Numerical study of the final cooldown from 4.5 K to 1.9 K of the large hadron collider

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To simulate and analyze the final cooldown process of a LHC standard cell (106.9 m length) including the filling operation at 4.5 K and the cooldown from 4.5 K to 1.9 K, a mathematical model is proposed and validated by experimental data. In this model, the mass equations for liquid and vapor, the momentum equation for liquid and the general equation for mixed flow are taken into account for the different filling and cooldown phases. As a result of the simulation, the temperature profiles of the cold mass of the cell as well as the evolution of the helium void fractions, filling ratio and HeII position are obtained. The filling and cooldown times have also been estimated, and some characteristics of heat transfer of the HeII bayonet heat exchanger have been presented.

INTRODUCTION

The cooldown operation of the eight LHC sectors from 300 K to 4.5 K has been simulated and analyzed numerically [1]. However, to model and analyze the final cooldown process including the filling operation at 4.5 K and the cooldown from 4.5 K to 1.9 K, a new mathematical model is required due to the two-phase flow and superfluid helium involved. In this paper, as a basis of simulating the whole sector, the mathematical model describing the final cooldown process of a standard cell of LHC is presented.

MATHEMATICAL MODEL

Main assumptions

1) One-dimensional compressible flow for both liquid and vapor phases;
2) One-dimensional wall made of several kinds of materials with zero longitudinal thermal conductivity (due to the laminated structure of the magnet) and infinite transverse thermal conductivity;
3) Stratified flow with a smooth interface between liquid and vapor phases;
4) Saturation state at any position of channel where both liquid and vapor exist;
5) The local liquid pressure increases hydrostatically with the vertical distance from the surface;
6) No jump of pressure across the liquid-vapor interface;
7) Heat input entirely used for the vaporization of liquid helium;
8) Negligible flow between nodes of the cold mass during cooldown.

Flow scheme

The simplified flow scheme for the final cooldown of a LHC standard cell [2] is shown in Figure 1.

