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ABSTRACT.

.A cryogenic diffusion pump has been developed and tested. It uses the main constituent of the fusion reactor exhaust gas, i.e. D-T, as a working fluid in a diffusion pump operating at low temperature, to separate and compress the minor constituent ^{4}He.

A prototype was tested using mixtures of deuterium with 1%, 2% and 4% helium. As the deuterium is pumped by cryocondensation at 4K, the entrained helium is staying in the gas phase, is compressed and leaves the pump outlet at pressures up to 80% of the total inlet pressure. Compression ratios of up to 80 (for 1% helium) and inlet pumping speeds ranging from 1 to $2m^3 s^{-1}$ for operating pressures between 3 and 10 Pa have been measured. Deuterium carry-over into the helium exhaust was below the detection limit of the equipment.

A design is presented incorporating the cryogenic diffusion pump in a complete fusion reactor forevacuum system, including the separation of impurities from hydrogen isotope mixtures.

I   INTRODUCTION

In a previous paper [1], the requirements for the primary vacuum system for a tokamak-type controlled thermonuclear reactor with 1-GW thermal output were analyzed. We quote from this paper:

"The need for recovery, purification, and recycling of deuterium-tritium (D-T) fuel to the reactor leads to the following basic requirements for vacuum pumps (i.e. primary pumps) at the reactor exhaust:

- effective pumping speed ~ 250 m^3 s^{-1}
- inlet pressure   ~ 0.1 Pa
- outlet pressure $\geq$ 10 Pa
  (at full flow rate of ~ 25 Pa m^3 s^{-1})
- compatibility with tritium, nuclear radiation, static and dynamic magnetic fields, mechanical shock and up-to-air accidents
- no contamination of pumped gases (primarily D-T and ^{4}He) by vacuum pump media such as lubricants, operating fluids (vapours) or gases other than D-T and ^{4}He."

It was further stipulated, that ideally the vacuum system should perform the major process task to purify and separate D-T fuel from ^{4}He and impurities such as DTO, CO_2, hydrocarbons.

From this analysis accrues the duty of an ideal forevacuum system:

- effective pumping speed $\geq$ 2.5 m^3 s^{-1}

- inlet pressure $\qquad$ $\leq$ 10 Pa

- separation of ^{4}He from D-T fuel and compression to ~ 100 kPa at a
  flow rate of 1.3 Pa m^3 s^{-1}

- purification of D-T fuel and compression to ~ 100 kPa

- collection of impurities for processing to recover tritium

- compatibility with tritium and up-to-air accidents; since a
  forevacuum system can be located in a safe distance from the reactor,
  it can be shielded from nuclear radiation, static and dynamic
  magnetic fields and mechanical shock

- no addition of other gases nor contamination of processed gases by
  pump media.

The development of a cryogenic forevacuum system for the tritium operation
of JET [2, 3] led to a device - the cryogenic diffusion pump - which permits
the design of a forevacuum system meeting above requirements.

II   THE CRYOGENIC DIFFUSION PUMP (CDP) OPERATING PRINCIPLE

The operating principle of the CDP is shown in Fig 1.

A mixture of D-T gas with 1 to 5% ^{4}He and some impurities enters a dip-stick
cold trap with an axial thermal gradient between ambient temperature (top)
and 4 K (bottom). As the mixture thermally accommodates to the wall, the
gas density increases (the mean free path decreases accordingly) and
constituents of the mixture - excluding ^{4}He - are eventually pumped by

cryocondensation. The entrained ⁴He is compressed and can be collected at the outlet at a pressure between 60 to 80% of the total inlet pressure. Thus, the device works as a diffusion pump for ⁴He using only the other constituents of the reactor exhaust as operating medium. A further advantage of this pump geometry: any condensate, which may peel off the cold walls, drops to the bottom of the device and remains safely frozen at 4 K. In conventional cryopumps, such an event would lead to flash evaporation of the condensate and spontaneous defrosting of the pump by thermal conduction between LN_2 shield and 4 K condensation surface.

