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A Continuous Cryogenic Diffusion Pump For Fusion Reactors

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Abstract—**A pumping system designed to pump magnetic fusion reactors has been operated pumping deuterium, hydrogen and hydrogen- helium mixtures. A 500 mm bore liquid helium cooled "snail" cryocondensation pump was used to pump the hydrogen species. The snail pump is equipped with a unique regeneration head which continuously removes the hydrogen ice from the cryocondensation surfaces while the pump is in operation. The hydrogen ice is evaporated inside the snail head and pumped with a 500 m^3/h roots blower. The snail cryopump is attached to a 500mm bore x 3m long liquid nitrogen cooled entrance duct. The "cold duct" provides several important functions of the pumping system, it: 1) provides the conduit between the diverter and the cryopump, 2)pre-cools the gases allowing the elimination of a restrictive entrance baffle, 3) reduces the molecular mean free path allowing the duct to operate in the fluid flow regime. The fluid flow regime increases conductance and allows compression of the helium stream by diffusive drag. With the large compression of the helium, it can be pumped with a conventional turbomolecular pump. The cryopump effectively strips the hydrogen species from the helium stream before it enters the turbomolecular pump. The pumping system thereby separates the hydrogen and helium streams.**

Mass flow controllers were used to inject the hydrogen (deuterium) and helium into a standard AVS test dome fitted with a capacitance manometer. Pure hydrogen was pumped at flow rates from 1.7 to 67.4 Pam^3/s (the limit of the flow system) with the test dome pressure varying from 0.1 to 0.52 Pa, the effective pumping speed varied from 17 to129 m^3/s which is in good agreement with Poiseuille flow. Deuterium was pumped at rates up to 33.6Pam^3/s, at 0.39 Pa, pumping speed 86 m^3/s. Pure helium was pumped to0.32 Pa m^3/s at .49 Pa, pumping speed 0.67 m^3/s. Hydrogen with 1% helium was pumped to32.7 Pa m^3/s at 0.52Pa, effective pumping speed of both species was 63m^3/s. The helium compression varied from 31 up to 93 at the maximum flow. The flow was limited by the pumping capacity of the turbomolecular pumps.

The design of the pumping systems, the test results and comparisons to fluid flow theory is presented.

Keywords-vacuum; cryopump; fusion; tritium;helium;diffusion pump.

I. INTRODUCTION

Fusion power plants which "burn" hydrogen isotopes (D/T) will produce neutrons and helium. For a 3 GigaWatt plant[1] the helium, which is produced at a rate of 2.0 Pam3/s, must be removed from the plasma through the diverter. The helium in the diverter is maintained at 1% of the D/T gases which are at a pressure of one Pascal. While it is not necessary to pump the D/T from the diverter, all known high speed pumping systems which pump helium also pump hydrogen, thus requiring a pumping speed of 200m^3/s and a plant to separate the He from the D/T which is re-injected into the plasma. Large liquid helium cooled charcoal cryosorption pumps [1] could be used as the primary pumps. Since these pumps capture and store the gases, they rapidly accumulate large inventories of tritium and must be valved off and regenerated frequently. A cryocondensation pump which regenerates itself during operation with a "Snail" head [2] which continuously removes the frozen gases from the cryocondensation surfaces has been developed. This pump has previously demonstrated the capability of pumping large throughputs of hydrogen and deuterium in the desirable pressure range of 0.1 to 1 Pa[3]. However, since this pump is a cryocondensation pump, it does not pump helium which is really what needs to be pumped. Attempts of producing a continuous argon frost cryosorption pump[3] were not successful. A compound cryopump with a first stage consisting of a Snail cryocondensation pump followed by a charcoal cryosorption pump [4] was designed. In this configuration, the hydrogen isotopes would be pumped and regenerated continuously with a Snail head and the helium stream would be pumped and periodically regenerated by a charcoal cryosorption pump. While this would not be totally continuous, it could significantly extend the regeneration times of the charcoal stage if the first stage stripped a large fraction of the tritium from the gas stream. In analyzing the baffling structures required for this configuration, it was determined that the cryocondensation stage of the pump was well into the fluid flow regimes at cryogenic temperatures. A new pumping system was then designed and constructed [4] which utilizes the enhanced conductance of fluid flow at low temperatures and also achieves significant compression of the helium stream by the diffusive drag of the hydrogen stream, allowing conventional turbomolecular pumps to be used. This pumping system was designed and constructed at *CAFI* and tested at *LANL* under DOE STTR grant # DE –FG02-98ER86075.