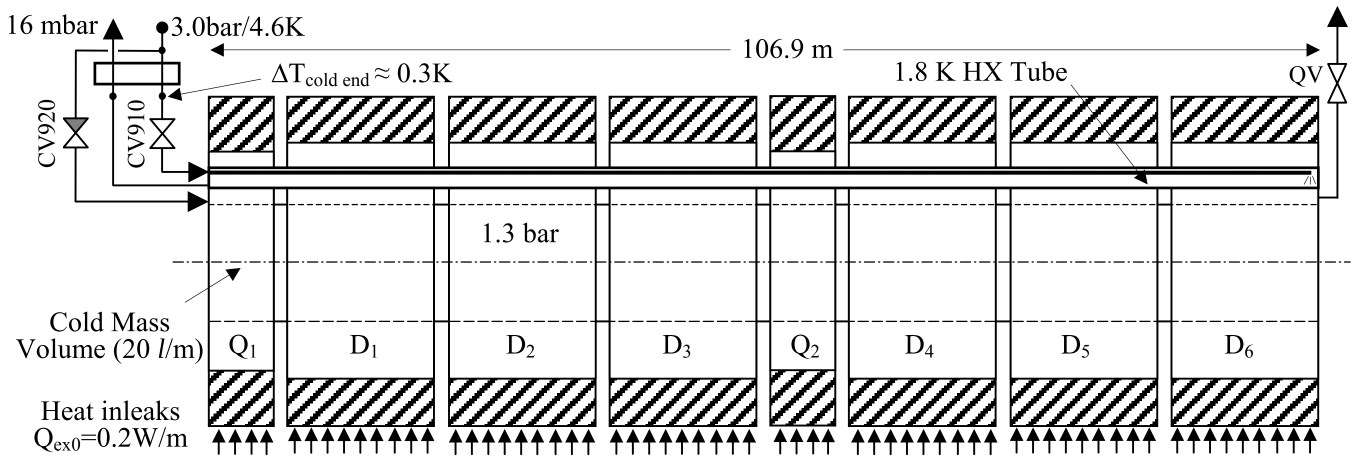


Figure 1 Simplified flow scheme of a standard cell for final cooldown

The final cooldown process is composed of two phases: filling phase at 4.5 K and cooldown phase from 4.5 K to 1.9 K (which also includes the last part of the filling). During the filling phase, the liquid helium is taken from header C and flows into the cold mass volume (the volume of the helium inside the cold mass is 20 l/m) via CV920. The liquid helium receives heat from the cold mass and then the vapor is discharged from QV to the return header. During the cooldown phase from 4.5 K to 1.9 K, two phase helium at about 16 mbar enters the bayonet heat exchanger tube (1.8 K HX tube). The helium inside the 1.8 K HX tube, after vaporizing, is pumped away via the subcooling heat exchanger. During the two phases, distributed heat inleaks Q_{ex0} have also been taken into account.

Models

For the sake of simplicity, only key equations which are applicable to the helium inside the 1.8 K HX tube and to the helium inside the cold mass volume (during the first filling phase only) are listed hereafter.

(1) Mass continuity equation for liquid helium flow:

$$\frac{\partial[(1-\alpha)\cdot\rho_l]}{\partial t}+\frac{\partial[(1-\alpha)\cdot\rho_l V_l]}{\partial x}=-\frac{\dot{m}_{vl}}{A_l+A_v} \tag{1.1}$$

where subscripts *l* and *v* represent liquid and vapor phases respectively, *A* is cross-section area, α is void fraction, *V* is velocity, ρ is density, $\dot{m}_{vl}$ is net mass transfer rate per unit length between vapor and liquid.

(2) Momentum equation for liquid helium flow:

$$\frac{\partial[(1-\alpha)\cdot\rho_l V_l]}{\partial t}+\frac{\partial\left[(1-\alpha)\cdot\rho_l V_l^2\right]}{\partial x}= -\frac{\dot{m}_{vl}(V_v-V_l)}{A_{tot}}-\frac{\tau_l S_l}{A_{tot}}+\frac{\tau_i S_i}{A_{tot}}+(1-\alpha)\cdot\rho_l g\sin\beta-\frac{\partial[(1-\alpha)\cdot p_l]}{\partial x}+p_v\frac{\partial(1-\alpha)}{\partial x} \tag{1.2}$$

where τ, S are shear stress and wetted perimeter of the helium with the wall, τ_i, S_i are interface shear stress and interface perimeter between the phases, β is channel inclination (positive or negative), g is acceleration of gravity, p_l is mean pressure of liquid helium.

(3) Mass continuity equation for helium vapor flow:

$$\frac{\partial(\alpha\rho_v)}{\partial t}+\frac{\partial(\alpha\rho_v V_v)}{\partial x}=\frac{\dot{m}_{vl}}{A_l+A_v} \tag{1.3}$$

(4) General energy equation for helium flow:

$$\frac{\partial[\rho_l(1-\alpha)\cdot e_l+\rho_v\alpha e_v]}{\partial t}+\frac{\partial[\rho_l(1-\alpha)\cdot V_l e_l+\rho_v\alpha V_v e_v]}{\partial x}-\frac{\partial[(1-\alpha)\cdot p_l+\alpha p_v]}{\partial t}= -\frac{1}{A_l+A_v}\frac{\partial Q_i}{\partial x}-\frac{\tau_l S_l V_l}{A_l+A_v}-\frac{\tau_v S_v V_v}{A_l+A_v}+\frac{Q_h}{A_l+A_v} \tag{1.4}$$

where $e = h + V^2/2 + g\cdot x\cdot sin\beta$ is the total energy transferred by the convection of unit mass of He, h is specific enthalpy and Q_h is heat flow in liquid He.

