NUMERICAL ANALYSIS OF THE FINAL COOLDOWN OF A 3.3 KM SECTOR OF THE LARGE HADRON COLLIDER

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Abstract

The final cool-down of a 107-m standard cell of LHC, which consists of the helium filling operation at 4.5 K and the further cool-down from 4.5 K to 1.9 K, has been previously simulated and analyzed numerically. To model and analyze the final cool-down process of a whole 3.3-km sector of the LHC, additional boundary conditions must be introduced. In this paper, the slope of the sector, the efficiency of the sub-cooling heat exchanger, the pressure drops and heat loads in different headers of the cryogenic distribution line as well as the fact that both the filling flow of the cold mass and the vaporized flow in the 1.8 K heat exchanger are concurrently supplied have been taken into account. The simulation results, such as the temperature evolution in the LHC magnet cold mass and the pressure profiles in cryogenic line headers during the filling and cool-down from 4.5 K to 1.9 K of a LHC sector are presented. Taking into account the required distribution of the total flow to each cell, all the cells can be filled up to 67% of the volume and further cooled down to 1.9 K simultaneously in 15 to 20 hours.

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Presented at the CEC-ICMC'05 Conference
29 August-2 September 2005, Keystone, Colorado, USA

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ABSTRACT

The final cool-down of a 107-m standard cell of LHC, which consists of the helium filling operation at 4.5 K and the further cool-down from 4.5 K to 1.9 K, has been previously simulated and analyzed numerically. To model and analyze the final cool-down process of a whole 3.3-km sector of the LHC, additional boundary conditions must be introduced. In this paper, the slope of the sector, the efficiency of the sub-cooling heat exchanger, the pressure drops and heat loads in different headers of the cryogenic distribution line as well as the fact that both the filling flow of the cold mass and the vaporized flow in the 1.8 K heat exchanger are concurrently supplied have been taken into account. The simulation results, such as the temperature evolution in the LHC magnet cold mass and the pressure profiles in cryogenic line headers during the filling and cool-down from 4.5 K to 1.9 K of a LHC sector are presented. Taking into account the required distribution of the total flow to each cell, all the cells can be filled up to 67% of the volume and further cooled down to 1.9 K simultaneously in 15 to 20 hours.

KEYWORDS: Cool-down, two-phase flow, superfluid helium

PACS: 44.35.+c

INTRODUCTION

Previous studies were devoted to the cool-down of a whole 3.3-km sector from 300 K to 4-5 K, the helium filling operation at 4.5 K and the further cool-down from 4.5 K to 1.9 K, for a 107-m standard cell of LHC [4]. In this paper the mathematical model and corresponding results for the helium filling operation at 4.5 K and the further cool-down from 4.5 K to 1.9 K of a whole 3.3-km sector are presented.

FLOW SCHEME

The generic flow schemes for the filling operation and further cool-down of a typical LHC sector (sector 7-8) are shown in FIGURE 1. As shown in FIGURE 1, the refrigerator is hydraulically connected to each cell of the sector via the cooling headers B, C and D and control valves. All LHC cells, which belong to the regular arc (about 107 m each), Dispersion Suppressor next to and opposite to the refrigerator (DSN/O, cell length varying from 80 to 95 m) and the Long Straight Section next to and opposite to the refrigerator (LSSN/O, cell length varying from 7 to 21 m) respectively, are filled and cooled down in parallel. During the filling phase, the helium is supplied to the magnet cold mass via header C (ϕ 100 mm) and returned via header D (ϕ 150 mm) and the quench valve QV which is forced open and has a k_V -value of 40 m³/h. Cool-down and fill valves (CFV) are installed between header C and the magnet cells to control the mass-flow rate, and the corresponding k_V -values vary from 5 m³/h (stand-alone magnets, SAM) to 32 m³/h (standard cell in the arc). For all magnet cells in the LSSN/O and a special cell in the arc, one valve serves one cell, while for the other cells in the arc and in the DSN/O, two neighboring cells are served by one valve. Due to magnet geometry this phase ends when the magnets are filled at 67 %. During the further cool-down, the helium is supplied to the 1.8 K heat exchanger via header C and returned via header B (ϕ 267 mm), and to the cold mass to complete the filling and to compensate for the density variation as during this phase the cold mass pressure has to stay above atmospheric pressure to avoid air inleak in the helium circuit. The supply and return flows of the 1.8 K heat exchanger exchange their enthalpy at the sub-cooling heat exchangers (HR, see FIGURE 1). Both the filling flow of the cold mass and the vaporized flow in the 1.8 K heat exchanger are concurrently supplied via header C, which constitutes a hard constraint for the simulation of the final cool-down of a 3.3-km sector. Due to the variety of sector the slopes, different cells may have different helium supply configurations to the cold masses and 1.8 K heat exchanger.

