GA–A22903

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JULY 1998

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This is a preprint of a paper to be presented at the 20th Symposium on Fusion Technology, September 7–11, 1998, Marseille, France, and to be published in the *Proceedings.*

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Work supported by
the U.S. Department of Energy
under Contract DE-AC03-94SF20282,
Subcontract No. ITER-GA-4002
Raytheon Engineers and Constructors
Ebasco Division

GA PROJECT 3994
JULY 1998

Enthalpy Recovery System for ITER Cryopumps

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The primary pumping system of ITER consists of sixteen cryopumps. The cryopanels in these pumps are cooled using supercritical helium (SCHe), at 4.5°K and 4 bar. During plasma operations twelve cryopumps are in pumping mode and four are in various stages of regeneration. The pumping time of each cryopump is limited to 900 s to maintain hydrogen inventories at acceptable levels. During the regeneration phase, a pump is warmed up to ~ 80°K to desorb the gases accumulated on the 4.5°K cryopanel. Following desorption, the cryopump is evacuated with a mechanical pumping system for a period of 75 s to remove desorbed gases. The final phase of the regeneration sequence, lasting 75 s, is to re-cool the cryopanel to 4.5°K. If, during warm up and cool down of the cryopanels, the cold cryogen can not be recovered, the consumption of SCHe will be over 4000l/hr. This can be reduced by about 60% by an arrangement that will allow the enthalpy of a cold panel to be recovered during warm up and transfer this enthalpy to a panel undergoing cool down. The efficiency of this energy recovery will depend on the temperature profiles of the exhaust gases from both the warming and cooling panels. The purpose of this task was to develop an analysis tool to 1) Insure that the warm up and cool down can be carried out in 75 s and 2) to evaluate reduced consumption of SCHe by enthalpy recovery.

A computer model of the ITER cryopump was developed. The model represents the important geometrical features of the pump and solves the transient energy equations for the solid and the fluid. All thermophysical properties are variable with temperature. A similar model has been previously used to design the DIII–D cryopump and shows good agreement between analysis and experiment.

The results show that each cryopump can be cooled from 80°K to 4.5°K in 75 s by using a SCHe flow of about 150 g/s at 4.5°K. The enthalpy recovery system consists of two pumps connected in series: the first undergoing cool down and the second undergoing warm-up. Supply sources are adjusted to achieve the cool down and warm up in 75 s. Such a system reduces the cryogen requirement by about 60%.

1. INTRODUCTION

ITER uses sixteen cryopumps in the primary pumping system. During plasma operations twelve are in pumping mode and four in various stages of regeneration. This regeneration of each cryopump consists of a four stage cycle lasting 300 s with each stage of the process lasting 75 s. During the regeneration sequence, every 75 s, one pump moves from pumping mode to regeneration and another pump, which has completed its regeneration cycle, is returned to its pumping mode. On entering the regeneration phase, a pump is warmed up to ~ 80°K in 75 s to desorb the gases accumulated on the 4.5°K cryopanel. The final phase of the regeneration sequence, lasting 75 s, is to re-cool the cryopanel to 4.5°K before returning to the pumping mode.

The cryopanels are cooled using supercritical helium (SCHe), at 4.5°K and 4 bar. The thermal mass, comprising the 4.5°K panel and the inlet and return piping to the cryogenic valves, is ~160 kg. This thermal mass accounts for an enthalpy change of ~ 1 MJ on cycling from 80 to 4.5°K.

If the enthalpy of a cold panel is recovered by the gas during panel warm up and transferred to a panel undergoing cool down, cryogen consumption could be reduced. In an ideal situation this would result in zero energy being required for the regeneration sequence. The efficiency of this energy recovery will be dependent on the temperature profile of the exhaust gases from both the warming and cooling panels.

2. THE MODEL

Each of 20 cryopanels in a cryopump is cylindrical in shape. Each pump includes a pneumatically driven valve which is used to control the pumping speed and to isolate the pump from the torus during regeneration. For the purpose of this task, it is sufficient to consider that the pump consists of:

1. Entrance piping (8 m)
2. Entrance manifold (3.25 m)
3. 20 cryopump panels which are connected in series/parallel arrangement (6.5 m)
4. Outlet manifold (3.25 m)
5. Outlet piping (8 m)

The mass of valves and other hardware was included as part of the piping. The steady state heat load for each pump is 320 W. A model of two cryopumps connected in series is shown in Fig. 1. The 20 cryopanels of each pump have been connected in a series parallel (4 parallel paths) arrangement. This arrangement is a compromise between trying to achieve highest heat transfer coefficient (all series) and minimum pressure drop (all parallel).