SIMULATION RESULTS AND DISCUSSION

Filling phase

During the filling phase, the mass flow rate of 4.5 g/s for normal operation is considered. Figure 2 gives the void fraction in the cold mass volume as a function of time at each cell position. From this figure we can see that, after 14.5 h, about 2/3 of the volume is filled with liquid helium. Due to the position of the inlet and outlet tappings, 2/3 of the volume is the limitation for the filling phase and to complete the filling, the cooling by the 1.8 K HX has to be started. Figure 3 gives the temperature of cold mass as a function of time. This figure shows that before the liquid helium arrives, the temperature of the cold mass increases over time, and that the highest rise is less than 1.6 K. This happens because the helium vapor warms up as it flows past the warm magnets.

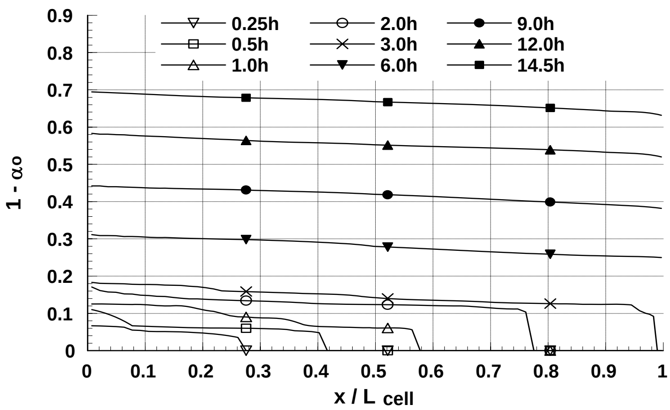


Figure 2 Development of liquid helium during filling of a standard cell (α_o is void fraction of He outside HX)

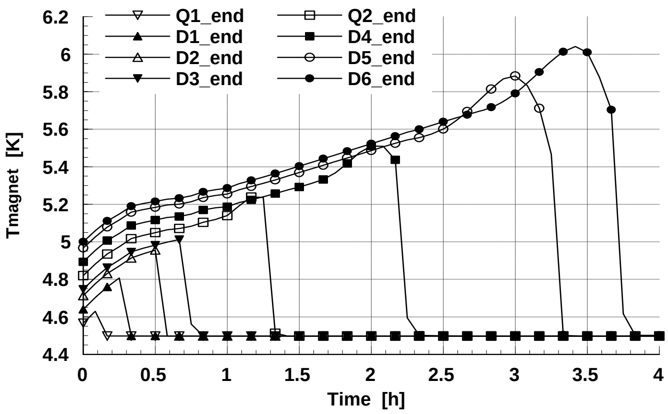


Figure 3 Temperature of each magnet versus time versus filling of a standard cell

Figure 4 shows the overall filling ratio of liquid helium versus time. At the beginning the filling ratio does not rise linearly with time as the vaporization increases gradually (finite number of nodes during discretization explains the small waves of the curve). The vaporization postpones the accomplishment of the filling of the 2/3 of the volume of the cold mass tube from 10.8 h to 14.5 h. As soon as the liquid helium reaches the opposite end of the cold mass (after about 3.1 h), the temperature of cold mass at any cell position reaches 4.5 K. As a consequence, the vaporization remains fixed and the filling curve becomes linear.

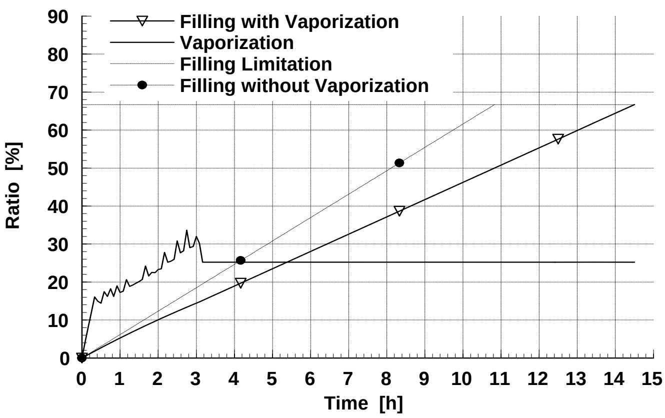
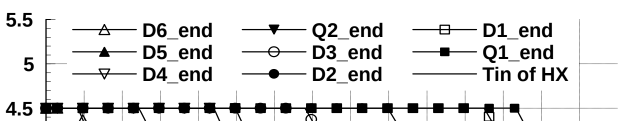


