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Donald S. Slack

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A NOVEL SCHEME TO HANDLE HIGHLY PULSED LOADS WITH A STANDARD HELIUM REFRIGERATOR

Don Slack

Lawrence Livermore National Laboratory
University of California
Livermore, California 94551

ABSTRACT

Helium refrigerator performance degrades rapidly when it has to handle a varying or pulsed heat load. A novel scheme is presented to handle highly pulsed 4.5 K cryogenic loads with a standard helium refrigerator by isolating it from these pulses. The scheme uses a relatively simple arrangement of control valves, heat exchangers, and a storage dewar. Applications include pulsed tokamak machines such as TPX (Tokamak Physics Experiment) and ITER (International Thermonuclear Experimental Reactor). For example, the TPX (currently in the conceptual design phase in a DoE contract) requires an average 4.5 K refrigerator capacity of about 10 kW; however, pulsed loads caused by eddy current and nuclear heating will exceed 100 kW. The scheme presented here provides a method for handling these pulsed loads. Because of the simple and proven nature of the components involved and the thermodynamic properties of the helium, the system could be implemented for projects such as TPX or ITER with little or no development.

INTRODUCTION

The scheme uses a partially filled liquid-helium storage dewar to adsorb pulsed heat loads. The pulsed loads cause boiling and associated temperature and pressure increases in the dewar. An arrangement of valves and heat exchangers ensures that the refrigerator does not see these transients, but continues to operate with constant input and output conditions. This is important, since even small changes in operating conditions tend to temporarily destroy refrigerator capacity.

The key to the systems workability involves the fact that the enthalpy of saturated helium gas does not increase, but decreases slightly with increasing

temperature and pressure. Consequently, the heated gas in the storage dewar can undergo isenthalpic expansion through a regulator to a constant-pressure, saturated gas before returning to the refrigerator. Heat pulse energy is adsorbed by a phase change in the partially filled dewar and by the liquid helium in the dewar.

The following example uses average and pulsed loads from a tokamak design to demonstrate how the scheme works. The design used is TPX.^{1,2} TPX recently completed its conceptual design phase, and present plans are to build the machine at Princeton. Design details of component valves and heat exchangers are also discussed. Since these components are relatively simple and proven and the thermodynamic aspects of the cycle (NBS 631 helium tables) are proven, little or no development should be required before constructing the system for applications such as TPX or ITER.

FUNCTIONAL DESCRIPTION OF THE CYCLE

Figure 1 is a schematic of the system. Table 1 shows state point conditions before and after a 5 MJ pulse heat load using a 30 kL dewar. The left side of Table 1 gives state point conditions prior to a heat pulse. The right side gives conditions after a rapid, high energy heat pulse is applied and time is allowed for flow to carry the pulse energy back to the dewar, where it is adsorbed by boiling helium. Conditions within the load during application of the heat pulse are a separate problem reported elsewhere.¹ For the purposes of considering impact on the refrigeration system, we assume here that the heat pulse goes to the dewar instantaneously. This is conservative, since the actual pulse will reach the dewar over a finite, but short, period of time. The current, approximate TPX design parameters are used for the sample problem shown in Table 1 and the following described cycle.

Figure 1. Pulse heat-load leveling system schematic.