III EXPERIMENTAL SETUP AND RESULTS

Based on equipment used to test the prototype of a cryogenic forevacuum pump for the JET Active Gas Handling System [3], a demonstration model was built as shown in Fig 2 with the following main features:

- pump diameter 200 mm

- pump length   2000 mm

- diameter of ⁴He return tube 100 mm

- the axial temperature gradient is established in a cooling coil supplied with LHe at the bottom of the device, pumped by a vacuum pump connected to the return line (evaporation cryostat principle).

The inlet was equipped with a gas feed to supply a mixture of deuterium with 0, 1, 2 and 4% helium. The use of tritium would only be possible after commissioning and operational authorisation of the JET Active Gas Handling System. The mixture was prepared in a mixing tank of 500 ℓ volume; gas

-4-

inlet was controlled by a mass flow controller in a range from 2 to 20 Std ℓ min^{-1} (~ 3 to 30 Pa m^3 s^{-1}). The outlet was pumped by a combination of turbopump/mechanical pump, the outlet pumping speed could be manually adjusted by means of a throttle valve from 0 to 0.3 m^3 s^{-1}.

Inlet and outlet pressures were monitored by capacitance manometers. The outlet was also fitted with a cold cathode high vacuum gauge to establish a correct "0" reference pressure for the capacitance manometers and to measure maximum permissible feed flow rates.

The following measurements were performed:

1. Deuterium breakthrough

   With the helium outlet fully closed, deuterium (without helium) was admitted to the inlet and the pressure on the outlet was monitored by the cold cathode gauge. Deuterium "breakthrough", i.e. rise of the outlet pressure to > 10^{-3} Pa, occurred at an inlet flow rate of ~ 25 Pa m^3 s^{-1} at an inlet pressure of 12 Pa. From this result, a safe maximum flow rate of ~ 50% (13.3 Pa m^3 s^{-1}) was selected for all helium separation runs.

2. Helium separation runs with 1%, 2% and 4% He in D$_2$

   At the beginning of each run, a flowrate of 10 Pa m^3 s^{-1} was established with the outlet turbopump throttle valve fully open. Subsequently, the throttle valve was gradually closed until the outlet pressure was at a value of 60 to 80% of the inlet pressure. The helium

flow rate at the outlet was inferred from the total flow rate at the inlet (1, 2 or 4% respectively). With the outlet pressure measured, this resulted in outlet pumping speeds of approximately 30, 60 and 120 ℓ s^{-1} for the respective helium concentrations. With the outlet pumping speed fixed at these values, the inlet flow rate was varied from 2 to 8 Std ℓ min^{-1} (3.33 to 13.3 Pa m^3 s^{-1}).

The result of the average values of all three helium runs is shown in Fig 3, where the inlet pumping speed is plotted against inlet pressure on a linear scale. The linear relationship between pumping speed and pressure indicates that the device operates in the viscous flow regime, where the conductance is proportional to pressure.

The scatter of the data indicated by error bars is mainly due to fluctuations in coolant supply which was only controlled manually, keeping the lower end of the condensation coil at a temperature between 3.5 and 4 K. The temperature was measured by a ^{4}He vapor pressure thermometer welded to the condensation coil.

Judging from the characteristic system dimensions (i.e. the 5 cm wide ring gap between outer wall and helium return line), the viscous-molecular transition flow regime should occur around 0.2 Pa (i.e. mean free path ~ 5 cm). Extrapolation of the measured characteristic as indicated by a dotted line permits to estimate the molecular flow pumping speed of this prototype to about 0.8 m^3 s^{-1}. The range of the mass flow controller used in this experiment (0 to 30 Std ℓ min^{-1}) did not permit to explore this region accurately. This would have required a model of much lower flow rate range (e.g. 0 to 0.1 Std ℓ min^{-1}).