II. THEORETICAL BASIS OF THE PUMP

Conventional cryopumping systems operate in high vacuum in the free molecular flow regime [5] where the mean free path is long as compared to the pump diameter. In this regime the gas wall collisions determine the flow characteristics and each species of gas flows independently of the other. In high vacuum, the thermal conductivity through the gas is very low so that no insulation is required to isolate the cryopanels from the room temperature vacuum walls. However, when these pumps operate at higher throughput and pressure, they become unstable as the increased thermal conduction to the cryopanels causes the condensed gases stored in the pump to evaporate. This has led to the general misunderstanding that cryopumps cannot operate at high inlet pressures. However the thermal instability can be prevented by surrounding the cryopanels with a separate vacuum insulation jacket or Dewar. This configuration has allowed the Snail cryopumps to operate stably at very high throughput levels.

In free molecular flow the throughput is proportional to a constant, called the conductance [5], times the pressure. The conductance of the inlet pipes is independent of both the pressure and is also independent of the temperature of the pipe when including the thermal transpiration pressure drop. The fluid flow regime occurs when the mean free path is small in comparison to the pump diameter. The Hagen-Poiseuille flow equations [5]for the flow of a gas in a pipe is

$$dm/dt= MQ/RT=M*(P_1-P_2)*0.5*(P_1+P_2)*\pi*d^4/(128 *l*RT* \eta)$$

where M is the molar mass, R is the gas constant, Q is the throughput, P_1 is the inlet pressure, P_2 is the outlet pressure, d is the diameter, l is the length, T is the temperature, η is the viscosity. Using [5] ,

$$\eta= [0.499*(4*m_H*k*T)^{1/2} /(\pi^{3/2}*d_0^2)]$$

for the viscosity, where d_0 is the molecular diameter; and substituting the pressure ratio $\chi =P_2/P_1$ gives

$$dm/dt= 0.069*M*P_1^2*(1-\chi^2)*d^4*d_0^2/(l*RT*(m_H*k*T)^{1/2} .$$

The mass throughput is proportional to $P^2/T^{3/2}$. In fluid flow the conductance is not a very relevant concept since it changes with pressure, the "effective conductance" would change as $P/T^{3/2}$. At high pressures and low temperatures a much smaller duct and pump is required than what would normally be prescribed for a cryopump operating in free molecular flow.

III. Design and Construction of the Pump.

The inlet pipe of the new pump is called the "Cold Duct". It operates in the fluid flow regime at cryogenic temperature and would replace the vacuum ducts connecting the diverter to external vacuum pumps in a conventional design. It consists of a 500mm bore by 3m long vacuum insulated pipe refrigerated by liquid nitrogen. By operating at high pressure and reduced temperatures a 500mm cold duct pump will outperform a collection of six 1000mm bore conventional cryopumps operating in free molecular flow. At the entrance to the duct the incoming gases are reduced in temperature within one pipe diameter. The lower temperature increases the density which puts the gas further into the fluid flow regime. The cold duct is contained in a vacuum insulation jacket which would provide for the dual containment of tritium. It is refrigerated by a cooling trace to 80K with liquid nitrogen or 30K with He gas. By pre-cooling the gas, the cold duct also eliminates the need for the flow-restrictive entrance baffles typically used in conventional cryopumps.

