SUMMARY OF THE EXPERIMENTAL STUDIES OF COLD HELIUM PROPAGATION ALONG A SCALE MODEL OF THE LHC TUNNEL

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Abstract

The Large Hadron Collider will contain more than 95 tons of liquid and supercritical helium. The accelerator will be located in the 26.7 km underground tunnel. Some potential failures of the LHC cryogenic system might be followed by helium discharge into the tunnel and as a consequence the oxygen concentration might decrease below the safe level or the ambient temperature might drop significantly. In order to investigate the helium propagation in the tunnel a dedicated test rig, representing a section of the LHC tunnel at scale 1:13 has been designed and built. The basic construction of the scale model has been also modified by adding special modules to simulate the presence of the LHC accelerator inside the tunnel, tunnel enlargements and the influences of the LHC tunnel elevation. This paper presents and discusses the results of the performed experiments. Helium-air mixture flows corresponding to different initial conditions of the ventilation air and discharged helium have been visualized. Five types of mixture flow have been observed. Measured oxygen concentration and temperature profiles have been presented for the different flow patterns. The results have been scaled to the LHC conditions.

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ABSTRACT

The Large Hadron Collider will contain more than 95 tons of liquid and supercritical helium. The accelerator will be located in the 26.7 km underground tunnel. Some potential failures of the LHC cryogenic system might be followed by helium discharge into the tunnel and as a consequence the oxygen concentration might decrease below the safe level or the ambient temperature might drop significantly. In order to investigate the helium propagation in the tunnel a dedicated test rig, representing a section of the LHC tunnel at scale 1:13 has been designed and built. The basic construction of the scale model has been also modified by adding special modules to simulate the presence of the LHC accelerator inside the tunnel, tunnel enlargements and the influences of the LHC tunnel elevation. This paper presents and discusses the results of the performed experiments. Helium-air mixture flows corresponding to different initial conditions of the ventilation air and discharged helium have been visualized. Five types of mixture flow have been observed. Measured oxygen concentration and temperature profiles have been presented for the different flow patterns. The results have been scaled to the LHC conditions.

INTRODUCTION

The Large Hadron Collider (LHC) located in the underground tunnel will contain more than 95 tons of liquid and supercritical high-density helium. The helium will be supplied to the LHC cryomagnets from the cryogenic distribution line (QRL) via so-called jumper connections. The largest amount of helium will be 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 helium ring line (695 kg per volume of length 27 km) [1, 2].

Although the LHC cryogenic system is characterized by high reliability, its failure is still possible. As it was specified in the Preliminary Risk Analysis (PRA) [1] some of potential LHC cryogenic system failures might be followed by helium discharge to the tunnel. As a consequence a decrease of the oxygen concentration below the safety level of 18 % or a significant drop of the ambient temperature cannot be excluded. Therefore people working nearby might be exposed to asphyxiation or body injury.

The processes occurring inside the cryogenic installation and leading up to helium discharge to the environment have been analyzed in the PRA [1]. As a result potential failure modes of the accelerator, which may be followed by helium discharge to the tunnel, have been identified. The potential amount of helium vented into the machine tunnel has been also estimated [1, 2]. Total break of jumper connection, break of header C and break of the helium ring line have been detailed as three critical events leading to the most intensive helium discharge.

A dedicated test tunnel was built and experimental simulations of helium discharge into the LHC tunnel were performed. The test conditions simulated the LHC tunnel ventilation, elevation, enlargements and the presence of the LHC machine. The work contributes to identify and describe the processes and phenomena following helium discharge to the tunnel allowing estimating the Oxygen Deficiency Hazard (ODH) and temperature drop in the tunnel. Oxygen concentration and temperature profiles were measured in selected test tunnel cross sections, at some distances from the helium discharge point. The measurements were performed for combinations of different helium mass flow rates, air velocities and tunnel slopes. According to the mist visibility some characteristic helium-air mixture flow patterns could be observed and classified. The results have been scaled to the LHC tunnel taking into account the conditions of each sector.

TEST SET UP AND EXPERIMENT DESIGN

The general features of the experimental test set-up were described in [3]. Some modifications of the test rig were done in order to investigate the influence of the LHC tunnel elevation on the helium propagation. In order to change the slope of the test tunnel a flexible tube was placed at the outlet of the reservoir buffer and on the opposite extremity the test tunnel was supported by a dedicated lift system. Additionally the mock-up of the LHC machine was put into the test tunnel as well as the enlargement made from Plexiglas® was placed between the main pipe modules of the tunnel as shown schematically in FIGURE 1.

