Testing superconducting magnets for the Large Hadron Collider (LHC) in superfluid helium requires large-capacity refrigeration at 1.8K. At CERN, this is provided by a combination of a cold compressor and a set of warm vacuum pumps capable of handling up to 18g/s at 1 kPa suction pressure. The cold helium vapour, after the cold compressor, is warmed up from about 5K to ambient temperature in a 32 kW electrical heater. The device is designed to operate reliably at flow rates varying from 1 to 18g/s, inlet pressure of 1 kPa to 3 kPa, with pressure drop 100 Pa. Design and construction of the heater, completely realised at CERN, are presented, as well as measured performance. Some technological problems are discussed.

Requirements

The main functional requirements, which lead to the choice of the above mentioned parameters were:

a) heat exchange at low pressure
b) low pressure drop
c) long operational life and reliability
d) quick reparability

In order to reach a compromise for these requirements, an assembly of two cartridges of modules consisting of parallel copper plates heated by electrical elements and longitudinally rubbed by the gas flow was chosen. This solution requires to ensure a good thermal contact between copper plates and electrical heating elements. Type of the heating element and his electrical connection with power cable must exclude any corona discharge possibility, (1).

Design and construction

The heater in its vacuum vessel is shown in Figure 1. The two cartridges are installed in series and each one include six modules screwed together. Each module consists of two copper plates (one flat and one "C" shaped) welded longitudinally together and forming an oblong channel. The heating element is brazed on the flat plate. The total heat exchange area is 10 m², the total number of heating elements is 12, each of them powered up to 2.65 kW. The chosen geometry ensures low pressure drop and low maximum working temperature. Two spare heating cartridges are kept ready for possible replacement in few hours.
The flexible, vacuum-tight shielded, heating element consists of a resistive wire prolonged on both of its ends by "non" resistive wires, placed in a continuous stainless steel tube and electrically insulated with ceramic powder. Both ends of this unit are tightly closed by ceramic feedthroughs*. The length of the resistive part of the heating element is 5.55 m, the length of its "cold" ends is 2.5 m. The shaped heating element without its ceramic feedthroughs is put on the copper plate of 1.5 m length, 280 mm width and 1.5 mm thick and covered by copper bars in which were machined a channel for the heating element of 4 mm external diameter; and oblong holes for brazing material, see Figure 3. Afterwards the heating elements are brazed with an Ag alloy at about 800°C to the copper plates in a vacuum furnace. To ensure a good quality of brazing, the stainless steel sheath of the heating element is Ni plated. As the brazing area is enclosed in the copper bar, the quality of brazing could be degraded by oxygen released by standard copper. It is therefore preferable either to use OFHC copper or to thermally treat standard copper in vacuum to reduce its oxygen content. After brazing, the "cold" ends are cut to the required length. Stainless steel fittings are brazed on the "cold" ends of each heating element to be fitted to vacuum tight feedthroughs, welded to the flange of the cartridge (C in Figure 1). The same system of seal is used for mineral-insulated, metal-sheathed thermocouples and Pt thermometers. Both terminations are finally plugged by ceramic feedthroughs brazed to them. Eventually an insulation test is performed to check the electrical strength of mineral insulation. Before assembling, each complete module is tested in low pressure gaseous helium at its full power. To avoid frosting of the cartridge flange when cold helium gas is flowing, a few baffles have been installed between the heating modules and top flange.

The temperature of each heating element is measured by K type thermocouples. Signals from these thermocouples are used to display measured temperatures and trigger hard-wired interlocks in case of excessive temperature. Earth current and frost detections are also triggering hard-wired interlocks. Pt 100 and Pt 1000 resistance thermometers measure helium gas temperature at outlet and inlet, respectively. A Programmable Logic Controller handles alarm in case of high temperature of the gas, and calculates the driving signal to be sent to the Pulsed Width Modulation power converter of the three-phase 400 V power supply. This signal is equal to the algebraic sum of a PID algorithm based on outlet temperature deviation and the required power calculated from measured mass-flow and temperature difference.

**Calculated and measured parameters**

To obtain a uniform distribution of flow through the heater, all 22 channels have nearly the same hydraulic diameter (30 mm). For the designed geometry, heat exchange and pressure drop were calculated (2) assuming linear longitudinal temperature gradient in the gaseous helium, constant exchanged heat along the heater, constant temperature of heating

* The heating elements were manufactured by Thermocoax and delivered by Dimeca
plates in each transversal section, constant temperature of gaseous helium in each transversal section and the two cartridges in line. Calculations were done for helium inlet temperature of 5 K, outlet temperature of 300 K and for flows of 6 g/s at 1.1 kPa and 18 g/s at 3.1 kPa.

Calculated temperature gradient of heating plates for 6 g/s is presented in Figure 4, for 18 g/s in Figure 5. In additional Figure 4 and 5 shows calculated and measured temperatures of heating elements. The difference between calculated temperature of heating elements and calculated temperature of heating plates is due to the temperature gradient in each cross-section of the module. Calculated heater pressure drops are presented in Figure 6. The changes in direction of the flow and connecting pipework produce an additional 50 Pa (calculated). Measured values of the total pressure drop for mass-flows between 3 g/s and 8.5 g/s were nearly independent on the flow. Average measured pressure drop was 110 Pa.

Conclusion
The measurements confirmed the required pressure drop and temperature of the heating elements. The heater and its power control is able to work very reliably even at pressures down to 50 Pa. For the maximum helium flow of 18 g/s the warmest heating element temperature never exceeded 200°C. The heater has been working more than one year at pressures between 0 and 1 kPa and flows varying between 0 and 18 g/s.

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