A key feature of the cold duct/fluid flow design is that it can function as a classical condensation diffusion pump[6]. In the cryogenic diffusion pump [7], the majority hydrogen stream functions as the working fluid; and, as in a conventional diffusion pump, is condensed out after the minority gases are compressed. The helium and impurity minority streams are entrained in the majority hydrogen stream and can be compressed to a high outlet pressure. The helium back-diffusion upstream is prevented by multiple collisions with the streaming hydrogen flowing downstream. The achievable compression is limited to about 1/2 of the inlet pressure, since the downstream pressure cannot rise to a value which affects the total flow in the duct. Since the helium is only 1% of the hydrogen flow coming from the diverter a helium compression of about 50 can be achieved without impairing the hydrogen flow. This allows the partial pressure of the helium in the cryopump to increase to about 0.1 to 0.2 Pa which is the pressure at which turbomolecular pumps operate at their maximum throughput.

The cold duct mates to the Snail cryodiffusion pump with a bayonet coupling flange. A drawing of the Snail pump is shown in Fig 1. In order to pump the helium stream with conventional turbomolecular pumps, a compound pump arrangement was produced which strips the hydrogen stream upstream from the helium pumps. This configuration produces a separation of the impurity, hydrogen and helium streams. The impurities are cryopumped at the pump entrance in a baffle structure refrigerated with the liquid helium boil-off gas to

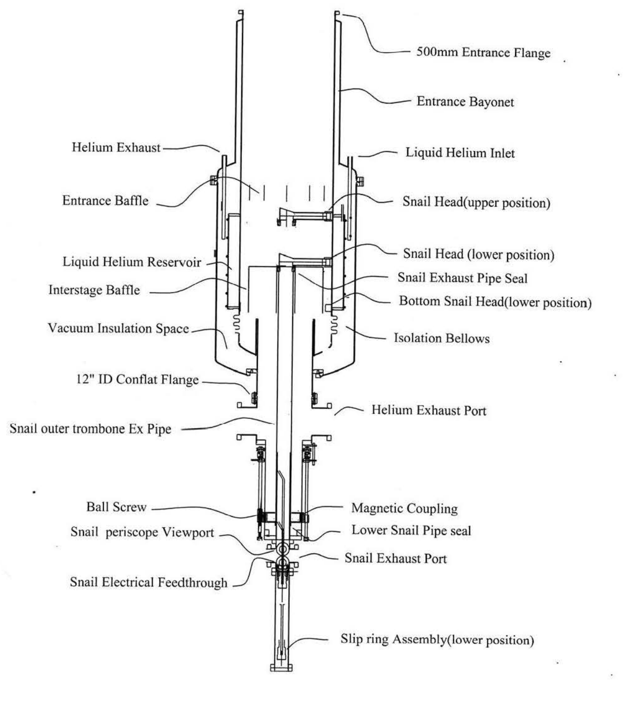

Figure 1. Drawing of the Snail Cryogenic Diffusion Pump.

20K. The baffle was designed with wide apertures so as to not restrict the hydrogen flow. The helium is pumped from the lower chamber by turbomolecular pumps. The hydrogen isotopes are cryopumped and exhausted by the snail cryocondensation pump.

The cryosurface consists of the interior of a 500mm bore by 500mm long tube which is the inside wall of a surrounding annular liquid helium vessel. The hydrogen cryocondensation pump is configured as a Snail cryopump. In a Snail pump the hydrogen ice deposited on the cryosurface is continuously cleaned off by a moving Snail head, analogous to a snail removing algae in an aquarium. The Snail head spirals around and up the cylindrical cryosurface. The upper half of the cryosurface is serviced by the top snail head which shaves the hydrogen ice with a heated knife into an interior chamber (stomach) of the snail where it is vaporized by internal heaters. The gas is then exhausted out of the cryopump through a 75mm diameter pipe which is connected to a 500m^3/h roots blower. The snail is driven by an external mechanism mounted in the bottom of the pump coupled through the vacuum wall by a set of rare earth magnets which drive the internal section of the Snail exhaust tube on which the snail heads are attached.