FIGURE 1. Schematic representation of the test set-up.

The test set-up was designed to simulate the LHC air ventilation conditions and average helium mass discharges, which might follow potential failures of the LHC cryogenic system [2]. The value of Re_{lim} needed to obtain self-similarity conditions of the air flow in the LHC and test tunnel is equal to 7300 (Eq. 1, where ε is roughness coefficient of tunnel walls). The airflow in the LHC tunnel is strongly turbulent (Re is over 130000) and the self-similarity conditions are reached. The lowest air velocity resulting from Re_{lim} , needed for self-similar conditions in the test tunnel is 0.37 m/s. To scale the helium discharge rate, the Bakke number Ba , resulting from the ratio of Reynolds and Archimedes numbers [3], was considered as a similarity constant (Eq. 2, where v_{air} is the air velocity in the tunnel, g the gravitational acceleration, q_{m_He} the helium mass flow rate, ρ_{He} the helium density at a helium initial temperature and atmosphere pressure, ρ_{mix} the mixture density obtained in jet just before tunnel boundary, ρ_{air} the air density, d_{tunnel} the tunnel diameter).

$$Re_{lim} = \frac{217,6 - 328 \lg \varepsilon}{\varepsilon} \quad (1)$$

$$Ba = \frac{v_{air}}{\sqrt[3]{\frac{g \cdot q_{m_He} \cdot (\rho_{mix} - \rho_{air})}{\rho_{He} \cdot d_{tunnel} \cdot \rho_{air}}}} \quad (2)$$

The parameters, which were varied in the experiments, were: the helium mass flow rate (1 to 3 g/s), air velocity (0, 0.5, 1 and 2 m/s) and tunnel slope (-2.8 to $+2.8$ %). The helium initial temperature was kept constant and equal to 25 K, which is the estimated helium temperature after a potential break of header C. The pressure in the helium dewar was kept at the level of 0.1 to 0.2 MPa overpressure depending on the required helium mass flow rate. The diameter of the outlet nozzle used was 3 mm. A single discharge experiment lasted from 5 to 10 minutes and this was the time needed to obtain stable flow conditions. The average temperature of the ambient air was 293 K, the ambient pressure varied in the range of 980 to 1020 hPa, and the humidity was between 50 and 60 %.

EXPERIMENTAL RESULTS

Helium-air Mixture Visualization

As a result of the helium-air mixture flow visualization, five types of flow patterns were identified. Propagation of the visible mist, which resulted from condensation of the moisture of the humid air, was taken as a criterion for identification of flow type. The moisture location depends on the value of Bakke number. The types of flow patterns are shown in FIGURE 2. These results were obtained for horizontal position of the test tunnel (slope 0). Type 1 was a fully stratified flow observed for any helium mass flow rate and Ba number less than 2, when the forced airflow was absent. The mist was visible in the upper part of the tunnel as a stable compact layer of a constant thickness along the tunnel. In case of type 2 a dense mist occurred in the lower part of the tunnel and filled it up to the level of 0.8 to 0.9 D (where D is the pipe diameter). Ba ranged from 2 to 4. Type 3 was detailed while a trail of the mist was located in the middle of the tunnel and the value of Ba was between 4 and 8. When Ba was above 8 the mist spread in the bottom of the tunnel. Then the trail of the mist raised and moved chaotically filling almost the whole tunnel cross

section. This behavior was typical for type 4 and also for type 5. The difference was the length of the region where the mist was spreading close to the bottom. For type 4 it was visible up to the distance 5 to 7 D from the helium outlet while for type 5 merely up to 1 to 3 D. Type 5 was observed for the strong air velocity (1 and 2 m/s) and for low helium mass flow rate (1 g/s), when the ratio of q_{m_air} / q_{m_He} was above 70.