3. FORMULATION

We have used the Lagrangian coordiate system in which the coordinate system moves with the fluid.

Enthalpy for stainless steel and the enthalpy, viscosity, thermal conductivity and Prandtl number for the helium are considered functions of temperature. Since the pressure drop for 4.5°K helium is negligible (0.003 bar at 190 gm/s flow rate per pump), the pressure of helium was assumed constant in this analysis. A single pump model was prepared and mass and enthalpy balance were checked. This was within 99% (the pump was divided into about 1000 divisions and a time step

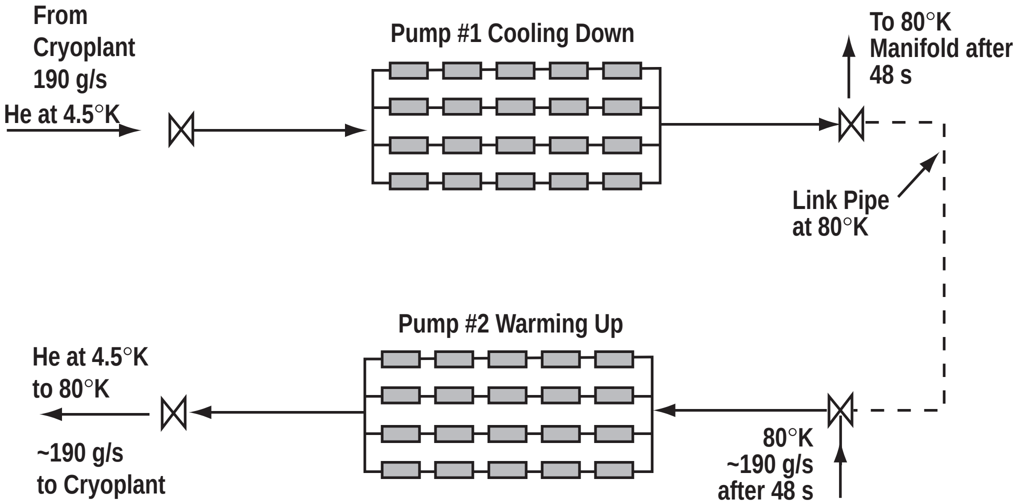

Fig. 1. Model of two pumps connected in series. Each pump consists of 20 cryopanels connected in a series parallel arrangement (model shown for alternate scheme discussed in Section 4).

was less than 0.1 s). A similar analysis previously performed for DIII–D has shown very good agreement with experiments [2].

4. ANALYSIS

The simplest procedure to cool down and warm-up the pumps will be to use supplies of 4.5°K and 80°K helium, respectively. Analysis shows that to do this in 75 s, a flow rate of 150 gm/s is required (Fig. 2). Since one pump out of 16 is always being cooled, consumption of SCHe at 4.5°K will be 4000 l/hour.

We could try to reduce this consumption by recovering some of the (negative) enthalpy stored in the cold pump. Referring to Fig. 1, it is required that pump # 1 be cooled down in 75 s and pump # 2 be warmed up in 75 s. Initial temperature of pump #1 is 80°K and initial temperature of pump #2 is 4.5°K. The link pipe is always at 80°K. Pump #1 receives SCHe supply at 4.5 and is connected in series with pump # 2. In the beginning, flow out of pump #1 will be at about 80°K and outlet from pump #2 will be at about 4.5°K. The outlet from pump #2 could be returned to the cryoplant for recooling. If a flow rate of 150 gm/s is used in this circuit, pump # 1 will cool down to 4.5 but pump # 2 warms up to only 25°K in 75 s. This happens because although the inlet flow to pump #1 is 150 gm/s, the outlet flow from pump #1 (which is equal to inlet to pump #2) is only about 2.7 gm/s due to lower density of helium at 80°K compared to 4.5°K. Thus, this scheme will recover enthalpy from pump #2 without warming up the pump completely. Adding a heater in the circuit also did not achieve the desired result.

An alternate scheme is to increase 80°K flow rate to pump #2 after certain time, called transition time. The outlet flow from pump #2 is always directed to the cryoplant. Outlet flow from pump #1 flows to pump #2 until the transition time after which it is directed to 80°K inlet header. An Additional desirable parameter for the cryoplant operation is a constant outlet flow from pump #2 (which is an input to the cryoplant). Figure 3 has two plots. The first plot shows the transition time at various flow rates in order to keep the outlet flow constant. The second plot shows the transition time in order to achieve complete warm up of pump #2 in 75 s. From this plot we conclude that a flow rate of about 190 gm/s is required in this scheme and the transition time should be about 48 s.

