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EXPERIMENTAL SIMULATION OF HELIUM DISCHARGE INTO THE LHC TUNNEL

M. Chorowski[1], G. Konopka[1], G. Riddone[2] and D. Rybkowski[2]

Abstract

The LHC cryogenic system contains about 100 tons of liquid helium. The highest amount of helium is located in the magnet cold mass (about 58 tons @ 1.9 K, 0.13 MPa), in the QRL supply header C (about 26 tons @ 4.6 K, 0.36 MPa) and in the ring line (about 0.7 tons @ 290 K, 2 MPa). The rupture of header C is one of the failures leading to the worst scenario of helium discharge into the tunnel. To investigate the consequences of this failure an experiment has been performed. This paper presents the layout of the test set-up and compares the experimental results with calculated data.

1 Wroclaw University of Technology, Wroclaw, Poland
2 LHC Division, CERN, Geneva, Switzerland

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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Experimental simulation of helium discharge into the LHC tunnel

Chorowski M., Konopka G., Riddone G.,* Rybkowski D.*

Wroclaw University of Technology, Wyspianskiego 27, 50-370 Wroclaw, Poland
* LHC Division, CERN, 1211 Geneva, Switzerland

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INTRODUCTION

The Large Hadron Collider (LHC) presently under construction at CERN will contain about 100 tons of high-density helium (liquid, supercritical) mostly located in the underground tunnel. The LHC cryogenic system is based on a five-point feed scheme with eight refrigeration plants serving the eight sectors of the accelerator. Helium is supplied to the LHC cryomagnets from the cryogenic distribution line (QRL) via so-called jumper connections (see Fig. 1). The largest amount of helium is located in the magnet cold mass (475 kg per one sub-sector of 214 m length), in the QRL header C (3300 kg per one sector of length 3.3 km) and in the ring line (695 kg per volume of length 27 km). As a result of the performed preliminary risk analysis (PRA) the following few failure modes leading to intensive helium discharge into the tunnel have been identified [1]:

- total break of jumper connection, followed by helium discharge from one sector of header C and one sub-sector of magnet cold mass (3775 kg of the helium)
- break of header C, followed by helium discharge from one sector (3300 kg of the helium)
- break of helium ring line, followed by helium discharge of 695 kg.

Taking into account the probability of each failure as specified in the PRA and the amount of discharged helium, the break of header C has been chosen to analyse experimentally the consequences of helium discharge to the tunnel. This event has been simulated with a 107 m long Test Cell of the cryogenic distribution line [2, 3].

TEST SET-UP AND INITIAL CONDITIONS

The Test Cell comprises a thermal shield cooled by header F at about 70 K and three headers at 4 to 20 K, namely headers B, C and D, where header C is the supply header, while headers B, D and F are the return headers. A DN25 bursting disk (corresponding to a discharge cross-section of about 5 cm^2) opening at 2.3 bar overpressure has been mounted on header C at the interconnection between the service module A and the return box (see Fig. 1 and 2). The vacuum jacket has been protected by a DN100 safety valve, opening at 0.040 bar overpressure, placed at about 5.8 m from the axis of jumper connection of the service module type A (see Fig. 2). To reproduce the LHC conditions as close as possible, a mock-up tunnel has been built around the Test Cell over a length of 40 m. Once the pressure in the header reaches 2.3 bar the bursting disk opens. Then the helium is vented to the QRL insulation vacuum space up to the vacuum barrier at a length of 55 m. Once the pressure in the vacuum jacket reaches 1.04 bar, the safety valve protecting the vacuum jacket opens and the helium discharge begins (see Fig. 2). Initial condition of the helium before the experiment and main dimensions of the test set-up are given in Table 1.