BOUNDARY CONDITIONS

The final cool-down has been studied according to the flow-scheme shown in FIGURE 1. In this study in addition to the standard cell boundary conditions, as applied in [4], those for a sector follow:

1. The maximum mass-flow rate of helium at the inlet of header C is 125 g/s during the filling phase and 135 g/s during the cool-down phase;
2. The helium pressure and temperature at the inlet of header C are 0.3 MPa and 4.6 K respectively;
3. The maximum mass-flow rate of helium at the outlet of header B is 125 g/s during the further cool-down phase;
4. The helium pressure at outlet of the header B is 1.6 kPa during the further cool-down phase;
5. The helium pressure at the outlet of header D is 0.13 MPa during the filling phase;
6. The helium pressure inside the cold masses is 0.13 MPa during the further cool-down phase;
7. The heat inleaks into the cold masses, headers B, C and D are 0.2 W/m, 0.08 W/m, 0.05 W/m and 0.06 W/m respectively;
8. The transition from filling phase to further cool-down phase is imposed when 67 % of the volume of the cold mass is filled.

FIGURE 1. Generic flow-scheme for the final cool-down of a typical LHC sector

SIMULATION RESULTS AND DISCUSSION

Based on the mathematical model for the final cool-down of a cell and the boundary conditions mentioned in the previous chapter, the model for the final cool-down of a whole sector has been developed. By imposing a specific distribution of the total mass flow rate available to implement a simultaneous cool-down of all cells, the cool-down time of the whole sector has been optimized [4].

Headers During Filling Phase

FIGURE 2 provides the helium pressure and temperature profiles of header C during the filling phase. The helium pressure in header C is mainly governed by the gravity effect which predominates the frictional pressure drop. The rise of the header C temperature is due to the contribution of the heat inleaks into this header. FIGURE 3 presents the optimized mass-flow rates of all cells and the mass-flow rate distribution in header C during the filling phase.

FIGURE 2. Pressure and temperature profiles in header C during filling and further cooldown phase.

FIGURE 3. Mass-flow rate (Q) profiles in header C and cells during filling phase.

Headers During Further Cool-down Phase

The pressure, temperature profiles of header C during further cool-down are rather stable with time and equal to those calculated for the filling phase (refer also to FIGURE 2).

During the first 18 h, the mass-flow rate does not vary significantly with time (see FIGURE 4) and its profile is comparable to that for the filling phase. On the contrary, the pressure and temperature profiles of header B (FIGURE 5) vary significantly with time (results are shown for different times of the further cool down phase, from 1 h to 20 h) mainly due to the corresponding change of mass-flow rate in header B (FIGURE 4).

FIGURE 4. Mass-flow rate profiles of headers C and B during further cool-down phase.

FIGURE 5. Pressure and temperature profiles of header B during further cool-down phase.

The mass-flow rates in the 1.8 K heat exchanger and cold mass of the different cells also vary with time (FIGURE 6). At the beginning, most of the helium flows into the cold masses to complete their filling. When the cold mass is filled, the flow to the 1.8 K heat exchanger can increase. FIGURE 7 shows that, as a result of the flow distribution optimization, the different types of cells are cooled and finally filled almost simultaneously. In case the flow distribution is not optimized, the delay in the cooldown time is directly proportional to the mass-flow rate deviation to the optimized value.

Cells During Filling Phase

As the filling process of a standard arc cell has been simulated and presented before [4], only the filling phase of a cell belonging to Inner Triplets (IT) (cell length L_{IT} about 30 m) [3] is shown in this paper (FIGURES 8 and 9). The IT cell is composed of a dipole magnet (D1) and three quadrupole magnets (Q3, Q2 and Q1). From the corresponding figures, we can notice that it takes about 15.4 h to fill the IT cell, which is also the time needed for filling the other cells as all the sector cells are filled simultaneously. As the mass-flow rate distributed to each cell is slightly smaller than in the previous calculation [4], the filling time increases by 0.9 h (from 14.5 h to 15.4 h).

