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Thermo-Mechanical Analysis of Cold Helium Injection into Gas Storage Tanks Made of Carbon Steel Following Resistive Transition of The LHC Magnets

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Abstract

A resistive transition (quench) of the LHC sector magnets will be followed by cold helium venting to a quench buffer volume of 2000 m^3 at ambient temperature. The volume will be composed of eight medium-pressure (2 MPa) gas storage tanks made of carbon steel, which constrains the temperature of the wall to be higher than -50 ^{o}C (223 K). The aim of the analysis is the assessment of a possible spot cooling intensity and thermo-mechanical stresses in the tank wall following helium injection.

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Thermo-mechanical analysis of cold helium injection into gas storage tanks made of carbon steel following resistive transition of the LHC magnets

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A resistive transition (quench) of the LHC sector magnets will be followed by cold helium venting to a quench buffer volume of 2000 m^3 at ambient temperature. The volume will be composed of eight medium-pressure (2 MPa) gas storage tanks made of carbon steel, which constrains the temperature of the wall to be higher than -50 ^oC (223 K). The aim of the analysis is the assessment of a possible spot cooling intensity and thermo-mechanical stresses in the tank wall following helium injection.

1 INTRODUCTION

A resistive transition (quench) of the LHC magnets will be followed by helium discharge expulsion from magnet cold mass to the helium recovery system composed of vacuum-insulated header D in the cryogenic distribution line QRL, medium pressure tanks and auxiliaries - Figure 1 [1]. Then about1400 kg of helium per sector will have to be vented to a quench buffer volume of 2000 m^3 at ambient temperature. The volume will be composed of eight medium-pressure gas storage tanks, 250 m^3 each. The medium-pressure tanks are made of carbon steel, which constrains the temperature of the wall to be higher than -50 ^oC (223 K). The temperature of the helium flowing into a single tank will be about 12 K and its mass flow of about 2.5 kg/s for about 70 seconds. To avoid a single jet formation, pressurised helium may be injected through a number of small orifices drilled in a dedicated distributor pipe inside the tank - see Fig. 2. The aim of the analysis is the assessment of a possible spot cooling intensity and thermo-mechanical stresses in the tank wall following helium injection.

2 COMBINED ANALYTICAL AND FINITE ELEMENT (FE) MODELLING OF HELIUM INJECTION INTO A MEDIUM-PRESSURE TANK

Analysis of the helium injection into the medium-pressure storage tank and its effect on the thermo-mechanical stresses and deformations in the tank wall is done in three steps.

Step 1. An axisymmetric helium jet based on turbulent flow is analytically described and computed on the following assumptions:

- the helium pressurised at about 20 bar is injected through a number of small orifices to form conical jets reaching the inner surface of the tank wall (Fig. 2),
- the helium velocity profile at the jet exit is uniform block and the jet is injected into the medium-pressure tank approximately at the velocity of sound (the pressure inside the tank remains below 10 bar),
- the jet and reservoir gas are separated by a thin shear layer (boundary layer) containing vortices,
- since the Reynolds number is of order of 10^6 the flow within the jet is turbulent,

- an approximation is made to represent the turbulent flow near the tank wall - the velocity profile is again assumed uniform and equivalent in terms of the total axial momentum flux to the theoretical non-uniform velocity profile.

Step 2. The heat transfer across the boundary layer centred around the stagnation point and covered by the jet crown area is modelled, and the heat flux from the helium to the wall is estimated.

Step 3. A finite element model of a fragment of the tank wall in contact with the jet crown is built based on the coupled thermo-mechanical equations. The local thermal stresses and deformations in the tank wall are computed by using the coupled thermo-mechanical 3-D finite elements [2].

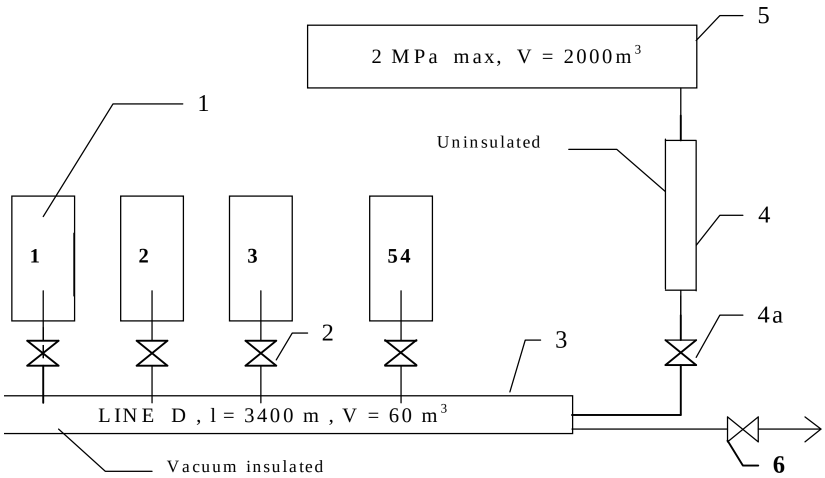

Figure 1, Helium recovery system, scheme for one LHC sector: 1 - cryogenic half-cells, 2 - quench relief valves, 3 - vacuum insulated line D, 4 - uninsulated vertical line, 5 - medium pressure gas tanks, 6 - auxiliaries

2.1 The turbulent axisymmetric jet model description

The rotationally symmetric conical jets exit from a number of circular orifices of dimensions small when compared to the inner tube diameter (Fig.2).