Results of O₂ Concentration and Temperature Measurements

The O₂ concentration and the temperature profiles measured at a distance 5 D from the discharge point (see also FIGURE 2) and corresponding to each type of the flow patterns are presented in FIGURE 3. In case of the type 1, the O₂ concentration decreased to 3 to 5 % in the upper stratified layer while in the bottom of the test tunnel it remained at 20 %. At the same time the temperature decreased to the value of about 230 K for 1 g/s of the helium discharge and 190 K for q_{m_He} equal to 3 g/s. From the safety point of view both the O₂ concentration and the temperature profiles increased with the ventilation air velocity. For q_{m_He} equal to 1 g/s and the air velocity of 0.5 m/s the O₂ concentration decreased to the average value of 17 %. For more intensive airflows (1 and 2 m/s) it stayed at 18 to 20 %. For the same conditions of the helium discharge the temperature increased immediately when airflow appeared. The lowest temperatures of about 260, 275 and 280 K were measured for v_{air} equal to 0.5, 1 and 2 m/s correspondingly. Worst conditions were observed for q_{m_He} of 3 g/s. Generally the highest temperature drops corresponded with regions of the lowest O₂ concentration conditions. For v_{air} equal to 0.5 m/s the lowest O₂ concentration (about 8 %) and the lowest temperature (240 K) occurred in the middle zone of the tunnel diameter. For v_{air} equal to 1 m/s the O₂ concentration decreased significantly to 11 % only in the top of the test tunnel, where the temperature reached about 250 K. In the bottom part of the tunnel the temperature stayed in the level of 275 K. For v_{air} equal to 2 m/s the O₂ concentration decreased to 15 % in the bottom up to the distance 5 D, while at 10 D the lowest O₂ concentration of 17 % was measure in the top. The temperature was about 270 K for both regions but at the distance 5 D from the discharge point it was measured in the bottom while for 10 D at the top of the tunnel.

FIGURE 2. Types of observed helium-air mixture flow patterns.

FIGURE 3. Measured O_2 concentration and temperature profiles corresponding to observed flow patterns.

Considering the helium-air mixture model based on a turbulent jet mechanism [3], the lowest O_2 concentration in a buoyant region of the helium-air mixture belongs to the range 3 to 10 %. The values are in a good agreement with the measured values. The lowest mixture temperature estimated in [3] lies in the range 80 to 170 K, while the lowest measured temperature never decreased below 180 K. The difference is the result of intensive heat transfer between the helium jet and the tunnel wall, not taken into account in the modeling.

Influence of the Tunnel Slope.

Because the helium-air mixture propagation is strongly dependent on buoyancy forces [3, 4], the tunnel slope influences the mixture flow. In order to investigate this influence the inclination of the test tunnel was varied from -2.8% to $+2.8\%$ (see FIGURE 1). The slope of 1.4% corresponds to the LHC conditions while the 2.8% was applied for comparative purposes. Flow patterns and shapes of the O_2 and temperature profiles did not change significantly for the inclined test tunnel (compare FIGURE 4 and 5, where sign minus corresponds to tunnel lowering while the plus to tunnel raising). The location of the lowest O_2 concentration and temperature decreased along the test tunnel with a minus slope. For the flow type 1 the lowest measured O_2 concentrations were in the range from 3 to 7 % while the lowest temperatures varied between 245 and 250 K. The values of both parameters increased when the test tunnel was raised.

Influence of an Accelerator Mock-up and an Enlargement.

The presence of the LHC mock-up (simulating the cryomagnets, the cryogenic distribution lines and the jumper connection) in the test tunnel caused only one noticeable change in the helium-air mixture propagation. The mixture gathered upstream the mock-up of the jumper connection (see TABLE 1). The region of the worst conditions in the tunnel with the LHC mock-up was located in a higher level in comparison with the conditions observed in the empty tunnel.

In order to verify if the helium-air mixture would gather in the LHC enlargements and caverns, a special module made from Plexiglas® was inserted between two main pipe modules of the test tunnel (see FIGURE 1). Seven O_2 sensors and ten thermocouples were installed inside the Plexiglas® module. No significant temperature drops were observed. On the contrary in the whole enlargement the O_2 concentrations reached 5 % for q_{m_He} equal to 3 g/s and 10 % for 1 g/s. For the air velocity of 0.5 m/s the worst conditions (about 5 % for 3 g/s and 13 % for 1 g/s) were in the middle zone of the enlargement. The air velocities of 1 and 2 m/s did not cause any changes when 1 g/s of the helium was discharged. For 3 g/s and the same air velocity measured O_2 concentration was still low in the middle and was about 14 and 15 % for 1 and 2 m/s of the air velocity respectively.