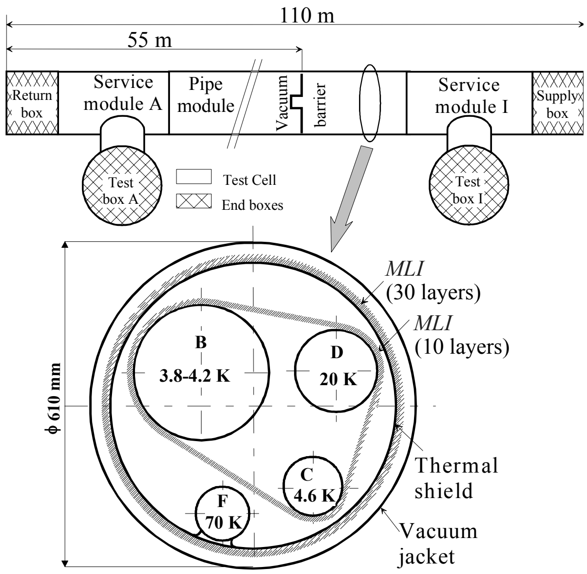

Figure 1 Simplified layout of the test cell.

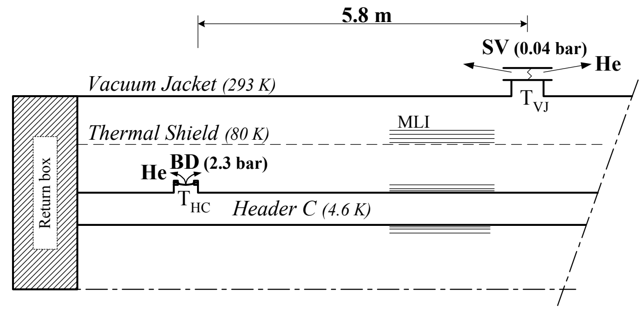

Figure 2 Conceptual scheme of the break of header C.

Figure 3 Photos of the test set – up.

Table 1 Initial helium conditions in header C

Helium initial properties in header C			Dimensions		
temperature before pressurisation	T_{in} [K]	4.6	diameter of header C	[m]	0.104
temperature after pressurisation	T_0 [K]	6.1	diameter of vacuum jacket	[m]	0.618
pressure before pressurisation	P_{in} [MPa]	0.13	diameter of bursting disk	[m]	0.025
pressure after pressurisation	P_0 [MPa]	0.23	diameter of safety valve	[m]	0.1
mass	M [kg]	106.8	length of test cell	[m]	110
density	ρ [kg/m^3]	123.6	volume of QRL vented space	[m^3]	11

EXPERIMENTAL RESULTS

To perform the test, header C has been isolated first and then pressurised by injection of warm helium. After about 13 s from the opening of the bursting disk, the helium discharge to the test tunnel started, generating intensive noise. Considering that the vacuum insulation space over 55 m was filled with the helium at 1.04 bar in 13 sec, we can deduce that the helium average temperature in the insulation vacuum was of about 65 K. The calculated peak of the helium mass flow resulted to be about 0.7 kg/s. During the first 120 sec the helium mixed with the air in the whole cross section of the tunnel up to a length of about 5 m. Then the helium-rich mixture started rising and a separated misty layer was observed at the upper part of the test tunnel. Oxygen deficiency meters have been mounted at different locations as shown in Fig. 4. The experimental results are shown in Fig. 5 to 7.

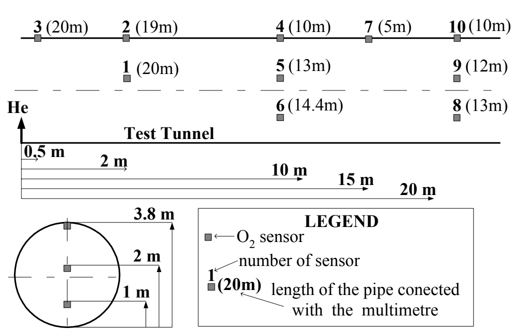

Figure 4 Location of the oxygen concentration sensors in the test tunnel.