Figure 4 Overall filling ratio of liquid helium versus time during filling

Final cooldown phase

In order to compare the calculation results with the test data of String 2 [3], we use the mass flow rate of 7.8 g/s to simulate the final cooldown phase and validate thus the mathematical model. Figures 5 and 6 give the simulation and the test results respectively. The calculation shows that the further cooldown will last about 7 h, which is in good agreement with the test results. Some differences between simulation and test curves can be explained by the assumption No.8. As a consequence of this assumption, the discretization nodes are filled (last part of the filling) and cooled down one by one. This difference may be also explained by the instabilities during tests caused by the large flow. In the simulation only the pumping pressure of 16 mbar was used. A phenomenon can be observed from the computing results is that once the T_λ is reached, the temperature of cold mass reduces to 1.8 – 1.9 K rapidly due to the very high heat conduction in HeII.



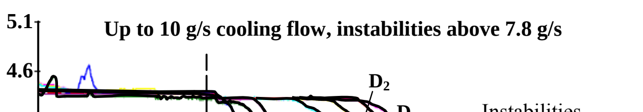


Figure 5 Temperature profiles of magnets during final cooldown of a standard cell

Figure 6 Test results of final cooldown of a standard cell

The normal final cooldown, performed with a mass flow rate of 4.5 g/s, has also been simulated and results are shown in Figure 7, which demonstrates that this phase will take about 13.3 h. It should be recalled that before T_λ is reached, helium in the cold mass tube is cooled mainly by the heat convection from the 1.8 K HX tube. From Figure 7 it can be also noticed that the position of the HeII front inside the 1.8 K HX tube fluctuates with time. This is due to the discretisation used in the mathematical model.

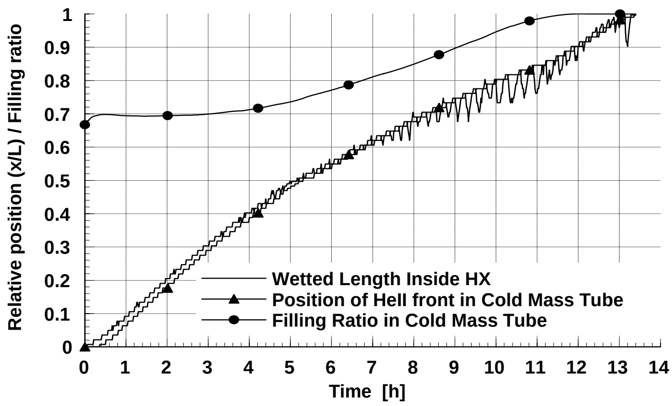


Figure 7 Position of the HeII front and overall filling ratio during final cooldown of a standard cell

CONCLUSIONS

A mathematical model developed for simulating the last phase of cooldown (filling at 4.5 K and cooldown from 4.5 K to 1.8 K) of a LHC standard cell is proposed and the results are in good agreement with experimental data. The filling at 4.5 K up to 2/3 of the cold mass volume takes 14.5 h and the last part of the filling and cooldown from 4.5 to 1.8 K takes 13.3 h. Before T_λ is reached, helium inside the cold mass tube is cooled mainly by the heat convection from the 1.8 K HX tube.

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REFERENCES

1. Liu L., Riddone G. and Tavian L., Numerical Analysis of Coolddown and Warmup for the Large Hadron Collider. Cryogenics, 2003, 43(6): 359~367
2. Lebrun, Ph., Superconductivity and cryogenics for the Large Hadron Collider, in Proc. of Beijing International Conference on Cryogenics, Beijing (2000): 28-34
3. Blanco, E., et al., Experimental validation and operation of the LHC test string 2 cryogenic system**,** Advances in Cryogenic Engineering 49, American Institute of Physics, 2004 (to be published)