TABLE 1. Influence of the LHC mock-up presence in the test tunnel (results for flow pattern type 1)

Tunnel description	Empty tunnel		Tunnel with the LHC mock-up	
Helium mass flow rate, g/s	1	3	1	3
h/D with minimum O_2	0.65	0.65	0.8	0.75
minimum O_2 concentration, %	4	3	5	4
mixture temperature at point with minimum O_2 , K	255	235	245	230

SCALING TO THE LHC CONDITIONS

The experimental results have been scaled to the LHC conditions. First the properties of the helium air mixture resulting from the turbulent jet mechanism have been estimated. The available length of the helium jet formation in the LHC tunnel is about 1.2 m. At this distance only in case of helium mass flow rate following the break of header C, the helium-air mixture may reach buoyant conditions (see FIGURE 6, where JC means break of jumper connection while HC break of header C). For all cases the inertia forces are higher than the buoyancy. Hence it can be expected that a so called “helium jam” (see Figure 7) will occur before the conditions of stratified flow are reached. The properties of helium jam corresponding to each LHC potential failures and resulting from turbulent jet mechanism at the height of the tunnel ceiling are given in Table 2. Average temperature of the helium jam (T_{mix}) and the corresponding minimum oxygen content (O_2) are presented. The velocity of helium jam propagation (v) has been also estimated. The flow direction of the helium jam depends on the ratio of the jam and the ventilation air velocities. In case of the peak of helium flow after the jumper connection break, the helium jam might flow upstream. The characteristic flow of the helium-air mixture will be formed after the helium jam density reaches at least a density lower than the density of the air and the buoyancy dominates over the inertia force. TABLE 3 presents the Bakke numbers calculated for each LHC failures and corresponding type of flow patterns.

Neither the slope of the tunnel nor the LHC machine presence will cause significant decrease in the O_2 concentration and the mixture temperature in the helium-air mixture. As it results from the measurements only the level of safe zone in the tunnel might change. In case of flow type 1 the lowest O_2 concentration (of about 3 %) and lowest mixture temperature (of about 180 K) will be observed at the height of 0.8 h/D when both the tunnel slope and the air flow velocity are upwards. When the ventilation air flows downwards through the tunnel the buoyancy is in the opposite direction.

The lowest O_2 concentration and the lowest temperature will be observed at the level of 0.4 to 0.5 h/D. In case of flow type 2 the lowest O_2 concentration of 12 to 14 % will be at 0.4 to 0.6 h/D. The lowest O_2 of about 3 % at the level 0.3 to 0.4 h/D might occur in the highest and the lowest points of the tunnel where the directions of the tunnel slopes are changing. Even in these cases the safe oxygen concentration of 18 % is always expected up to the distance of about 0.6 to 0.7 m from the tunnel floor. The O_2 concentration might also decrease to dangerous level of 5 to 10 % in the atmosphere of the tunnel enlargements while the temperature drop will not occur.

FIGURE 6. Helium air mixture densities versus distance from the helium outlet corresponding to potential failures of the LHC

FIGURE 7. Helium jam in the LHC tunnel

TABLE 2. Features of the helium jam in the LHC tunnel

Failure description	L, m	T _{mix} , K	O ₂ minimum, %	v, m/s
header C – peak flow	16	145	7	0.35
header C – average flow	6	160	8	0.12
jumper connection – peak flow	60	60	2	1.10
jumper connection – average flow	7	90	3	0.16

TABLE 3. Bakke numbers and flow types corresponding to the LHC tunnel

Failure description	Ba	Ba	Flow type	Flow type
	v _{air} =0.55 m/s	v _{air} =0.88 m/s	v _{air} =0.55 m/s	v _{air} =0.88 m/s
header C – average, 1 kg/s	1.13	2.44	Type 1	Type 2
header C – peak flow, 3 kg/s	0.90	2.01	Type 1	Type 2/1
jumper connection – average, 2 kg/s	0.56	1.21	Type 1	Type 1
jumper connection – peak flow, 25 kg/s	0.71	1.53	Type 1	Type 1

CONCLUSIONS

When helium is vented into the tunnel, different flow patterns can be observed depending on the different helium and air mass flow ratios. The flow patterns can be categorized with respect to dimensionless Bakke number. The performed experiments enabled to measure distribution of oxygen concentration and mixture temperature across the test tunnel. Scaling the results to the LHC conditions showed that in cases of potential helium discharge to the tunnel, stratified flow patterns are expected in all cases of LHC potential failures in case of normal air velocity. Although the oxygen concentration at the upper part of the tunnel may drop to the values as low as 3 %, the concentration at the tunnel bottom, up to the level of about 0.7 m, will remain at safe level of 18 to 20 %. Due to the tunnel height limitations, development of a stratified flow will be preceded by creation of “helium jam” up to about 60 m long. Change of the tunnel slope influences the level at which worst conditions occur. The lowest oxygen concentrations and the lowest temperatures are expected at 0.8 to 0.7 h/D when the tunnel slope is positive and at 0.4 to 0.5 when it is negative.

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