**PERFORMANCE ASSESSMENT
OF 239 SERIES HELIUM SUB-COOLING HEAT EXCHANGERS
FOR THE LARGE HADRON COLLIDER**

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Abstract

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These components are of compact design, featuring low-pressure drop and handling very low pressure vapor at low temperature.

Following a qualification phase of prototypes, a contract has been placed in European industry for the supply of 239 heat exchanger units. Different levels of extracted heat load require three different variants of heat exchangers.

This paper will describe the manufacturing phase with emphasis on the main difficulties encountered to keep the production quality after a brief recall of the prototype phase. Finally, the acceptance tests performed at room temperature and at the nominal cryogenic condition at the factory and at CEA-Grenoble will be presented.

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ABSTRACT

Helium sub-cooling heat exchangers of the counter-flow type are used to minimize the vapor fraction produced in the final expansion of the 1.9 K distributed cooling loops used for cooling the superconducting magnets of the Large Hadron Collider (LHC).

These components are of compact design, featuring low-pressure drop and handling very low pressure vapor at low temperature.

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KEYWORDS: LHC; sub-cooling; heat exchanger

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INTRODUCTION

The superconducting magnets of the LHC [1] under construction at CERN will be cooled at 1.9 K by distributed cooling loops working with saturated two-phase helium, and supplied with cold supercritical helium. In order to minimize the vapor fraction produced in the final expansion, 223 counter-flow heat exchangers will be needed. These sub-cooling heat exchangers will be housed in the valve boxes of the cryogenic distribution line [2] which runs all along the 27-km circumference of the LHC ring. Different heat loads require three different variants of heat exchangers:

- 190 units of HXA type with a capacity of 4.5 g/s for the so-called “standard arc” cooling loops;
- 29 units of HXD type with a capacity of 8 g/s for the so-called “dispersion suppressor” cooling loops, located at the end of each arc;
- 4 units of type HXI with a capacity of 20 g/s for the so-called “inner triplet” cooling loops, located around the beam collision points.

239 units sub-cooling heat exchangers have been manufactured by a French company (DATE): 223 are integrated in the cryogenic distribution line (QRL) and 16 are spare. As only a few tests and performance measurements have been performed on HXD and HXI heat exchangers, and due to the small number of exchangers of this type, this paper will solely deal with the HXA series.

MAIN TECHNICAL SPECIFICATION

These heat exchangers have to subcool by counter-flow the incoming flow of supercritical (SC) helium, using the very low-pressure (VLP) vapour returning from the magnet cooling loop at around 1.8 K. FIGURE 1 shows the flow scheme of the heat exchanger circuits. To fulfil CERN specifications, the heat exchangers shall comply with constraints on thermal efficiency and pressure drop of the different streams.

The heat exchanger shall operate at nominal and reduced capacity. TABLE 1 gives the imposed inlet conditions as well as the functional requirements which must be fulfilled by the heat exchanger in steady-state operation mode for which the mass-flow in the two streams is equal. For any operation mode, on the VLP stream, the pressure drop shall remain below 100 Pa. This restrictive specification is imposed by the pumping facility and is the necessary condition to guarantee the temperature of 1.9 K in all the LHC magnets. Concerning the SC stream, the maximum pressure drop in any operation mode shall not exceed 20 kPa. In addition, the heat exchanger must show limited longitudinal thermal conduction to reduce irreversibilities at very low temperature.

FIGURE 1. Subcooling heat exchanger flow-scheme.

TABLE 1. Steady-state operation conditions for HXA type.

Conditions		Units	Operation mode	
			Nominal	Reduced
Process points Imposed by CERN	Inlet SC pressure	[kPa]	240 to 360	240 to 360
	Inlet SC temperature	[K]	4.9	4.9
	Inlet SC flow-rate	[g/s]	4.5	1.5 to 4.5
	Inlet VLP pressure	[kPa]	1.64	1.64
	Inlet VLP temperature	[K]	1.8	1.8
	Inlet VLP flow-rate	[g/s]	4.5	1.5 to 4.5
To be fulfilled by the heat exchanger	Outlet SC temperature	[K]	≤ 2.2	≤ 2.2
	VLP stream pressure drop	[Pa]	≤ 100	≤ 100
	SC stream pressure drop	[kPa]	≤ 20	≤ 20

As the subcooling heat exchangers have to be integrated in the QRL they must fulfil several constraints [2]. The heat exchangers must be placed vertically with the warmer end located at the top. The overall height must be less than 450 mm and the standard cross-section must not exceed 120 mm x 120 mm.