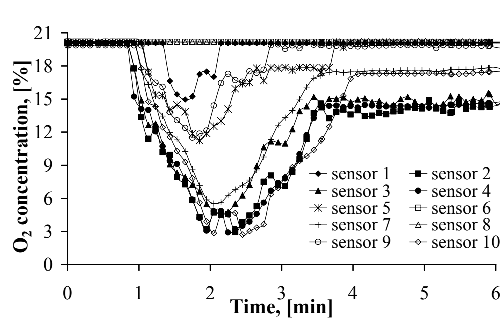

Figure 5 Experimental results of oxygen concentration measurements.

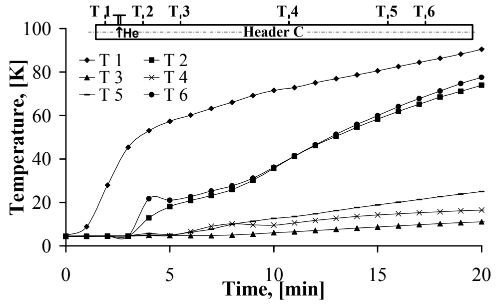

Figure 6 Experimental distribution of helium temperature in header C.

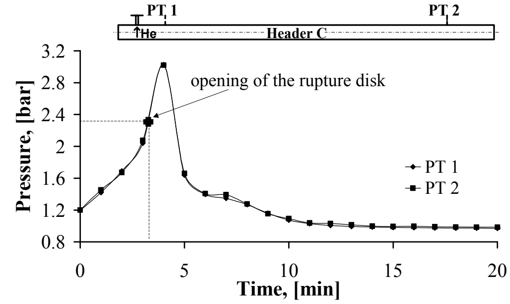

Figure 7 Experimental distribution of helium pressure in header C.

The violent decrease of oxygen concentration at the beginning of helium discharge results from the peak mass-flow, which causes full filling of the tunnel cross section by the helium rich mixture. Due to the low temperature of the vacuum jacket, condensed moisture was visible in the vicinity of the jacket lower part.

MODELLING OF HELIUM-AIR MIXTURE PROPERTIES

Numerous experiments and observations [5] allow us to conclude that helium discharging from the cryogenic system to the environment has a form of a turbulent jet (see Fig. 8). The jet is described by the equation of momentum conservation (1):

$$\frac{d(\rho A w^2)}{dx} = 0 \qquad \text{and} \qquad A(x) = \pi \cdot x^2 \cdot \mathrm{tg}^2\,\alpha \qquad (1)$$

The value of the angle α has been estimated experimentally [4] and it is equal to 13°. The pressure along the jet axis is equal to the pressure of environment.
To conserve the jet momentum and to keep a constant angle of the jet, a sufficient amount of surrounding air must be added to the helium. As a consequence such parameters as the mixture density, temperature and oxygen concentration are changing along the jet axis.
We have calculated the above parameters along the jet axis using the ideal gas model of the mixture:

$$\rho_{mix} = \frac{p_{mix}}{R_{mix} \cdot T_{mix}} \qquad \text{and} \qquad T_{mix} = \frac{\sum_{i=1}^{k} \frac{n_i}{n_{mix}} \cdot \frac{\gamma_i}{\gamma_i - 1} \cdot R_{univ} \cdot T_i}{\sum_{i=1}^{k} \frac{n_i}{n_{mix}} \cdot \frac{\gamma_i}{\gamma_i - 1}} \qquad (2)$$

where k is equal to 2 (helium-rich mixture and air) and γ it is the ratio of c_p and c_v.
The results have been calculated for two different initial helium temperatures (T = 65 K and T = 10 K) and are presented in Fig 9 to 11.