The following additional assumptions are made:

- all further considerations concern the region far downstream,
- the jet velocity profile u(x,r) becomes self-preserving - see Eq.(1),
- cross-stream scale is small compared to the length of the jet.

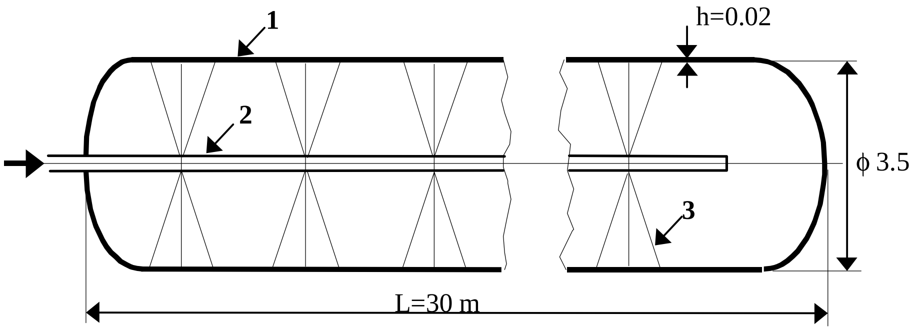

Figure 2, Helium storage tank with the axisymmetric conical jets: 1- medium-pressure tank, 2- inner tube with drilled orifices, 3- jet.

The analytical description of the jet is based on the following equations:

- Preservation of the total axial momentum flux (J):

$$J = \rho \iint u^2 dS = \text{const}, \qquad (1)$$

where *u(x,r)* is the velocity and ρ stands for the helium density.

- The radius δ of the turbulent zone is proportional to the distance from the jet exit [3]:

$$\delta(x) = C_1 x\,. \qquad (2)$$

- The condition of similarity of the velocity profiles:

$$\frac{u(x,r)}{u(x,0)} = f\left(\frac{r}{\delta}\right). \qquad (3)$$

- Final velocity profile (shown schematically in Fig. 3a):

$$u = C_0 u_0 \sqrt{\pi}\,\frac{R_0}{x}\left(1-\mathrm{tgh}^2\eta\right), \quad \eta = \frac{r}{\delta} \qquad (4)$$

Here R_0 denotes the effective radius of the orifice whereas u_0 stands for the centreline velocity. An uniform velocity profile in the jet crown resulting from turbulent flow induced intensive mixing of gas is assumed. The uniform velocity profile u_∞ is based on a similar assumption of the axial momentum flux being constant over the area of the jet crown:

$$J_R = 2\pi\rho\int_0^R u^2 r dr = \pi R^2 \rho u_\infty^{\ 2} \quad ; \qquad u_\infty = \sqrt{\frac{J_R}{\pi R^2 \rho}} \qquad (5)$$

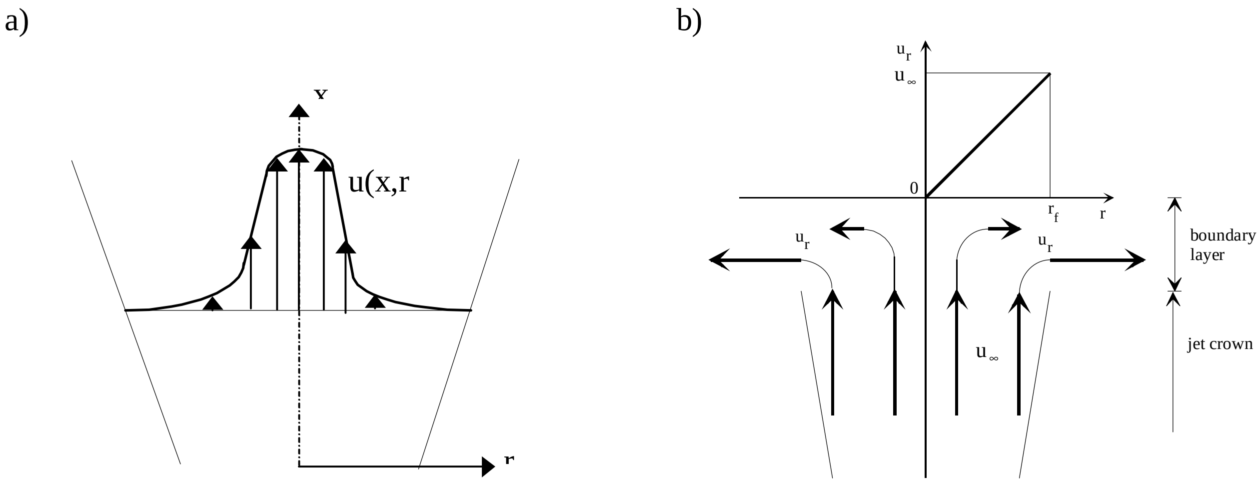

Figure 3, a) velocity profile of a turbulent jet; b) uniform velocity profile in the jet crown

<u>2.2 Heat transfer through the axisymmetric boundary layer</u>

A conceptual view of the jet crown reaching the tank wall is shown in Fig. 3b. The gas being close to the tank wall will slow down, pressurise and then expand changing the velocity direction from perpendicular to parallel with respect to the tank wall.

