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CRYOGENIC PERFORMANCE OF A SUPERFLUID HELIUM RELIEF VALVE FOR THE LHC SUPERCONDUCTING MAGNETS

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ABSTRACT

The high-field superconducting magnets of the Large Hadron Collider (LHC) project at CERN will operate below 1.9 K in static baths of pressurized helium II. In case of resistive transition ("quench"), the resulting pressure rise in the cryostats must be limited to below their 2 MPa design pressure. This is achieved by discharging helium at high flow-rates into a cold recovery header, normally maintained at 20 K. For this purpose, we have designed, built and tested a cryogenic quench relief valve with a nominal diameter of 50 mm and an opening time of below 0.1 s. The valve, which can be opened on an external trigger, also acts as a relief device actuated by the upstream pressure when it exceeds 0.4 MPa. In normal operation, the closed poppet must be helium-tight, for hydraulic and thermal separation of the magnet baths from the recovery header. Following mechanical qualification tests under vacuum, we have mounted the relief valve in a dedicated cryogenic measuring bench, in order to perform precision thermal measurements with pressurized helium II.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is based on the large-scale use of superconducting high-field magnets [1]. They will be operated at a temperature below 1.9 K in pressurized helium II. The high cost of low-temperature refrigeration imposes strong requirements on cryogenic components to minimize heat loads. Independent studies of these components in dedicated heat leak measuring benches are carried out in order to optimize the system [2]. The quench relief valve developed at CERN [3], has been tested in a thermal

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measuring bench. The objective of these tests was to measure heat and mass leak of the valve under normal operating conditions.

VALVE DESIGN

In LHC, two quench relief valves are installed inside the cryostat vacuum every 53 m. In case of a quench, each valve has to discharge about 400 l of liquid helium into a recuperation line kept at 20 K. The valve is controlled by the quench detection signal via an electro-pneumatic actuator mounted outside the cryostat. The valve and actuator are connected through a metal rod sealed to the cryostat tank by a bellows feed-through. If the quench signal fails the valve opens once the pressure setting is reached. A cross-section of the relief valve is shown in figure 1.

Figure 1. Cross-section of the quench relief valve.

EXPERIMENTAL SET-UP

The measuring bench

The quench relief valve was mounted in a specially built cryostat to simulate LHC conditions (see Figure 2). The cryostat contained three cryogenic reservoirs filled with nitrogen, normal liquid helium (4.2 K, 1 bar) and saturated superfluid helium (~ 1.6 K). Thermal screens at 80 K and 5 K shielded the valve from thermal radiation. The cell (magnet side of the valve) was cooled by the saturated He II - bath of the cryostat through a copper plate which served also as a calibrated thermal impedance (heatmeter) [4]. In order to maintain one bar in the cell, it was connected to the He I - reservoir of the cryostat via a capillary tube of 1.5 mm inner diameter and a length of about 1 m.

In our experiment, the heat flow was measured as a function of the temperature difference of the two He II - baths (T1 and T2 in figure 2). For the calibration of the heatmeter, the valve was replaced by a steel cylinder, in order to avoid parasitic heat load. A heater inside the cylinder was used for the calibration to generate the temperature difference over the two temperature sensors. As the main thermal impedance of the heatmeter comes from the Kapitza resistance on the two faces of the copper plate, which varies strongly with the temperature, the temperature T1 was kept constant at 1.65 K. With T2 = 1.80 K, the temperature difference over the heatmeter was 0.15 K, which corresponds to a heat flow of 800 mW. The temperature in the recuperation line, T3, was controlled with a heater piloted through a PID regulator.

Figure 2. Schematic view of the quench valve mounted in the cryogenic measuring bench.