At the end of each run, the test pump was warmed up to 77 K, releasing the condensed D_2. The D_2 was returned to the mixing tank by means of a metal bellows transfer pump. Within the accuracy range of our equipment ($\sim$ 1%), no measurable loss of D_2 was observed. This confirmed, that in the presence of ^{4}He no D_2 was carried over to the helium exhaust.

IV   THE CRYOGENIC DIFFUSION PUMP IN A FUSION REACTOR FOREVACUUM SYSTEM

The experiment has shown, that a cryogenic diffusion pump, using the main constituents of the reactor exhaust as a working fluid, can compress helium to a pressure of $\sim$ 5 Pa with a mixture inlet pressure of $\sim$ 6 Pa. As a consequence, the total ^{4}He production of a 1 GW fusion reactor (i.e. 1.3 Pa m^3 s^{-1}) can be compressed to atmospheric pressure by a backing pump with a pumping speed of $\sim$ 0.27 m^3 s^{-1} or $\sim$ 1000 m^3 h^{-1}. Suitable mechanical pumps for this range are commercially available: dry scroll blowers of the Normetex type are built with pumping speeds up to 1300 m^3 h^{-1}. The selection of such a fully tritium compatible dry pump is necessary: although the results indicate no carryover of D_2 (in a reactor application D-T) in quantities of concern to the process itself, safety considerations require, that the compressed helium is passed through an efficient regenerable hydrogen getter to remove and recover even traces of tritium. The efficiency of this getter can only be maintained by feeding it with pure helium-hydrogen mixtures free of any other contaminants such as air or hydrocarbons.

So far, we have shown that the cryogenic diffusion pump performs the task of separating helium from the remainder of the reactor exhaust. The second

task of separating impurities from D-T can also be performed at cryogenic temperatures: work on a cryotransfer pump for the JET Active Gas Handling System [3] has shown, that distillation of liquid D_2 at temperatures of 20 to 25 K, passing the evaporated D_2 through a large surface area metal packing (such as fine wire mesh or Helipac) at the same temperature, removes impurities to the parts per million level or lower.

Combining all these features, we obtain the complete fusion reactor forevacuum system shown in Fig 4.

While on-line, the cryogenic diffusion pump backs the reactor primary vacuum pump. The D-T and impurity constituents are cryocondensed, ^{4}He is compressed and pumped by a scroll blower. The scroll blower discharges helium through a regenerable hydrogen getter to remove traces of tritium. The pump can stay on-line for a cycle time of 0.5 to 1 hours, during which it condenses between 25 to 50 moles of D-T mixture, containing between 75 to 150 g tritium.

For recovery of D-T, a second pump (not shown) is put on-line, the first one being isolated for regeneration.

D-T regeneration takes place in 4 steps:

1. The pump is isolated and the cryocondensation stage temperature is raised from 4 K to 20 K. D-T liquefies and is subsequently transferred by opening Valves 1 and 2 into the evacuated purification column.

2. Valve 2 is closed. D-T distillation starts in the purification column, delivering pure D-T through valve 3. Simultaneously, a small cryocondensation coil in the cryo-transfer stage is cooled to 4 K, evacuating the remaining D-T gas from the cryodiffusion pump.

3. Valve 1 is closed, the cryo-transfer stage is heated to 20 K and the liquid D-T released to the purification column via valve 2.

4. During this procedure, the D-T condensation stage is being cooled to operation temperature of 4K.

Cycling of the system for D-T regeneration can be done very fast and economically, as it requires only temperature cycling between 4 K and 20 K. A cycle time of ½ h appears feasible. Complete recycling for impurity removal requires warm-up to at least 77 K, possibly to above 300 K, depending on impurity composition. However, with an impurity concentration in the reactor exhaust at or below 1%, this extended regeneration cycle will be necessary only once in 50 D-T regeneration cycles. Depending on recycling temperature, this impurity regeneration cycle may extend to several hours. A fusion reactor forevacuum system will therefore require a minimum of three cryogenic units:

- two for alternating fast D-T recycle
- one for extended regeneration and standby.