PROTOTYPE PHASE

Three manufacturers developing each a different technology (stainless steel plate heat exchangers, perforated copper plate heat exchangers and coiled tube heat exchangers) were qualified for the prototype phase [3]. Each of them provided two prototypes which were tested at their nominal conditions in CEA-Grenoble. For their qualification, thermal performance as well as pressure drop were measured. The three manufacturers fulfilled the requirement of CERN specification. On the bases of lower price, the contract for the series was adjudicated to DATE, La Motte d'Aveillans (France). As the prototype heat exchangers supplied by DATE presented a pressure drop at low temperature close to the maximum allowed by the CERN specification, it was decided for the series production to shorten the active length by 30 mm to optimize their thermo-hydraulic performance.

ENGINEERING DESIGN

The heat exchangers developed by DATE are of stainless steel plate type and due to space constraints they are of very compact design (see FIGURE 2). They consist in a stack of 36 stainless steel plates oriented parallel to the flow direction. The plates are 0.6 mm thick (nominal value) and permit a good thermal exchange between the streams while keeping longitudinal conduction low. The very low-pressure (VLP) channels and supercritical (SC) channels are respectively 1.0 mm and 0.6 mm wide. The length of the plates is 220 mm. The width of the channels is kept constant due to small mechanical indentations regularly embossed on the plates. The stack of plates is then TIG welded. The trade-off between pressure drop and thermal performance depends mainly on the VLP channel width, the number of plates and their length. The warmer end is located at the top, and the colder end at the bottom.

FIGURE 2. Stainless steel stack during construction phase and view of a completed DATE heat exchanger

FABRICATION PHASE

The fabrication of the heat exchangers was carried out in 3 years, from September 2001 to September 2004. The heat exchangers were produced in batches of ten units each. The global production consisted of 21 unit batches.

The first period of the fabrication was devoted to the finalization of the quality assurance procedures, namely those concerning the cleanliness and final tests at factory. The first 70 heat exchangers showed problems of cleanliness. The inspection test at CERN confirmed the presence of metallic particles and dust from the inner regions of the heat exchangers and as a consequence they had all to be re-cleaned. The revised cleanliness procedure was then based on a forced flow circulation with a specific product (Solvane 30 made by DACD, St. Marcel les Valence, France). Following the problem on quality assurance the production was stopped for about one month in the first quarter of 2002. An inspector was also sent by CERN to DATE for the follow-up of the production.

As several heat exchangers of the first batches tested at cryogenic temperature showed SC outlet temperature at the limit of the specification (see FIGURE 8), it has been decided to increase the length of the body by 15 mm (from 220 to 235 mm) to improve the thermal performance of the HXA. As a consequence the pressure drop increased by about 25 %, while still remaining within the specification. About 140 heat exchangers have been built with increased body length.

At the end of 2002, thermo-hydraulic tests of the last produced batch showed degraded thermo-hydraulic performance. Several investigations on the test bench, cleanliness procedures and fabrication sequence have been made. Insufficient compression strength on the stainless steel plates was identified as the main cause for the unexpected thermo-hydraulic performance. This batch was produced with thinner stainless steel plates (0.53 mm instead of 0.57 mm) for which a lower compression strength was applied to keep the same external width. This lower compression strength created deformations of the plates during the welding operation, producing singularities and additional pressure drop. The error was corrected and the following batch showed acceptable performance.

PERFORMANCE TESTS

Reception tests have been performed at the factory and at CEA-Grenoble. The thermo-hydraulic performance of the heat exchangers were estimated from measurements of the mass-flow rate and outlet temperatures and pressures of the VLP and SC circuits.

FIGURE 3. VLP pressure drop at room temperature at the factory.

Tests at Room Temperature at the Factory

The whole production of each type of heat exchangers has undergone flow tests at ambient temperature with the same Reynolds number. Pressure drops on each channel were measured, adjusted to correct inlet condition variations and compared to the mean value (see FIGURE 3). For each batch the heat exchanger showing the largest deviation from the specified requirements, was selected to be tested at nominal cryogenic conditions. The DATE test bench was equipped with a double-stage air blower capable to provide the necessary mass-flow rates and pressure ratio to test at identical Reynolds number all types of heat exchangers. During the tests, the SC stream was pressurized up to 0.3 MPa in order to simulate the pressure forces and associated deformations on the plates during normal operation.

Tests at Room and Cryogenic Temperature at CEA-Grenoble

22 HXA heat exchangers (one per batch) were tested at CEA-Grenoble at room and cryogenic conditions. Using an existing liquid nitrogen storage tank and an atmospheric heater to produce nitrogen gas at 300 K, a test facility was set up in CEA-Grenoble to measure the VLP pressure drop of the HXA heat exchangers (see FIGURE 4). During the tests, the SC stream was pressurized up to 0.3 MPa in order to simulate the pressure forces and associated deformations on the plates during normal operation.

