STUDY OF THE COOLDOWN AND WARMUP FOR THE EIGHT SECTORS OF THE LARGE HADRON COLLIDER

L. Liu¹, G. Riddone², and L. Tavian²

Abstract

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ABSTRACT

The LHC cryogenic system [1] is based on a five-point feed scheme with eight refrigerators serving the eight sectors of the LHC machine [2]. The paper presents the simplified flow scheme of the eight sectors and the mathematical methods including the program flowchart and the boundary conditions to simulate the cooldown and warmup of these sectors. The methods take into account the effect of the pressure drop across the valves as well as the pressure evolution in the different headers of the cryogenic distribution line. The simulated pressure and temperature profiles of headers of the LHC sector during the cooldown and warmup are given and the temperature evolutions of entire processes of cooldown and warmup are presented. As a conclusion, the functions of the input temperature for the normal and fast cooldown and warmup, the cooldown and warmup time of each sector and the distributions of mass flow rates in each sector are summarized. The results indicate that it is possible to cool down any of the LHC sector within 12.7 days in normal operation and 6.8 days in case of fast operation.

INTRODUCTION

Studies on thermal transient modes of a LHC typical sector [3, 4, 5] have been carried out and continually improved since 1997. Having successfully applied the mathematical model to a typical sector of LHC (sector 8-1), we have then used the model to simulate the other seven LHC sectors. In this paper, the overall results, such as the cooldown and warmup time of each sector and the corresponding distributions of mass flow rates, are presented. Details such as the pressure and temperature profiles of headers of a typical sector during cooldown and warmup and the temperature evolutions of entire processes of cooldown and warmup are also provided.

FLOW SCHEME

The generic flow scheme for the cooldown and warmup of LHC sectors is shown in FIGURE 1. The refrigerator is hydraulically connected to each cell of the sector via cooling headers E, F, C and D and control valves. All LHC cells [6], which belong to 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 cooled down and warmed up in parallel. The different sectors have specific layout for DSN/O and LSSN/O (which are shown in TABLE 1 where the cells are marked by their quadrupoles' and dipoles' codes) but almost the same regular arc, which includes 23 standard cells. During a "normal" cooldown and warmup, one refrigerator is used to supply one sector, while for a "fast" process, two neighboring refrigerators are coupled to one sector with twice the total mass flow rate and refrigeration capacity.

TABLE 1. The cells of LSSN, DSN, DSO and LSSO of eight sectors

Sector*	LSSN	DSN	DSO	LSSO
8-1	Q3~Q1, Q4, Q5, Q6	Q8~Q7, Q9~Q10	Q10~Q11, Q9~Q8	Q7, Q6, Q5, Q4, Q3~Q1
2-1	Q3~Q1, Q4, Q5, Q6, Q7	Q9~Q8, Q10~Q11	Q9~Q10, Q8~Q7	Q6, Q5, Q4, Q3~Q1
2-3	Q3~Q1, Q4, Q5, Q6	Q8~Q7, Q9~Q10	Q10~Q11, Q9~Q8	Q7, Q6
4-3	D3, Q5, Q6, Q7	Q9~Q8, Q10~Q11	Q9~Q10, Q8~Q7	Q6
4-5	D3, Q5, Q6	Q8~Q7, Q9~Q10	Q10~Q11, Q9~Q8	Q7, Q6, Q5, Q4, Q3~Q1
6-5	Q4, Q5	Q10~Q8, Q11	Q9~Q10, Q8~Q7	Q6, Q5, Q4, Q3~Q1
6-7	Q4, Q5	Q9~Q8, Q10	Q10~Q11, Q9~Q8	Q7, Q6
8-7	Q3~Q1, Q4, Q5, Q6, Q7	Q9~Q8, Q10~Q11	Q9~Q10, Q8~Q7	Q6

* The refrigerator is located at the first point (for example, it is located at Point M if the sector is M-N)

In FIGURE 1, the helium to the magnet cold mass is supplied via header C ($\phi 100$ mm) and returned via header D ($\phi 150$ mm). Headers C and F ($\phi 80$ mm) are interconnected using valves at the middle and at the end of the sector. This configuration enables to supply helium to header C from header F. Headers F and E ($\phi 80$ mm) are interconnected using a valve at the end of the sector. Cooldown and fill valves (CFV) are installed between header C and the magnet cells to control the flow-rate, and the corresponding k_V -values vary from $5 \text{ m}^3/\text{h}$ (stand-alone magnets, SAM) to $32 \text{ m}^3/\text{h}$ (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 standard cells in the arc and all cells in the DSN/O, two neighboring cells are served by one valve. Quench valves (QV) are implemented between header D and most magnet cells (there is no QV for some cells in LSSN/O), with k_V -values always higher than $30 \text{ m}^3/\text{h}$.