V CONCLUSIONS

With its demonstrated characteristics, the cryogenic diffusion pump permits a straightforward engineering design of a fusion reactor forevacuum system. Furthermore, with its features of helium separation and impurity separation it performs the major task of fuel reprocessing. During reactor standby, i.e. at reduced throughputs and in the absence of helium, it is capable of achieving pressures in the UHV range (working as a cryocondensation pump). To complete the fusion reactor vacuum system, only one more step is now required: the development of primary vacuum pumps with compression ratios in the order of ~ 100, bridging the gap between the reactor exhaust at a pressure of ~ 5 x 10^{-2} Pa and the proposed forevacuum system operating at ~ 5 Pa. Prime candidates for this purpose would be the thermo-molecular pump proposed earlier [1] or a simplified turbomolecular pump with the "low" compression ratio of 100. This relaxed design requirement for turbomolecular pumps may well lead to a viable solution compatible with the reactor operating conditions.

Acknowledgements

References

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     J Vac Sci Technol A6(1), Jan/Feb 1988, p.144.

[2] J L Hemmerich, A Dombra, C Gordon, J Gowman, E Groskopfs, R Haange,
     M Huguet, A Konstantellos, E Küssel, M Tschudin, K Walter, The JET
     Active Gas Handling System: Concept and Status, Proceedings 12th
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     2 (IEEE Catalog No 87CH2507-2) p 1235.

[3] E Küssel, J L Hemmerich, The Cryogenic Forevacuum System for the JET
     Active Gas Handling Plant, Fusion Technology, 14 (1988), p 552.
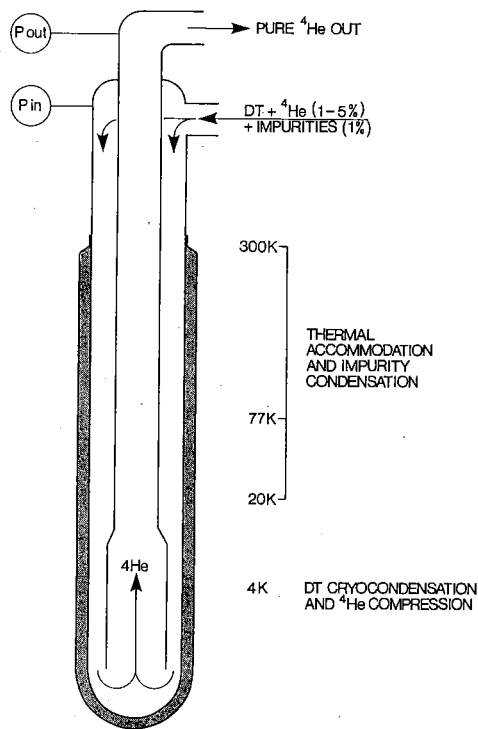
Fig 1   Schematic of cryogenic diffusion pump; the device is based on a
dip-stick cold trap geometry with an axial temperature gradient
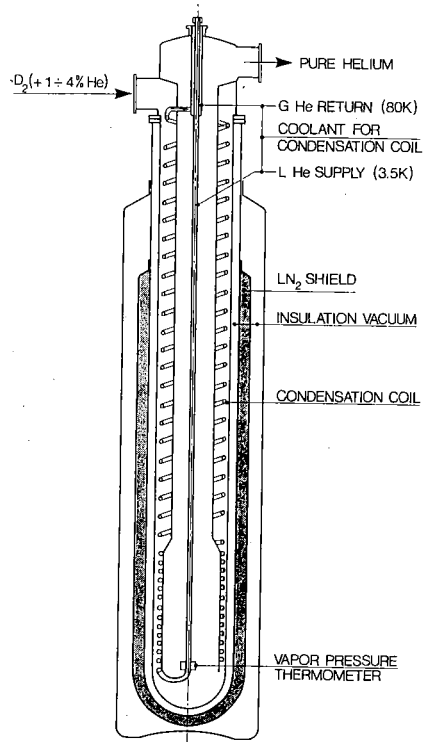ranging from 300 K to 4 K.

