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by

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TWO PHASE LIQUID HELIUM FLOW TESTING TO SIMULATE THE OPERATION OF A CRYOCONDENSATION PUMP IN THE DIII-D TOKAMAK*

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A liquid helium-cooled cryocondensation pump has been installed in the DIII-D tokamak fusion energy research experiment at General Atomics. The pump is located within the tokamak vacuum chamber beneath the divertor baffle plates and is utilized for plasma density and contamination control. Two-phase helium flows through the pump at 5 to 10 g/s utilizing the heat transfer and constant temperature characteristics of boiling liquid helium. The pump is designed for a pumping speed of 32,000 l/s. Extensive testing was performed with a prototypical pump test fixture. Several pump geometries (simple tube, coaxial flow plug, and coaxial slotted insert) were tested, in an iterative process, to determine which was the most satisfactory for stable cryocondensation pumping. Results from the different tests illustrating the temperature distribution and flow characteristics for each configuration are presented.

INTRODUCTION

The DIII-D tokamak (Fig. 1) is a magnetic fusion energy experiment that has been in operation at General Atomics since 1986. The tokamak is a torus shaped device designed to contain a high temperature plasma in a magnetic field for the purpose of investigating fusion energy concepts.

The divertor region is located at the bottom of the tokamak vacuum chamber. The advanced divertor is designed to help study plasma density and impurity control, enhancement of plasma performance, and divertor engineering studies and improvements [1].

A liquid helium-cooled cryocondensation pump was installed in the divertor region as a continuous loop under the divertor baffle plates to facilitate particle exhaust. Liquid helium flows in the cryopanel which is surrounded by a liquid nitrogen-cooled radiation shield (Fig. 1). Helium cryopanel surface temperatures required to pump hydrogen and deuterium are 4.6 K and 6.3 K respectively. The steady-state heat load to the pump is calculated to be 10 W. During a 10 second plasma discharge, the pump encounters pulsed heat loads consisting of Joule heating (due to changing tokamak magnetic fields) with a calculated energy deposition of 220 J and particle loads as high as 20 W [2].

Early in the project there were serious technical concerns regarding surface temperature rise and flow instabilities due to the pulsed heat loads. A testing program was carried out to address these concerns and develop an optimized cryopanel design. During the testing some interesting phenomena were observed concerning two-phase helium flow in long thin tubes which led to design improvements.

HELIUM CRYOPANEL CONFIGURATIONS

Three main designs for the helium cryopanel were considered and tested: (1) simple tube, (2) tube with solid insert, and (3) tube with slotted insert. Each configuration shared a common external pumping surface consisting of a 25 mm o.d. $\times$ 0.9 mm wall, 10 m long Inconel 625 tube providing 1 m² of pumping surface [3]. Inconel was chosen rather than stainless steel due to its higher resistivity which limits Joule heating in the pump [4]. The simple tube design consisted of a hollow 25 mm o.d. Inconel tube through which the liquid helium would flow under the force of differential pressure.

The solid insert design had a 19 mm o.d. solid Teflon rod positioned coaxially inside the 25 mm Inconel tube. The Teflon rod was located in place by small nylon screws positioned circularly around the rod 120° apart and staggered longitudinally at approximately a 5 cm spacing. It was reasoned that the

solid insert would force the helium to the outer annular space where it would flow at a high velocity thereby increasing both the heat transfer and flow stability.

The slotted insert design had a 19 mm o.d. $\times$ 0.3 mm wall Inconel tube positioned coaxially inside the 25 mm Inconel tube. The tube surface was interrupted by transverse slots $\sim$ 5 cm apart. The slots provided access for liquid helium to enter the inner volume of the tube which was plugged at 75 cm intervals to discourage inner flow. The latent heat of the liquid helium in the inner volume would provide increased heat capacity while the insert forced high velocity in the annulus as in the solid insert scheme.

TEST DESIGN

A test fixture was designed and built utilizing a 5.8 m length of straight pipe as the main vacuum chamber. Helium cryopanel test specimens were made from two 5 m long straight 25 mm Inconel tubes joined with a 180° smooth turn at one end. Liquid helium flow was controlled by a valve on the cryopanel inlet. Two-phase helium leaving the cryopanel traveled through non-insulated pipe to be warmed by a bank of electrical heaters and returned to the helium system compressors at 1.08 bar. Helium mass flow rates were measured by an orifice flowmeter at the cryopanel inlet and a pitot tube in the gas return line. The cryopanel was tested at mass flow rates between 5 g/s and 10 g/s and the presence of liquid helium was verified by vapor pressure bulbs at the inlet and outlet. Fourteen silicon diodes were attached to the cryopanel outer surface to accurately determine surface temperature characteristics. Silicon diode types and installation techniques were chosen to provide best data resolution and minimize thermal response time.