The lower half of the cryosurface strips the hydrogen from the helium stream flowing into the lower chamber. An interstage baffle plugs the center of the pump and forces the flow through a 500mm diameter, 50mm wide 250mm deep annular channel along the lower cryosurface. The hydrogen ice deposited in the lower half of the cryopump is removed and vaporized by the bottom snail head and is re-deposited back to the upper section where it is removed by the top snail. A 300 mm bore tube connects the lower chamber to room temperature ports through which the helium is pumped by two 200 mm diameter conventional turbomolecular pumps. The cold duct and the snail cryodiffusion pump both have vacuum jackets which are pumped by a small turbo molecular pump.

A photo of the pump being tested at LANL is shown in Fig. 2. Because of the length of the pump assembly it was mounted diagonally rather than in a vertical orientation. At the top left of the assembly is an AVS style vacuum test dome.

Figure 2. Snail Cryodiffusion Pump Test Assembly at LANL.

The test gases are injected into the dome through separate mass flow controllers. The test dome pressure is measured by a one Torr MKS Baratron gauge. The test dome is mounted on the three meter long cold duct which mounts with a bayonet coupling flange, (located just above the venting helium gas) to the snail cryodiffusion pump. A second Baratron gauge monitors the pressure just above the pump entrance baffle. A third Baratron gauge monitors the pressure at the bottom of the pump where the turbomolecular pumps are mounted. Several Lakeshore silicon diodes monitor the temperatures in the cold duct, the cryopump and the Snail heads.

IV. RESULTS

After assembling the pump, it was tested with liquid helium at LANL for two days. A limited series of runs were made including pump tests with pure hydrogen, hydrogen with 1% helium, pure helium, and pure deuterium, all with the Snail heads off; and with deuterium with the Snail heads operating. The tests were made with the cold duct refrigerated with liquid nitrogen.

The results of the hydrogen test are shown in Fig.3 and compared to free molecular flow and fluid flow theory. The pump was capable of operation at flows up to 67.4 Pam^3/s which was the limit of the mass flow controllers. At this flow the test dome pressure was maintained at 0.52 Pa which corresponds to an effective pumping speed (at the test dome) of 129m^3/s. The mean free path in the cold duct is 5.5mm which results in a good fit with Hagen- Poiseuille fluid flow theory.

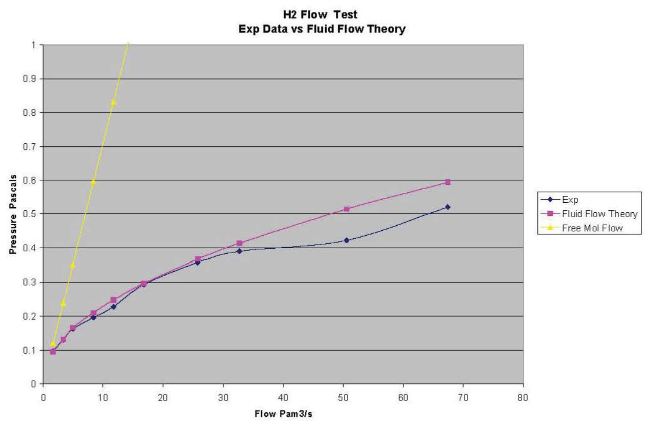

Figure 3. Hydrogen flow vs. pressure compared to theory.

The results for pumping hydrogen with helium are shown in Fig. 4. In this test the flow was limited to 32.6 Pam3/s at which the test dome pressure was 0.52 Pascal which results in an effective pumping speed of 63m^3/s. At this flow the pumping is being limited by the downstream pressure buildup of the helium stream. This is seen in the test with pure He which is also shown. In this case the helium stream is pumped only by the turbomolecular pumps which are at their throughput limit. At the maximum flow rate of 0.32 Pam3/s of He the test dome pressure is 0.48 Pa . In the mixed flow test the pressure of the Baratron at the turbopump entrance is 0.51 Pa. Since the gauge is at room temperature and the gas is in