Table 1. System State Points Before and After 5 MJ Heat Pulse

State Point	Before Pulse						After Pulse and Flow Carries 5MJ to 30 kL Dewar					
	Temp °K	Press atm	Mass Flow kg/s	Quality %	Enthalpy J/g	Mass g	Temp °K	Press atm	Mass Flow g/A	Quality %	Enthalpy J/g	Mass g
1.	5.4	10	1.0	N/A	17.94	N/A	5.4	10	1.0	N/A	17.94	N/A
2.												
3.		8	1.0	N/A	17.94	N/A		8+	1.0	N/A	17.94	N/A
4.	4.5	8	1.0	N/A	13.44	N/A	5.0	8+	1.0	N/A	15.4	N/A
5.	5.53	5	1.0	N/A	17.94	N/A	5.82	5	1.0	N/A	19.4	N/A
6.	4.42	1.2	1.0	2 Ø	17.44	N/A	4.76	1.6	1.0	2 Ø	19.4	N/A
7.	4.42	1.2	1.0	2 Ø	17.44	N/A	4.76	1.6	1.0	2 Ø	19.4	N/A
8.	4.42	1.2	N/A	0	10.8	1.21E6	4.76	1.6	N/A	0	13.1	1.04E6
9.	4.42	1.2	1.0	100	29.94	4.1E5	4.76	1.6	1.0	100	28.98	5.78E5
10.	4.42	1.2	1.0	100	29.94	N/A	4.76	1.6	1.0	100	28.98	N/A
11.	4.42	1.2	1.0	100	29.94	N/A	4.42	1.2	1.0	95-100%	28.98	N/A
12.	4.42	1.2	N/A	0 (SAT)	10.80	N/A	4.42	1.2	N/A	0 (SAT)	10.80	N/A
13.	4.42	1.2	1.0	100 (SAT)	29.94	N/A	4.42	1.2	1.0	100 (SAT)	29.94	N/A

Assumed TPX Load Conditions

Steady State—4 kW. This includes house keeping loads such as conduction, thermal radiation heating and equivalent current lead losses.

Pulse loads—5 MJ During a 30 s Period Every 830 s. This includes heating from eddy currents and nuclear radiation during ramp up and plasma burn.

This gives a total average refrigerator load of:

$$5 \text{ MJ}/830 \text{ s} + 4 \text{ kW} = 10 \text{ kW}$$

Cycle Description

Referring to Figure 1 and Table 1, helium flows from the refrigerator at state point (1). Back-pressure regulator BPR1 maintains the refrigerator discharge pressure constant under varying downstream conditions. BPR1 is set so pressure at (1) is always greater than downstream pressure (3). Pressure at (3) will vary some with changing load conditions since higher heat inputs will increase pressure drop across the load. By maintaining constant pressure at (1), a constant mass flow is assured from the helium refrigerator.

Heat exchanger HX1 reduces helium temperature going to the load to the lowest system temperature (i.e. 4.42 K or slightly above) to minimize the temperature at the load.

Steady state load Q_s and pulsed load Q_p raise the enthalpy and temperature at (5). Table 1 shows the values for state point (5) before and after the pulse, but not during the pulse. Conditions within the load during the pulse are a separate problem. In the case of TPX or ITER, sufficient helium inventory is required in the magnets to adsorb the heat pulse without excessive temperature rise. Here we are only concerned about this heat pulse when it returns to the dewar.

Back-pressure regulator BPR2 maintains a minimum pressure on the load. This ensures single-phase flow conditions in the load and adequate voltage stand off in the supercritical helium. In Table 1, we arbitrarily choose 5 atm to ensure good dielectric strength of the helium.

Heat exchanger HX2 cools the hot return gas during the pulse to near saturation temperature and prevents it from stratifying in the top of the dewar. HX2 also transfers the 5 MJ heat pulse to the dewar liquid. In the example of Table 1, this results in the dewar pressure rising from 1.2 to 1.6 atm, as calculated using mass and energy balance equations.

Gas returning to the refrigerator passes through HX3. This ensures that the return gas is reduced to saturated temperature even if the inlet at (9) is in a warmer gas pocket near the top of the dewar.

The saturated gas at (10) returning to the refrigerator passes through reducing regulator R3. R3 senses downstream pressure and ensures a constant return pressure to the refrigerator. The key to how the system functions is the fact that the enthalpy of the higher pressure saturated gas at (10) is slightly lower than saturated gas at the lower refrigerator return pressure. Two-phase flow will occur at (11) and a small amount of liquid will separate out in phase separator D2. Constant pressure (1.2 atm in this example) saturated gas will then return to the refrigerator via (13). Consequently, refrigerator supply and return conditions do not change when substantial heat pulses are applied to the dewar.