Cells During Further Cool-down Phase

The further cool-down process of a cell belonging to DSO (composed of two quadrupole Q and 4 dipole magnets D, in the sequence Q2D4D3Q1D2D1; cell length L_{DS}) has been simulated, and the corresponding results are shown in FIGURES 10, 11 and 12. In the updated mathematical model, the flow between the nodes of the cold mass has been taken into consideration. This is one of the differences with the previous calculation [4] where this phenomenon was neglected.

As a consequence, during the first 6 hours after the beginning of the further cool-down, even if the helium surrounding the cold mass is cooled by the 1.8 K heat exchanger, the helium still remains in the two-phase status and the temperature of the cold mass does not decrease (FIGURE 10). From FIGURE 11 we can see that due to the positive slope of the DSO cell, at the beginning of the further cool-down, the side of the cell close to the refrigerator is fully filled, whereas the other side is partly filled or empty, and the average filling rate is 67 %. During the first phase of the further cool-down process, the cold masses are filled with liquid helium up to 100 % in about 6 hours. Afterwards, the temperatures of the helium and of the cold mass begin to decrease.

FIGURE 6. Mass flow rate in 1.8 K heat exchanger and cold mass during further cool-down phase.

FIGURE 7. Filling ratio during further cool-down for 5 types of cell.

FIGURE 8. Temperature of magnets during filling of a cell belonging to IT.

FIGURE 9. Level and filling ratio of magnets during filling of a cell belonging to IT.

FIGURE 12 shows the relationship of the mass-flow rates between the 1.8 K heat exchanger and cold mass. If we neglect the fluctuation of the mass flow rates due to artifacts of the mathematical model, we conclude that the total mass flow rate for a cell is almost constant.

At the beginning of the further cool-down, most of the supplied helium is used to fill the cold mass. Afterwards, as the phase change inside the cold mass does not occur anymore, less liquid helium is needed for the cold mass and the mass-flow rate for the heat exchanger increases to create more cooling capacity. At the end of the further cool-down, all the helium for the cell is used to produce the cooling capacity.

FIGURE 10. Temperature of magnets during further cool-down of a cell belonging to DS.

FIGURE 11. Filling ratio during further cool-down of a cell belonging to DS.

FIGURE 12. Mass-flow rate during further cool-down of a cell belonging to DS.

FIGURE 13 presents the results of the further cool-down for three types of cells:

- standard cell with a positive slope [3] composed of two quadrupole magnets Q and six dipole magnets D in the sequence Q2D6D5D4Q1D3D2D1
- standard cell with a negative slope [3] composed of two quadrupole magnets and six dipole magnets in the sequence D1D2D3Q1D4D5D6Q2
- cell for inner triplets

Comparing the results shown in FIGURE 13 with those shown in FIGURE 10, we can conclude that with the maximum mass-flow rate of helium at inlet of header C of 150 g/s, the whole sector (sector 7-8) including the DS cells, regular arc cells with positive slope, regular arc cells with negative slope and IT cells, can be further cooled down to 1.9 K within 19.5 hours simultaneously.

FIGURE 13. Temperature of magnets during further cool-down of cells.

CONCLUSIONS

Based on the mathematical model for simulating the final cool-down of a standard arc cell the boundary conditions for a whole sector have been introduced to simulate the final cool-down of a typical sector. To reduce the cool-down time, the distribution of the available cold mass to the different cells has been optimized to fill and cool down them simultaneously. The simulation shows that it is possible to fill the sector with liquid helium up to 67 % within 15.4 hours and to further cool down the sector to 1.9 K within 19.5 hours.

REFERENCES

1. Lebrun, Ph., "Superconductivity and Cryogenics for the Large Hadron Collider," in *Proc. of Beijing International Conference on Cryogenics*, Beijing, 2000, pp. 28-34.
2. Evans, L. R., "The Large Hadron Collider: Present Status and Prospects," *IEEE Trans. Appl. Superconductivity* 10, 44-48 (2000).
3. Liu, L., Riddone, G., and Taviani L., "Study of the Cooldown and Warmup for the Eight Sectors of the Large Hadron Collider," in *AIP Conf. Proc. 711 (2004)*, pp. 332-339.
4. Riddone, G., Liu, L. and Taviani L., "Numerical Study of the Final Cooldown from 4.5 K to 1.9 K of the Large Hadron Collider," in *Proc. of 20th International Cryogenic Engineering Conference*, Beijing, 2004, (*in preparation*).