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Thermo-mechanical analysis of cold helium injection into medium-pressure (MP) gas storage tanks following resistive transition of a LHC sector

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1. Introduction

A resistive transition (quench) of the LHC magnets will be followed by helium discharge from magnet cold mass to vacuum-insulated header D in the cryogenic distribution line QRL. In case of a whole sector quench, about 6500 kg of helium will flow into header D. To keep the pressure in the header below the design value i.e. 20 bar, about 1400 kg of helium will have be vented to a quench buffer volume of 2000 m^3 at ambient temperature per sector. The volume will be composed of 8 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 °C (223 K). The temperature of the helium flowing into a single tank will be of about 12 K and its mass flow of about 2.5 kg/s for about 70 seconds. Due to the high heat capacity of the tanks the in-flowing helium will warm up while the average tank wall temperature will decrease by about 8 K, remaining well above the limit[1]. 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. 1. 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

Combined analytical and FE model description 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 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 (see Fig. 1),
- 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 very large (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.
- In the step 1, the jet crown radius close to the tank wall and velocity profile are calculated.

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 wall to the helium 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].

2.1 The turbulent axisymmetric jet model description

The model analysis of a turbulent jet is based on the following assumptions.

The rotationally symmetric conical jets exit from a number of circular orifices of dimensions small when compared to the inner tube diameter (Fig.1).
The zone close to the orifice is regarded as a transition region from the uniform velocity profile to a highly non-uniform profile. Thus, for the sake of simplicity the following additional assumptions are made:

- all the 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.

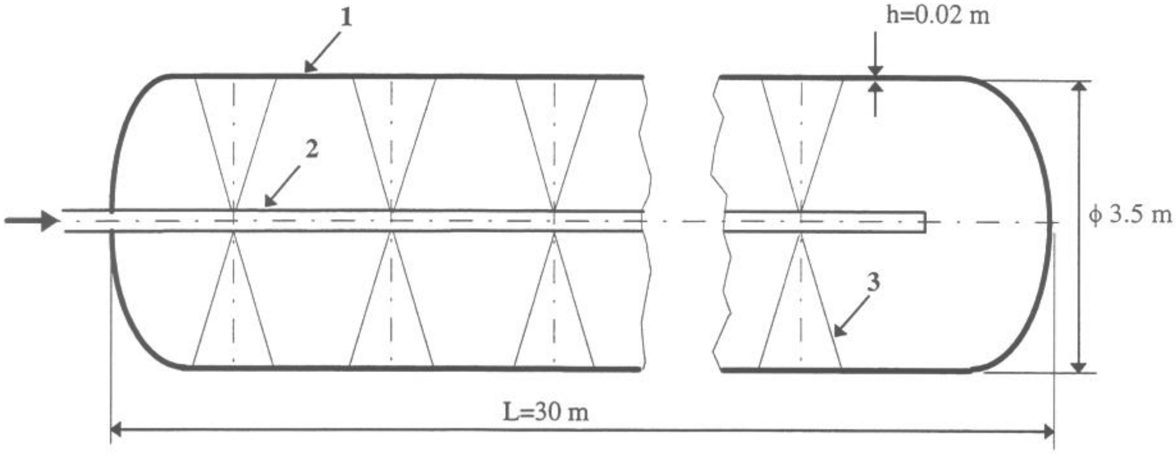

Fig.1 Helium storage tank with the axisymmetric conical jets:
1- medium-pressure tank, 2- inner tube with drilled orifices, 3- jet.