BOUNDARY CONDITIONS FOR COOLDOWN AND WARMUP

The cooldown and warmup have been studied according to the flow-scheme shown in FIGURE 1. During the study, the following boundary conditions were taken into account:

1. At any time, the total mass flow rate of a whole sector which is distributed into headers C, E and F is always 770 g/s in normal case and 1540 g/s in fast case when there is no flow limitation.

FIGURE 1. The generic flow-scheme for the cooldown and warmup of LHC sectors

2. At any time, the inlet and outlet pressures of the whole sector are 1.65 MPa and 0.45 MPa, respectively.
3. The inlet temperature of the whole sector varying from 293 to 4.5 K is given by the program according to the refrigerating capacity of the cryo-plant and the maximal temperature difference across any magnet.
4. The maximal temperature difference across any magnet is always less than 75 K.
5. V_1 , V_2 , V_3 , V_4 , V_5 are fully opened when T_{EF} shown in FIGURE 1 is higher than 70 K and are closed when T_{EF} is lower than 70 K as well as no flow limitation exists.
6. The openings of CFVs are regulated to control the mass flow rate in each cell.
7. At any time, QVs are fully opened.
8. The cooldown process stops when the highest temperature of the cold mass is lower than 6.0 K, the warmup process stops when the lowest temperature of the cold mass is higher than 273.5 K.

SIMULATION METHODS

The mathematical model used for simulation has been described in [2]. According to this model and taking into account the effect of the pressure drop across the valves as well as the pressure evolution in the different headers of the cryogenic distribution line, a FORTRAN program was developed and the corresponding flowchart is shown in FIGURE 2. P_{C-in} and T_{C-in} are the helium pressure and temperature at the inlet of header C respectively, $M_{C+E+F-in}$ is the total mass flow rate of the whole sector which is the sum of M_{C-in} , M_{F-in} and M_{E-in} (the inlet mass flow rates of headers C, E and F respectively), P_{D-end} is the helium pressure at the outlet of header D, P_{F-in} , P_{E-in} , P_{D-in} , P_{F-end} , P_{E-end} and P_{D-end} are the helium pressures at the inlet and outlet of headers F, E and D respectively, P_{C-mid} and P_{F-mid} are the helium pressures at the middle point (where V_4 is located) of headers C and F respectively, M_{FC-mid} is the mass flow rate flowing through V_4 , M_{F-mid} is the mass flow rate flowing through the second half part of header F, P_{C-0} is the helium pressures at the converging point (where the downstream and upstream converges) of header C, P_{Di-end} is the helium pressure at the outlet of section i of header D, $P_{Cell-in}$ is the inlet pressure of the cell corresponding to section i of header D (the downstream pressure of CFV).

SIMULATION RESULTS AND DISCUSSION

Pressure Profiles in Headers

FIGURE 3 gives the pressure profiles of headers at the beginning during a normal and a fast cooldown of a typical sector (sector 8-1). From the left-side diagram we can see that the inlet pressure of header C is higher than those of headers F and E due to the pressure drop in V_1 and V_3 . The trends of the pressure evolution of headers C and F change at the middle of the sector because of the flow from header F to header C via V_4 . At the end of the sector, the pressure of header C is lower than the others, which means the helium in headers E and F flows back to header C at that point. The right-side diagram shows that the pressure drops are much higher for a fast cooldown than for a normal cooldown.

FIGURE 2. Flowchart of the program

Temperature Profiles of Headers

FIGURE 4 gives the temperature profiles of headers C, D, E and F after 4 hours from the beginning during a normal and a fast cooldown of sector 8-1. The left-side diagram indicates that the highest temperature of header C occurs at 2.6 km away from the refrigerator, where the two flows from opposite directions converge (see FIGURE 1). This point is the last point cooled by the flow in header C, and its temperature is determined by the mixing of the two flows. Attention should be paid to avoid an unbalanced distribution of the flows. From the figure, the impact on the temperature of the influx of two flows at the middle of the sector as well as the three flows at the end of the sector can be observed.

Temperature Evolutions of Headers

The temperature evolutions of headers C and D during a normal cooldown of sector 8-1 are shown in FIGURE 5. From the figure we can notice that the temperature profile of header C decreases uniformly with time, whereas that of header D shows a drop at the end of the sector. This happens because the helium distributed to the LSSN cells has a larger value of $M_{\text{He}}/M_{\text{CM}}$ (where M_{He} is the mass flow rate of helium and M_{CM} is the cold mass including mass of piping to be cooled by the corresponding M_{He}) than that distributed to the arc and DSN/O cells (for the detail on helium distribution, refer to the following section), thus its temperature is relative low when it flows out from the cells.