Figures 4 and 5 show the transient variation in axial temperature distribution for pumps 1 and 2. Fig. 6 shows the outlet coolant temperatures from the two pumps achieved with this scheme. The amount of cold cryogen recovered is about 9700 g per cycle. Thus the net cryogen requirement has been reduced to 1640 l/hr. This is a 60 % saving.

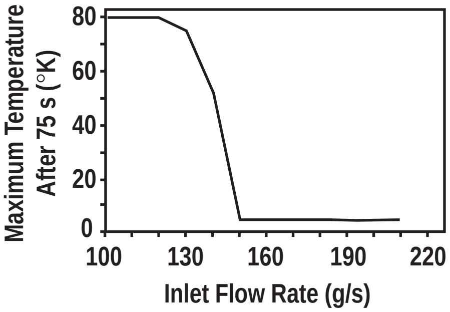

Fig. 2. Inlet flow rate versus maximum cryopump temperature after 75 s. Initial temperature is 80°K and inlet flow is at 4.5°K and 4 bar.

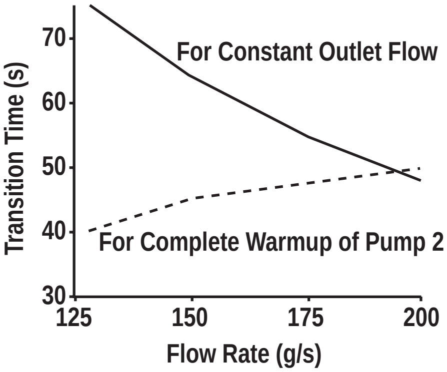

Fig. 3. Flow rate versus transition time. Transition time is the time at which 80 K flow to pump 2 is increased to inlet flow rate. This flow comes from the 80 K header.

The analysis procedure in this work has been verified by experiments during DIII–D cryopump design for two phase helium [2]. It is strongly recommended that work described here be confirmed by experiments.

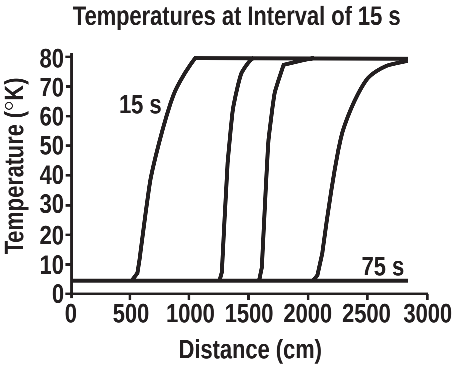

Fig. 4. Cool down of pump 1 with an inlet flow rate of 190 g/s.

5. CONCLUSIONS

1. It is possible to warm up or cool down a ITER cryopump in less than 75 s by proper choice of flow arrangement, flow rate and inlet temperature.
2. By using enthalpy recovery the cryogen consumption for cool down can be reduced by about 60%.
3. A verification experiment is strongly recommended.

ACKNOWLEDGMENT

Work supported by U.S. Department of Energy under Contract DE-AC03-94SF20282, Subcontract ITER-GA-4002, under Raytheon Engineers & Constructors, Inc.

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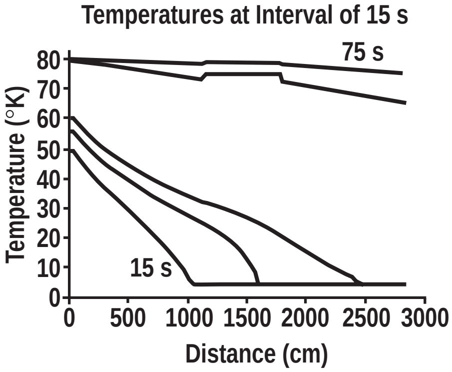

Fig. 5. Warm up of pump 2 with an inlet flow of 190 g/s and transition time of 48 s.

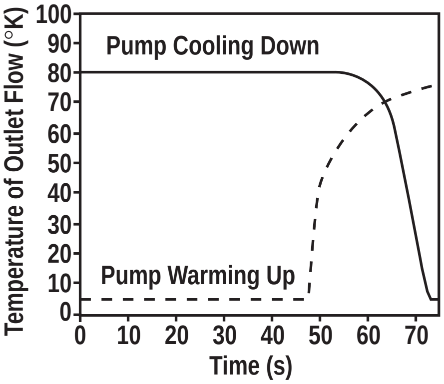

Fig. 6. Temperatures outlet flows from pumps 1 and 2. Flow rate from pump 2 is approximately constant at 190 g/s.