In the case of a constant density, round jet the velocity profile u(x,r) (see Fig.2) should satisfy the following condition:

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

where J denotes the total axial momentum flux and ρ stands for the helium density. Experiments show that the radius $\delta(x)$ of the turbulent zone is proportional to the distance from the jet exit[3]:

$$\delta(x) = C_1 x . \tag{2}$$

The condition of similarity of the velocity profiles leads to the following equation:

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

The Reynolds averaged momentum equations combined with the continuity equation for the mean flow and completed with the introduction of the stream function:

$$\psi = u_s F(\eta) \;,\; \eta = \frac{r}{\delta} \tag{4}$$

lead to the following velocity profile:

$$u = C_0 u_0 \sqrt{\pi}\, \frac{R_0}{x} \left(1 - \text{tgh}^2 \eta\right), \tag{5}$$

which is shown schematically in Fig. 2. Here R_0 denotes the effective radius of the orifice whereas u_0 stands for the centreline velocity. The constant C_1 shall be experimentally determined whereas C_0 may be f ound by substituting Eq. (5) into Eq. (1).
In order to simplify the assessment of the heat transfer through the axisymmetric boundary layer that forms close to the tank wall, a uniform velocity profile in the jet crown is assumed. This assumption is related directly to the following observation: the crown of the jet usually becomes completely turbulent at a certain distance from the

orifice and as a result of intensive mixing the above shown theoretical profile is no more valid.

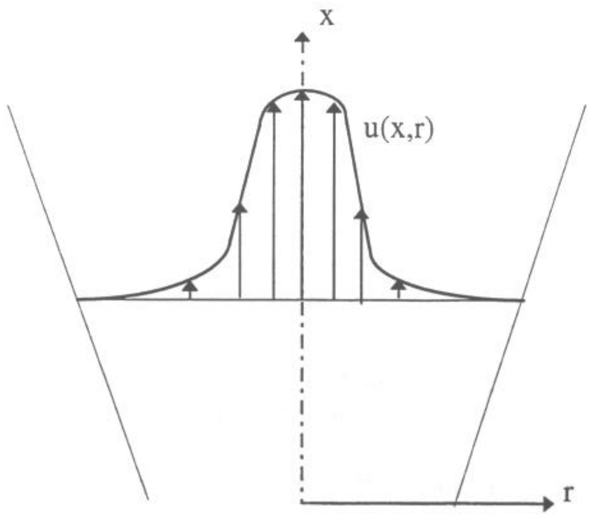

Fig.2 Velocity profile of a turbulent jet.

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:

$$J_R = 2\pi\rho \int_0^R u^2 r dr = \pi R^2 \rho u_\infty^{\ 2} \ . \quad (6)$$

Finally,

$$u_\infty = \sqrt{\frac{J_R}{\pi R^2 \rho}} \quad (7)$$

2.2 Heat transfer through the axisymmetric boundary layer

A conceptual view of the jet crown reaching the tank wall is shown in Fig. 3. The above defined uniform velocity profile u_∞ is assumed. 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. A full stoppage of the helium is assumed at the stagnation point lying in the centre of the jet crown. Then bifurcation of the flow along the inside of the tank wall around the stagnation point is observed.
The heat exchange between the gas and the wall will occur through a thin boundary layer.
The vicinity of the stagnation point is defined as the area for which $r < r_f$ (see Fig. 3) where r_f is the radius of the jet crown.