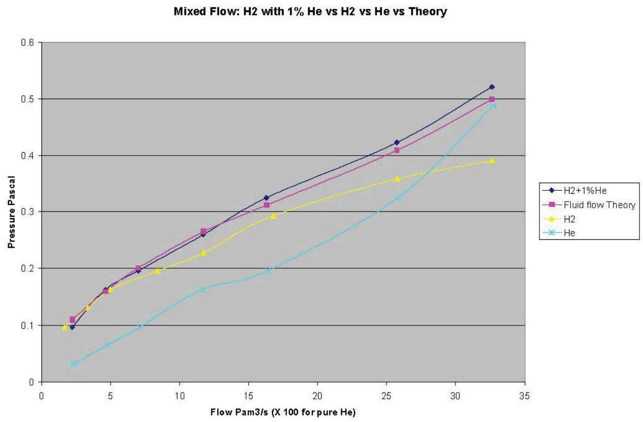

Figure 4. H_2 1% He mixed flow compared to pure H_2 and pure He.

free molecular flow the pressure in the cold chamber is reduced by thermal transpiration to 0.29 Pa. The pressure ratio χ across the cold duct would then be 0.56. These measured values of the backpressures were then used in equation (1) to calculate the test dome pressures, which are in good agreement with the mixed flow results.

By comparing the pressure at the turbomolecular pump for the mixed flow, pure H_2 and Pure He cases an estimate of the quantity of hydrogen in the helium stream can be made. At the throughput level of 32.7 Pam^3/s, the pure H_2 pressure is 0.03 Pa, the pure He pressure (at 0.32 Pam^3/s) is 0.48Pa and the mixed flow pressure is 0.52Pa which is close to the sum of the two pure gas cases. This indicates that in the mixed flow case, the stream at the turbomolecular pump is 92% He and 8% hydrogen; but since the helium is only 1% of the initial stream, 99.92% of the hydrogen has been removed upstream by the cryopump.

Data from tests with deuterium gas are shown in Fig.5. The results were very similar to the hydrogen tests. At 33.7 Pa m^3/s the test dome pressure was 0.39 Pa resulting in an effective pumping speed of 86.1 m^3/s vs. 83.6m^3/s for hydrogen at the same flow. The Snail was operated while

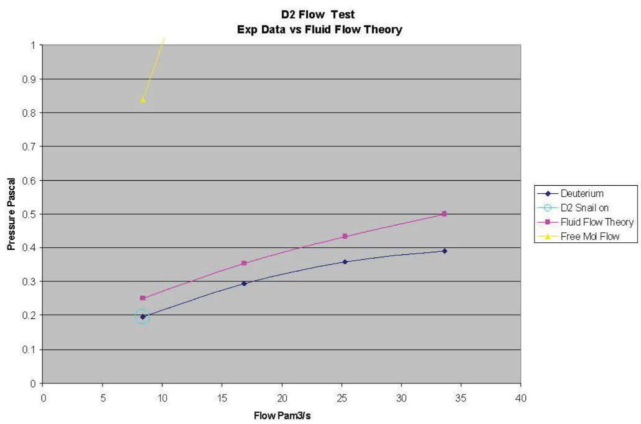

Figure 5. Deuterium flow compared to theory.

pumping deuterium at 8.4Pam^3/s with the test dome at 0.196Pa which was identical to the tests when pumping deuterium with the snail off. This single point is marked with the blue circle.

While limited, the test results demonstrated the key features of the pump. The cold duct operating in fluid flow had very large conductance values which scaled with the inlet pressure in accordance to viscous fluid flow theory. This scaling would allow mass flows up to 250 Pam^3/s at an inlet pressure of 1.0 Pa. The tests also demonstrated the capability of pumping helium at very high speeds using conventional turbomolecular pumps. The pumping speed at the test dome at a throughput of 32.6 Pam^3/s of Hydrogen with 1% helium was 63 m^3/s which; in fluid flow, is the speed for both the hydrogen and helium species. The maximum flow was limited by helium backpressure. Using larger turbopumps should allow mixed flow operation throughout the flow range of the cryodiffusion pump. The tests also demonstrated the capability of separating the hydrogen and helium into pure streams. This would allow the hydrogen stream to be recycled directly back to the diverter [4] as gas or be condensed into pellets for pellet fuel injectors [8]. The helium compression combined with the low value of the hydrogen in the helium stream would also allow a small charcoal cryopump to be used to pump the helium without accumulating large inventories of tritium.

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