Heat exchanger HX4 serves to evaporate the small amount of liquid generated during expansion through R3. It uses condensing heat transfer in the dewar D1 gas volume to boil off accumulated liquid. A liquid-level control stick and electric heater could be used instead of HX4; however, this would add about 5% to the overall cryogenic load in this example.

In summary, the refrigerator sees steady-state conditions during large heat pulses to the load and dewar because the valving and heat exchanger arrangement provides constant pressure, saturated vapor return to the refrigerator and constant pressure control from the refrigerator.

COMPONENT DETAILS

Pressure Control Regulator R3

Accuracy of the pressure regulator R3 (Figure 1) is important. It controls return pressure, thus temperature, of the saturated gas returning to the refrigerator. It is the key to ensuring that the refrigerator sees constant conditions regardless of changing conditions at the dewar and load. Ideally a pressure control on the order of ± 1 Pa (0.01 atm) is required. Figure 2 shows a regulator design that can achieve this. It is a dome load type that uses a large

sensing piston to achieve the required accuracy. Regulated, downstream pressure acts on one side of the sensing piston, and an accuracy-controlled dome loading pressure acts on the other side. Dome loading pressure is supplied by a small, highly accurate, commercially available regulator designed for this purpose, such as manufactured by Bellofram, Inc. Upstream pressure acting against the valve is balanced by a balancing piston of equal area. This ensures that regulated pressure is not affected by upstream pressure changes at the dewar.

The regulator could consist of a commercially available cryogenic long-stem valve fitted with the room-temperature sensing piston shown. A pressure tap from the downstream flow provides helium to the sensing piston. This helium is warmed to room temperature before reaching the piston. Thermal oscillations associated with these taps must be considered. However, this phenomenon is well understood, and the regulator geometry can be designed to avoid it.³

D1 Storage Dewar

The dewar in this example is arbitrarily sized at 30 kL. This results in a pressure rise from 1.2 to 1.6 atm when subjected to a 5 MJ heat input. A larger dewar would permit a lesser pressure rise or greater heat input. The dewar must be designed to handle the anticipated pressure rise and incorporate the heat exchangers and internal plumbing, shown in Figure 1.

Figure 2. Dome load-reducing regulator functional schematic

D2 Phase Separator

The purpose is to separate the slight amount of liquid generated by expansion through regulator R3 and ensure that only saturated gas at a constant pressure is returned to the refrigerator. Some care is required in its design. The neck extending into D1 should be sufficiently small to limit convective heat transfer from the warmer gas in D1 to flow returning to the refrigerator.

BPR1 and BPR2 Back Pressure Regulators

BPR1 ensures that the refrigerator sees a constant discharge pressure. This further ensures a constant mass flow from the refrigerator, so long as the refrigerator parameters, such as compressor slide valve settings, are not changed. BPR2 maintains pressure at the load. They are similar to R3, with sensing modified for back-pressure control.

HX2 Heat Exchanger

HX2 prevents superheated return gas from stratifying in the top of the dewar.

HX3 Heat Exchanger

Pockets of superheated gas can possibly occur near the top of the dewar. Boiling caused by the heat pulse can force existing gas in the dewar upward without complete mixing of the gas phase. In this case, heat of compression will tend to superheat gas in the upper part of the dewar in a somewhat isentropic process. This purpose of HX3 is to ensure that the gas is recooled to saturation temperature before returning to R3 and refrigerator.

HX4 Heat Exchanger

This uses condensing heat transfer from the 1.6 atm, 4.76 K gas in D1 to boil off 1.2 atm, 4.42 K liquid in D2. Alternately, a liquid level stick and electric heat could be used, however, this would add several hundred watts of 4.5 K load in the sample case presented here.

SUMMARY

A scheme is presented that permits a conventional helium refrigerator to operate under steady-state conditions, while handling highly pulsed heat loads. It involves a simple valving, heat exchanger, and storage dewar arrangement. It utilizes the unusual property of helium that enthalpy of the saturated vapor decreases as temperature increases. An important application is in tokamak fusion machines, such as TPX and ITER, where highly pulsed cryogenic loads are unavoidable.

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