with the cryogenic flow stability test. The purpose of the analysis was to predict the helium flow regime and thus conclude flow stability (the cryogenic flow stability test would actually confirm stability). A steady-state two-phase flow code was used to predict pressure, temperature, void fraction, flow regime, etc., of the test setup. Using results from the steady-state analysis, a lumped mass transient model was developed for the cryopump portion of the test setup. In addition,

Fig. 5. Simulated helium and nitrogen feedline in the cryogenic flow stability test setup.

approximations were made for cryopump flow regime using a generalized flow regime map for horizontal two-phase flow based on dimensionless parameters developed for fluids other than water [5]. The parameters were input into the steady-state code.

Steady-state analysis results showed that at 100, 140, and 240 W of heat load on the cryopump, the helium flow regime transitioned from intermittent slug or plug flow to stratified wavy flow as the helium traveled from the cryopump inlet to outlet. The pressure increase in the pump was predicted to be 13.1 kPa (1.9 psig) at 200 W. Test results showed that at more than 230 W of heat load, the pressure increase from helium vaporization was approaching 27.6 kPa (4 psig). It was concluded that this pressure increase caused choked helium flow at the cryopump inlet during the higher heat loading levels. This was verified during testing, as the helium inlet flow rate decreased when the heat loads were applied.

The lumped mass transient analysis results showed that with a 100 W heat load, the cryopump does not experience complete helium boil off. As the heat load increases by increments of 50 W, boil off is expected to occur. With 150, 100, and 250 W heat loads, complete boil off was predicted to occur at 90, 45, and 30 s, respectively.

CONCLUSION

Three new cryopumps are to be installed in the DIII-D tokamak in 1997 under the Radiative Divertor Program. The modal, dynamic, and thermal analysis of the cryopump design has been completed. Flow stability testing has also been completed, verifying RDP cryopump operation. Prior experience with the ADP cryopump plus the current analysis results suggest that the RDP cryopumps will be capable of pumping during deuterium plasma experiments. In addition, the pumps are designed to withstand a fatigue life of thermal growth from cryogenic cooldown to bakeout as well as disruption loads experienced during operation.

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