The tokamak environment heat loads were simulated by passing an electrical current through the 25 mm Inconel tube. A heat load profile consisting of a steady state 10 W heat load and a 30 s, 100 W pulse (Fig. 2) was implemented using a computer controlled current source. Most tests were conducted at this power level, however, higher levels were applied to determine cryopanel stability limits. Stability criterion were based on surface temperature rise, flow restriction, and fluid temperature as indicated by the inlet and outlet vapor pressure bulbs.

DISCUSSION OF RESULTS

Simple Tube

Cryopanel surface temperature rises rather quickly with application of heat (Fig. 2). The temperature remained high until the heat load was removed. It was surmised that the flow velocity of the helium was too low to properly cool the pumping surface.

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

Fig. 2. Surface differential temperature vs. time at the midway point of the cryopanel.

A curious temperature oscillation can be seen during the heat pulse. Similar corresponding oscillations occurred in the fluid flow rates. These oscillations typically started when the liquid helium in the cryopanel began to boil. The gas pushed against dense liquid downstream of the cryopanel creating a backpressure effect which slowed the incoming liquid flow. The corresponding reduction in cooling resulted in rising surface temperatures. As the gas left the cryopanel and the initial choked flow condition subsided, fresh cold liquid would enter the cryopanel resulting in a temporary cooling effect. Another temperature rise occurred as the cold liquid encountered the now warm tubing downstream of the cryopanel producing another, though less drastic, flow reduction [5]. When the heat load was removed these oscillations continued but were greatly damped and diminished quickly.

Solid Insert

Results for this design are significantly better than those for the simple tube (Fig. 2). The higher flow velocity in the annulus had a noticeable effect on cryopanel surface temperature. Temperature and flow oscillations were again encountered but were significant only at higher heat loads.

Figure 3 illustrates the surface temperature characteristics around the tube. This is an excellent indicator of phase separation in the cryopanel. A non-turbulent separation of gas and liquid occurs repeatedly in the simple tube. The solid insert shows no noticeable separation. The higher velocity in the annulus promoted turbulent flow which provided better mixing of the two phases.

The solid insert indicated that some type of flow plug would be needed for proper pump operation. Teflon, however, would not be satisfactory in the tokamak as it would not be able to survive the high temperatures (450°C) encountered during vacuum vessel baking.

Slotted Insert

The slotted insert proved superior in performance to the other designs. The high flow velocity in the annulus was supplemented by the heat capacity of fluid in the inner tube to provide the required cooling. The slotted insert equalled the performance of the solid insert at a lower flow rate (Fig. 2). The numerous slots provided ample flexibility to allow installation into the actual cryopanel circular tube.

PHASE SEPARATION TESTING

Temperature and flow oscillations occurred with the slotted insert at high heat loads as in the previous designs. Helium leaving the cryopanel boiled completely to gas as it entered the warm external pipe and the heaters. Gas produced in the cryopanel during a test would push against this two phase fluid and develop backpressure. Two series of tests were developed to investigate this: venting the helium directly to the atmosphere, and exhausting the two phase flow into a cold dewar utilized as a phase separator.

A vent valve was installed in the helium line as it emerged from the test chamber and was held open during test shots. The absence of backpressure, and corresponding oscillations, resulted in a gradual rise in surface temperature (Fig. 4). The cryopanel remained stable at heat loads up to 250 W. This action was wasteful, however, and not practical for cryopump operations.

The phase separating dewar concept was acceptable as it maintained the continuity of the closed loop helium system while significantly reducing the backpressure. A 100 l helium dewar was installed

downstream of the cryopanel external to the test chamber. A vacuum jacketed transfer line connected the cryopanel to the dewar to minimize the heat leak. The dewar was held at liquid helium temperature for proper phase separation and the boiloff gas vented out through a line to be warmed by the heaters.

Temperature and flow oscillations occurred but were significantly lower in amplitude than in previous tests (Fig. 4). Backpressure existed due to the pressure drop of two phase flow in the transfer line, however, the cryopanel remained acceptably stable. Operational experience to date has proved that such measures are not required.

CONCLUSIONS

An effective in-situ cryogenic pump configuration was developed for use in the DIII-D tokamak. Several different configurations based on a single long tubular pumping surface were identified and tested in the laboratory. The simple tube configuration was considered unsatisfactory. The cryopanel surface temperature requirements could not be achieved due to the low helium flow velocity.

The solid insert proved that some form of flow plug would be necessary for sufficient cooling. A Teflon rod would not be practical for use within the tokamak environment due to high temperature vacuum vessel baking. The slotted insert completely satisfied the design requirements. The coaxial tube provided sufficient annular flow speed and the additional volume of the inner tube provided the needed heat capacity. The slotted design was implemented and the pump has been operating with great success.

The atmospheric venting and phase separation potentially offer significant improvement in performance of the slotted configuration. However, since the operation of the system has been more than adequate for all experimental conditions such a system has not been installed.

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Fig. 3. Radial surface temperature rise profiles of the cryopanel during a 100 W heat pulse. Data measured at the cryopanel top 7.5 m from the inlet.

Fig. 4. Differential temperature vs time for phase separation testing. Data measured on the cryopanel top at the midpoint.

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