The heat transfer coefficient α is obtained from the following set of equations:

$$\mathrm{Nu}_r = 0.57 \cdot \mathrm{Re}_r^{\ 0.5}\,\mathrm{Pr}^{0.37} \quad ; \quad \alpha = 0.57\lambda\left(\frac{u_\infty}{r_f\gamma}\right)^{0.5}\mathrm{Pr}^{0.37} \qquad (6), (7)$$

for $\quad u_r = \dfrac{u_\infty}{r_f} r \quad ; \quad 0<x<r_f ,$

3. STRESS AND DEFORMATION ANALYSIS

The highly non-uniform heat transfer into the tank wall results in a localisation of thermal strains and stresses. In order to compute them a finite element model based on the coupled thermo-mechanical equations was made. The analysis was carried out by using ANSYS 5.3 [2] SOLID5 (3-D) thermo-mechanical finite elements.

The following jet parameters were established:

$$C_0 = \frac{1}{1.36 C_1} \approx 26.8 \ ; \qquad u_\infty = u_0 \frac{R_0}{R} \approx 1.93 \quad [\mathrm{m/s}] \qquad (8)$$

The maximum centreline velocity calculated according to the profile given by (4) is of 10 m/s. The jet crown diameter was estimated of about 0.38 m close to the tank wall. The estimated heat transfer coefficient $\alpha =$ 170 W/m^{2}K leads to a spot heat flux to the wall of 43 kW/m^2. The localisation of temperature gradients results in similar localisation of thermo-mechanical stresses and deformations. Tresca representation of the equivalent stresses (conservative approach) is shown in Fig. 3 for the inner face of the tank wall after 70 s of jet exposure. It turns out that the maximum total equivalent stress (based on membrane and flexural components) is of the order of 120 MPa (when compared to the yield strength of 330 MPa). The lowest calculated temperature is 233 K.

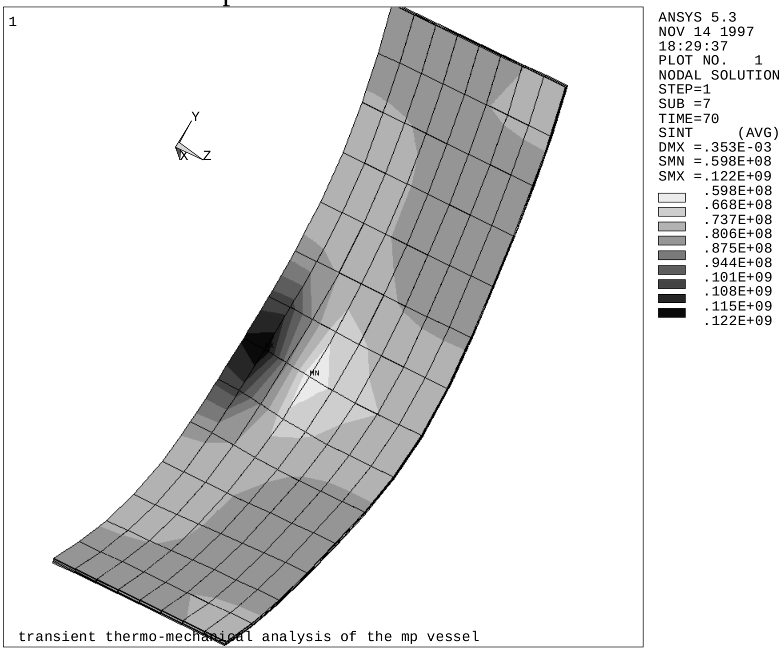

Figure 4, Tresca equivalent stress on the inner face of the tank (after jet decay).

Jet parameters have been confirmed experimentally. Centreline velocities measured 1.75 m from the jet exit were 8.5 and 10.2 m/s respectively for jet exit orifice diameters equal to 5 and 3 mm. The jet crown was 0.47 m in diameter.

4. CONCLUSIONS

- The analysis presented above shows that the 2 MPa carbon steel storage tanks may serve as the efficient quench buffer vessels, provided that the cold helium injection is redistributed over a sufficient length to form a number of jets.
- Both the temperature of the cold spots and the localised equivalent stresses are limited to their admissible values of -50 ^{o}C and 160 MPa, respectively.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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