FIGURE 3. Pressure profiles of headers C, D, E and F at the beginning during a normal and a fast cooldown of sector 8-1

FIGURE 4. Temperature profiles of headers C, D, E and F after 4 hours from the beginning of a normal and a fast cooldown of sector 8-1

Cooldown and Warmup of a Whole Sector

Cooling or warming a sector, attention should be paid to the flow distribution to each cell. Following several simulations, the optimized cooling scheme was found. In the LSSN, the original flow, which was calculated proportionally to the cold mass of the cell to be cooled, had to be doubled. In the LSSO, being on the opposite side of the refrigerator, a factor 4 with respect to the original flow had to be applied. With this mass flow consideration, for sector 8-1, the normal and fast cooldown take about 12.7 and 6.8 days respectively (FIGURE 6), the normal and fast warmup about 11.5 days and less then 6 days respectively (FIGURE 7). Compared with the previous results, which did not take into consideration the pressure drop effect in the headers [3], the average time increased by about 12%.

Cooldown and Warmup of 8 LHC Sectors

The thermal transient modes of all eight LHC sectors have been simulated using the program mentioned above. The optimized flow distributions of eight sectors are shown in TABLE 2 and the optimized functions of the input temperature for the beginning of the cooldown and warmup versus time are given in TABLE 3, whose curves, marked by "sector_in", have been shown in FIGURES 6 and 7. To make the operation convenient, the eight sectors share the same functions of input temperature at the first stage (T_{in} limited stage).

FIGURE 5. Temperature profiles of header C and D over time during a normal cooldown of sector 8-1

FIGURE 6. Normal and fast cooldown of sector 8-1

FIGURE 7. Normal and fast warmup of sector 8-1

The time for each mode is summarized in FIGURE 8. From this figure we can see that it is possible to cool down any of the LHC sector within 12.7 days in normal operation and 6.8 days in case of fast operation while to warmup any of the LHC sector within 11.5 days in normal operation and 6 days in case of fast operation.

TABLE 2. The optimized flow distributions of eight LHC sectors for the normal operation

Sector	Mass flow rate* [g/s]					
	LSSN	DSN	regular arc	DSO	LSSO	total
8-1	30.23	38.82	618.29	39.77	42.86	770.0
2-1**	30.96	39.94	617.21	38.98	43.03	770.1
2-3	32.36	40.74	648.89	40.99	7.04	770.0
4-3	29.88	41.15	651.66	40.15	7.07	769.9
4-5	28.44	38.22	620.36	39.91	42.99	769.9
6-5	3.00	48.99	634.17	39.82	43.97	770.0
6-7	3.16	50.59	666.84	42.13	7.24	770.0
8-7	32.38	41.75	649.12	39.72	7.04	770.0

* All the values of the mass flow rate will be doubled in case of the fast operation

** The flow scheme for sector 2-1 is peculiar (the cryo-plant is located between the two ends of the sector, instead of at one of the ends). Due to time reason, the results shown here were achieved based on the same flow scheme as for other sectors.

TABLE 3. The optimized functions of the input temperature (T_{in}) versus time of eight LHC sectors

Mode	T_{in} [K]	
	Cooldown	Warmup
Normal	$T_m(K) = \begin{cases} 293 - \frac{75}{4}t & (t \leq 4h) \\ 218 & (4h < t \leq 24h) \\ 218 - \frac{33}{30}(t - 24) & (24h < t \leq 54h) \\ 185 - \frac{42}{36}(t - 54) & (t > 54h) \end{cases}$	$T_m(K) = \begin{cases} 4.5 + \frac{75}{4}t & (t \leq 4h) \\ 79.5 + \frac{120}{44}(t - 4) & (4h < t \leq 48h) \\ 199.5 + \frac{100}{72}(t - 48) & (t > 48h) \end{cases}$
Fast	$T_m(K) = \begin{cases} 293 - \frac{75}{4}t & (t \leq 4h) \\ 218 & (4h < t \leq 12h) \\ 218 - \frac{33}{18}(t - 12) & (12h < t \leq 30h) \\ 185 - \frac{42}{18}(t - 30) & (t > 30h) \end{cases}$	$T_m(K) = \begin{cases} 4.5 + \frac{75}{4}t & (t \leq 4h) \\ 79.5 + \frac{120}{26}(t - 4) & (4h < t \leq 30h) \\ 199.5 + \frac{100}{36}(t - 30) & (t > 30h) \end{cases}$

FIGURE 8. Time of the thermal transient modes of all eight LHC sectors

CONCLUSIONS

The mathematical model has been used to simulate the thermal transient modes of the eight LHC sectors. The results show the pressure and temperature profiles of headers of the LHC sector during the cooldown and warmup as well as the temperature evolutions of entire processes of cooldown and warmup of a typical LHC sector. The validated mathematical model has been applied to the other LHC sectors. By selecting the rational functions of the input temperature and the flow distribution, the cooldown and warmup of eight sectors have been optimized. According to the results, it is possible to cool down any of the LHC sector within 12.7 days in normal operation and 6.8 days in case of fast operation. For the warmup situation, it will be within 11.5 and 6.0 days respectively.

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