The stratification is possible if the mixture density is lower than the density of the surrounding air, $\rho_{mix} < \rho_{air}$ (see Fig. 9). Furthermore air may be still intensively added to the helium-rich mixture if inertia forces f_i dominate over buoyancy f_b (3).

$$f_i = A \cdot \rho \cdot w \cdot dw \qquad \text{and} \qquad f_b = A \cdot \Delta\rho \cdot g \cdot dx \qquad (3)$$

The expected oxygen concentration lies between the values resulting from the conditions: $\rho_{mix} < \rho_{air}$ and $f_b / f_i = 1$ (see Fig. 11). Oxygen concentration measured during the experiment confirmed the above assumption. Because of the plate, which was placed about 20 cm above the helium outlet (see Fig. 3 and 8 b) the jet was disturbed and helium-rich mixture partly recycled. Consequently the measured oxygen concentration was very close to the condition $\rho_{mix} < \rho_{air}$.

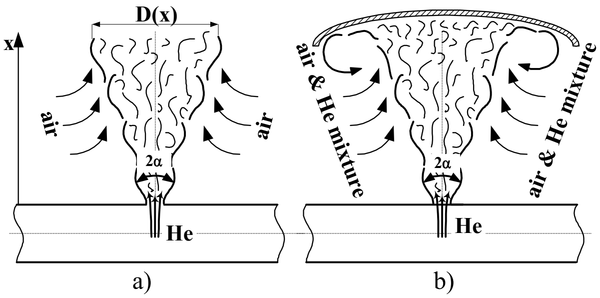

Figure 8 Turbulent jet as efficient mechanism of mixing; a) free, b) disturbed.

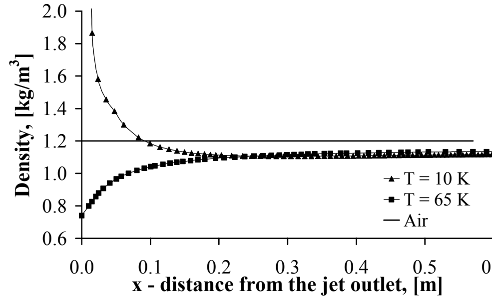

Figure 9 Density of the mixture versus distance from the jet outlet.

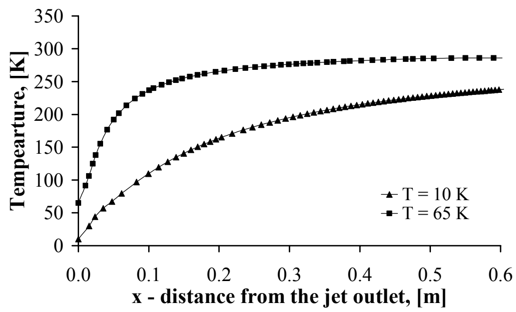

Figure 10 Mixture temperature versus distance from the jet outlet.

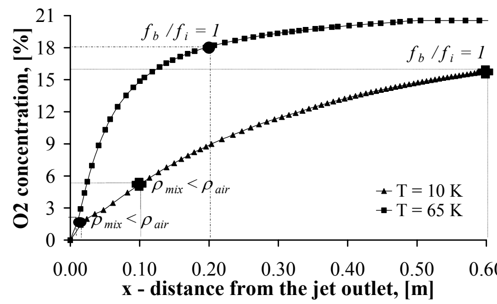

Figure 11 Oxygen concentration in the mixture versus distance from the jet outlet.

CONCLUSIONS

Break of header C was experimentally simulated to analyse helium discharging into the tunnel. Intensive noise was generated just after the beginning of the helium discharge. Also visible mist occurred in the tunnel. Measurement of oxygen concentration showed that the helium was mixed with the surrounding air. The lowest amount of oxygen was gathered on the top of the test tunnel (3 – 14 %) and no oxygen deficiency was measured in the lower part of the tunnel (always above 20 %). Expected stratification of the helium-air mixture on the top of the tunnel occurred. Analysis shows that conditions of the helium-air mixture result from free turbulent jet mechanism. Measured oxygen concentration in the stratified layer is included in the range resulting from the conditions of stratified flows: $\rho_{mix} < \rho_{air}$ and $f_i / f_b = 1$. Because of the plate close to helium outlet, the jet was disturbed and the measured oxygen concentration was found closer to that resulting from $\rho_{mix} < \rho_{air}$.

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