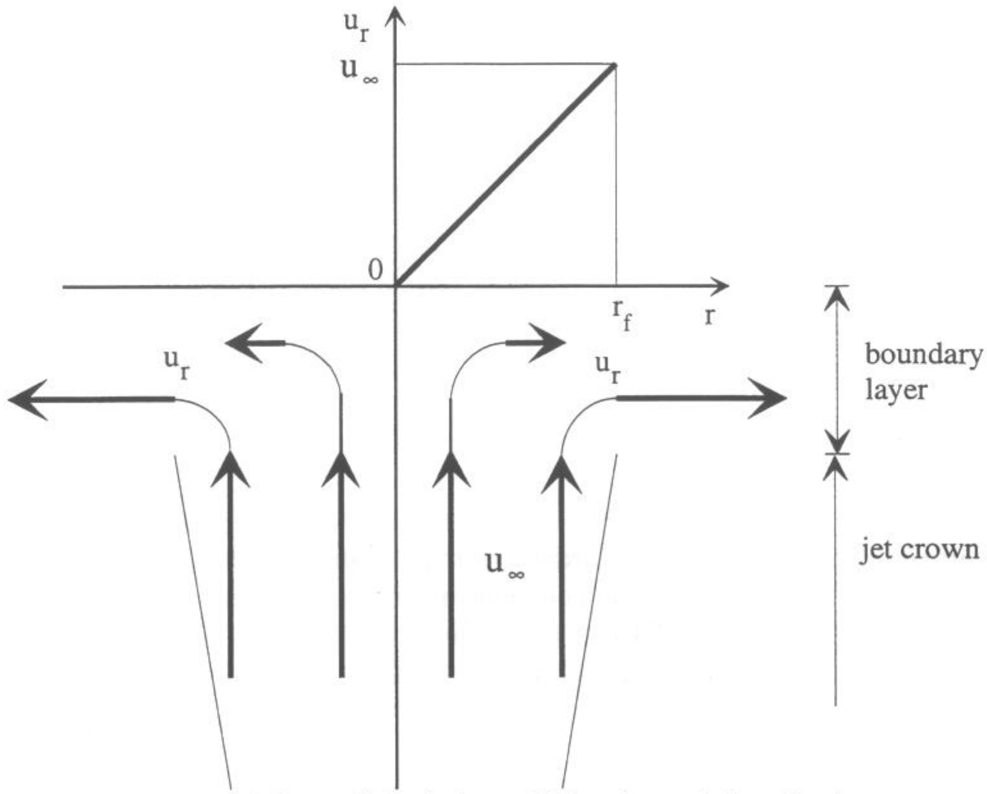

Figure 3. Jet crown and helium radial velocity profile in axisymetric boundary layer (stagnation point in 0).

In the vicinity of the stagnation point the equations of mass, momentum and energy conservation written for the boundary layer lead to the following dimensionless equation[4]

$$\mathrm{Nu}_r = 0.57 \cdot \mathrm{Re}_r^{0.5}\, \mathrm{Pr}^{0.37} \tag{11}$$

where: $\mathrm{Re}_r = \dfrac{u_r r}{\gamma}$,

$\mathrm{Nu}_r = \dfrac{\alpha \cdot r}{\lambda}$

and $\mathrm{Pr} = \dfrac{c\eta}{\lambda}$,

γ denotes kinematic viscosity, α - heat transfer coefficient, η - dynamic viscosity and λ stands for the helium conductivity.

We assume a linear velocity u_x profile in the vicinity of the stagnation point with the following boundary conditions - see Fig. 3:

$u_x = 0$ for $x = 0$ (stagnation point)

$u_x = u_\infty$ for $x = r_f$ (edge of the jet crown) hence for $0<x<r_f$ we get:

$$u_r = \frac{u_\infty}{r_f} r \quad (12)$$

Combining equations (11) and (12) we obtain heat transfer coefficient in the vicinity of the stagnation point, as a function of the gas velocity in the jet crown and helium properties only:

$$\alpha = 0.57\lambda\left(\frac{u_\infty}{r_f \gamma}\right)^{0.5} \mathrm{Pr}^{0.37} \quad (13)$$

2.3 The thermo-elastic finite element model

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 has been built. The analysis was carried out by using ANSYS 5.3[2]. SOLID5 (3-D) finite elements are based on the load vector coupling i.e. the coupled effect is accounted for in the load terms (right hand side of the matrix equations):

$$\begin{aligned} &[K]\{u\} = \{F^{nd}\} + \{F^{th}\} + \{F^{pr}\} + \{F^{ac}\} \\ &[C^t]\{\dot{T}\} + [K^t]\{T\} = \{Q^{nd}\} + \{Q^g\} + \{Q^c\} \end{aligned} \quad (14)$$

where:

[K] - structural stiffness matrix,
[C^t] - thermal specific heat matrix,
[K^t] - thermal conductivity matrix.

A square segment Ω of the tank wall, centred around jet axis, is considered (Fig.4).