Fig 2   Cross-section through the prototype model of a cryogenic diffusion
pump.   The condensation surface is formed by a coiled tube (16 mm O D
x 1 mm wall), supplied with lHe at the bottom.   The axial temperature
gradient is established by counterflow heat exchange between incoming
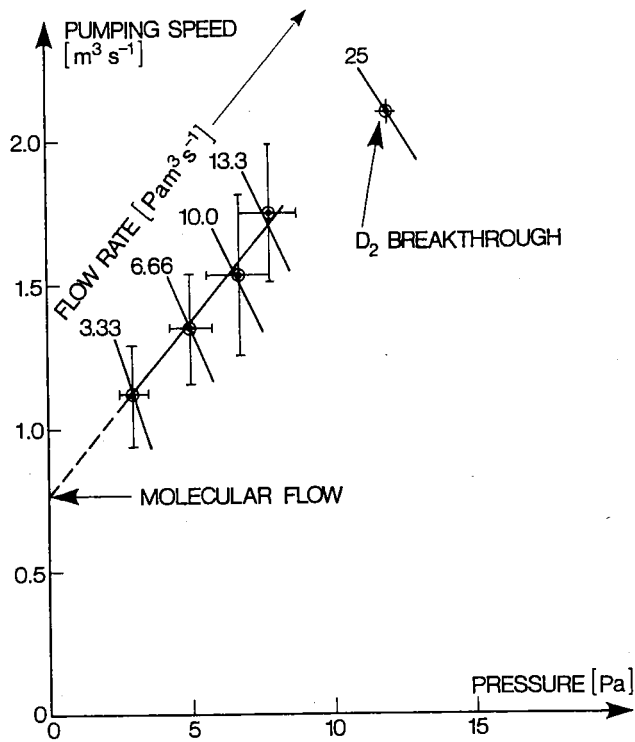gas and evaporated helium in the coil.

Fig 3 Cryogenic diffusion pump performance: pumping speed vs inlet

pressure, on a linear scale. Lines of constant inlet mass flow are

indicated. The data points are values averaged from three runs with

1%, 2% and 4% helium in deuterium. D_2 breakthrough was observed at

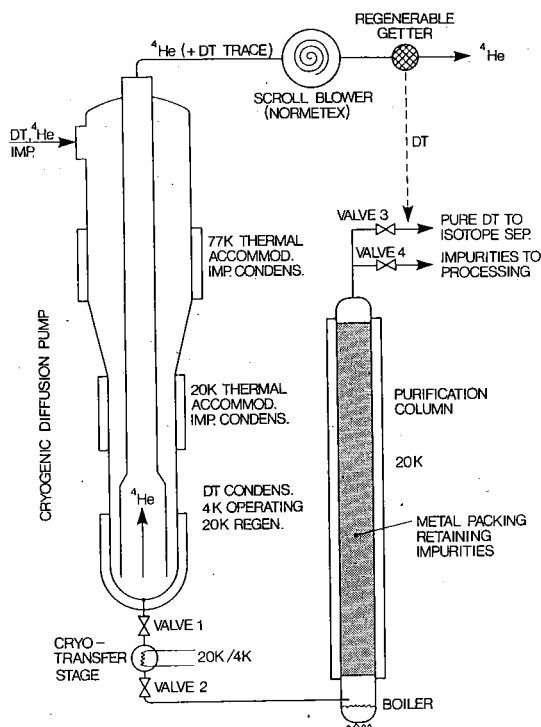an inlet flow rate of ~ 25 Pa m^3 s^{-1}.

Fig 4 Complete fusion reactor forevacuum system featuring the cryogenic

diffusion pump with cryotransfer stage, purification column, backing

pump (Normetex) and regenerable getter for D-T traces in the exhaust

helium.