For the cold tests, a dedicated test bench [4] had been set-up in CEA-Grenoble, in order to test the HXA type heat exchangers (one per batch) at their nominal mass-flow rate, pressure and temperature conditions and also at low mass-flow rate operation mode. In case of performance below the specification the whole batch had to be rejected. FIGURE 5 summarizes the results obtained for the VLP pressure drop measurements. To compare the measured values to the specified ones, the measured values have been adjusted to take into account the specified conditions at the inlet of the VLP streams (1.8 K and 1,64 kPa at 4.5 g/s). In FIGURE 5, the solid line refers to the specified value, whereas the dotted lines represent the averages of the measured values. From FIGURE 5, we can observe the high pressure drop measured for the first BA8 which was rejected by CERN, as well as the increase of pressure drop after the increase of length of the heat exchanger body (from BA7). The values for BA7 and BA8, 2 are still higher than expected due to the finalization of the fabrication process. Apart from the first heat exchanger from the 8th batch (BA8, 1), all the tested heat exchangers fulfilled the specified thermo-hydraulic performance.

FIGURE 4. Set-up for room temperature flow tests at CEA-Grenoble.

However some differences can be observed as illustrated in FIGURE 6 which shows the exchanged heat power across each stream. The difference between the VLP power and SC power represents the heat losses. This difference is not constant and this is mainly due to the uncertainty of the temperature measurements and to the high sensitivity of the estimated power to the precision in temperature measurement (see FIGURE 7). The outlet temperature of the VLP stream is an indication of the thermal performance of the heat exchanger. We notice a difference between the first batches (BA1 to BA8) and the following ones which is due to a higher temperature at the SC inlet (5 K instead of 4.9 K). Such a difference induces an increase of 8 % on the exchanged power which is likely to hide the influence of the increase in length of the heat exchanger body. In addition to this, the SC outlet temperature was always above 2.175 K (see FIGURE 8 where the solid line refers to the specified value and the dotted lines represent the averages of the measured values), which is still higher than T_λ . This confirms that the whole length of the plates takes part in the thermal exchange. The increase in length of the heat exchanger body by 15 mm had a significant influence on the VLP pressure drop. However, the corresponding improvement on the thermal exchange has been difficult to estimate, due to test conditions (unstable SC inlet temperature), uncertainties on measurements and also probably because the increase in thermal exchange was lower than expected.

FIGURE 5. Pressure drop on VLP stream at nominal mass flow.

FIGURE 6. Exchanged heat power at 4.5g/s.

FIGURE 7. VLP outlet temperature.

FIGURE 8. SC outlet temperature.

Comparison of Room Temperature and Cryogenic Measurements

To account for the fact that the heat exchangers operate in vertical position during cold tests and horizontal position during warm tests with corresponding influence on the pressure drop, as well as for the effect of inlet and outlet piping, some adjustment was necessary.

FIGURE 9. Friction factor comparison.

To compare the different measurements made at room and cryogenic temperature, only the pressure difference across the plates of the HXA exchangers has been considered. FIGURE 9 compares the value of the friction factor measured on the three test facilities, for the heat exchanger BA18, taken as an example. We can observe a good agreement between the three test benches: for the same nominal Reynolds number of about 4000, the friction factor is very similar.

CONCLUSION

After a prototype phase, where three European companies were in competition, the contract for the 239 units of heat exchangers has been adjudicated to DATE. The fabrication lasted 3 years, during which 21 batches have been produced. About 10% of the heat exchangers (at least one per batch) have undergone cryogenic tests at nominal and reduced conditions in a dedicated test facility at CEA-Grenoble. Apart from one heat exchanger which has been rejected, all the other tested heat exchangers fulfilled the specified thermo-hydraulic performance. The pressure drop on the VLP circuit was below the specified value of 100 Pa. For the different warm and cold measurements the friction factor at Reynolds number of about 4000 has been compared and the values are in good agreement.

REFERENCES

1. Lebrun, Ph., "Cryogenics for the Large Hadron Collider," *IEEE Trans. Appl. Superconductivity* 10, 2000, pp. 1500-1506.
2. Erdt, W., Riddone, G., Trant, R., "The Compound Cryogenic Distribution Line for the LHC: Status and Prospects," in *Conference Proceedings ICEC19*, edited by G. Gstaal Baguer, P. Seyfert, Narosa, Grenoble, 2002, pp. 59-62.
3. Roussel, P. et al., "Performance Tests of Industrial Prototype Subcooling Helium Heat Exchangers for the Large Hadron Collider," in *Advances in Cryogenic Engineering 47B*, edited by S. Breon et al., American Institute of Physics, New York, 2002, pp. 1429-1436.
4. Roussel, P., Jager, B., Tavian, L., "A Cryogenic Test Station For Subcooling Helium Heat Exchangers - For LHC," in *Conference Proceedings ICEC18*, edited by K. G. Narayankhedkar, Narosa, Bombay, 2000, pp. 319-322.