Instrumentation and data acquisition

Temperatures were measured with PT100 platinum sensors above 30 K and Allen-Bradley carbon resistors below 30 K. Two precision current sources were used to send a current of 10 μA and 100 μA through the carbon and platinum sensors respectively. A personal computer equipped with a multifunction card and IEEE card performed the data acquisition under LabVIEW 2.2 [5] where the multifunction card was used for monitoring and regulating temperatures. For the heatmeter measurements, a digital multimeter/scanner (DMM) was used to ensure a high accuracy.

RESULTS AND DISCUSSION

Heat leak

Experiments were performed to measure the mass leak and the heat leak as function of the temperature at the end of the recuperation line, T_3 in Figure 2. With the recuperation line closed, i.e. no flow of helium through the valve, the pressure became stabilized at 80 mbar. This overpressure originates from the fountain effect [6]. The liquid helium level behind the poppet was measured with three carbon resistors (Figure 3) where the lowest one was found to be at the λ -point. The heat load was measured as function of the temperature at the end of the recuperation line and the result is shown in figure 4. At 20 K, the heat load reached about 850 mW.

Figure 3. Schematic view of the positions of the heater and the three level indicators (carbon resistors) on the outside of the poppet.

Later, the recuperation line was opened and the mass flow through the valve was measured outside the cryostat with a mass flowmeter. The mass flow through the valve was

8×10^{-6} kg/s (160 L/h STP). The overpressure in the recuperation line was now 40 mbar due to the flow resistance of the flowmeter, and the heat leak dropped to 600 mW ($T_3 = 20$ K). This decrease of the heat load can be explained with a change of the convection conditions in the recuperation line when there was a mass flow. Helium leaking through the valve has to be replaced by helium from the 4.2 K reservoir. The supplementary heat load due to cooling that helium from 4.2 K to 1.8 K (~ 65 mW) was totally offset by forced convection.

Figure 4. The heat load as a function of the temperature in the recuperation line, T_3 , with no mass flow across the valve.

Leak rate as function of poppet pressure

The leak rate was first measured for different poppet pressures at room temperature and with a pressure drop over the valve of 1 bar. A pump with a capacity of $8 \text{ m}^3/\text{h}$ at 10^{-2} mbar was connected to the recuperation line (see Figure 3). The leak rate as a function of poppet pressure is showed in figure 5. There were no measurements below ~ 1.5 bar as the valve spring starts to open the valve at this value.

The mass leak was then measured at 1.9 K for poppet pressures between 3 and 6 bar with $T_3 = 20$ K with a mass flowmeter connected outside the cryostat (see Figure 2). The mass leak was found to be 8×10^{-6} kg/s (160 L/h STP) and independent of the poppet pressure within 10 %, which is two orders of magnitude higher than at room temperature. The difference in pressure between the magnet side the recuperation side was 40 mbar caused by the pressure drop over the flowmeter. When the counter pressure over the valve poppet was eliminated, the mass flow increased to 16×10^{-6} kg/s (280 L/h STP).

Figure 5. Mass flow through the valve as a function of poppet pressure at room temperature and under superfluid helium conditions. Note that during the measurement at 293 K the pressure in the recuperation line was 10^{-2} mbar while in the cell the pressure was 1 bar.

CONCLUSIONS

The heat leak at nominal LHC conditions, i.e. $T_3 = 20$ K and no mass leak through the valve, was measured to 850 mW. The pressure difference over the valve poppet was measured to be 80 mbar. As there was superfluid helium present behind the poppet, this pressure difference can be explained by the fountain effect. Therefore, a counter pressure was needed to prevent a flow of superfluid helium. When the counter pressure was eliminated, a significant mass leak of 16×10^{-6} kg/s (280 L/h STP), while the heat leak decreases to 600 mW.

The tests in the measuring bench simulated ideal operating conditions of the LHC dipoles. The tested valve is the first prototype and improvements will be necessary. Under real operating conditions, impurities will deposit on the poppet seat while the valve is open and change the tightness of the valve. Therefore, further investigation of the real conditions in the dipole magnets has also to be undertaken.

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