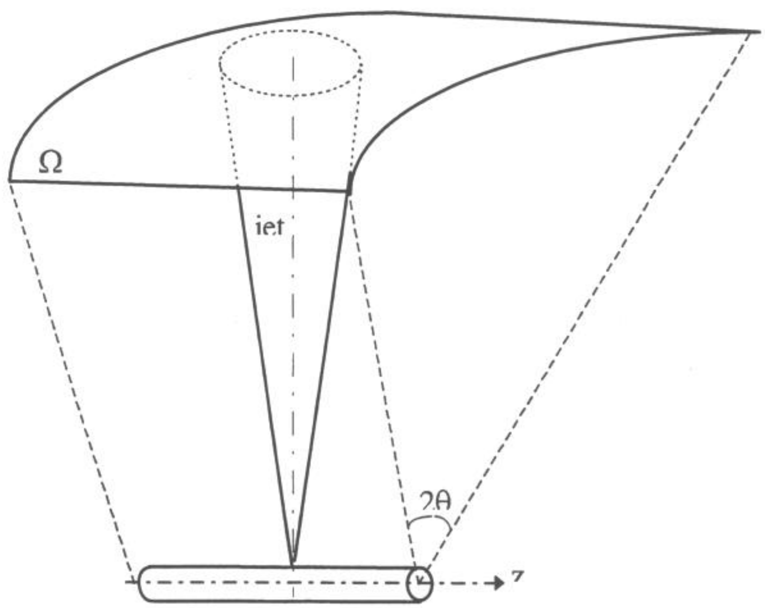

Fig.4 Position of the tank wall fragment with respect to jet.

The symmetry boundary conditions were imposed on the radial planes ($\pm\theta$). Since the cylinder being modelled is long enough, nodes at one edge in the longitudinal direction "z" are coupled to impose a plane strain condition.
In order to compute distribution of the strains and stresses across thickness, the tank wall is subdivided into 4 layers of elements.
Heat transfer between the outer surface and the environment is neglected (adiabatic conditions). The inner face is subjected to both the pressure of helium and the heat flux of constant intensity for a limited time (approximation of the real heat flux distribution). The heat flux intensity inside the jet crown is much higher than its outside intensity.
The transient thermal analysis is carried out over a time scale corresponding to the jet duration (up to the complete decay of the jet). The stress and strain fields induced by thermal gradients reach their maximum with the decay of the jet.

3. Stress and deformation analysis

The finite element simulations have been performed for the following general conditions.

- The helium is injected into the medium-pressure tank through 80 orifices drilled in the pipe threading its way along the tank (see Fig.1), the axial distance between the two adjacent orifices is 1.5 m and the circumferential one is 90 deg. The diameter of the orifice is 5 mm.
- The temperature of the the injected helium is 15 K and its density 60 kg/m^3, the helium is injected with the speed of sound, the total helium mass flow into a tank is 2.5 kg/s (31 g/s per orifice). The estimated jet duration is 70 seconds.

3.1 Calculation of the jet crown diameter and velocity profile

In order to compute parameters of the turbulent jet two constants have to be determined: C_0 - scaling factor for the maximum velocity downstream and C_1 - associated with the linearly increasing diameter of the mixing zone. The C_1 constant has been determined experimentally for a typical turbulent jet [5] and is equal to 0.0275. The other constant C_0 calculated from the condition (1) is equal to:

$$C_0 = \frac{1}{1.36 C_1} \approx 26.8 \qquad (15)$$

Assuming an injection speed of 240 m/s, the crown diameter at a distance of 1.7 m grows up to 0.38 m (the diameter of the zone of jet velocity decay in the radial direction is calculated as $8C_1x$, see Fig.2). Also, the maximum centreline velocity (cf. Fig.2), calculated according to the profile given by (5), is equal to around 10 m/s. Finally, the uniform, equivalent velocity for the turbulent helium flow (Eqs. 6 and 7) far downstream from the orifice (distance of 1.7 m) may be calculated as follows:

$$u_\infty = u_0 \frac{R_0}{R} \approx 1.93 \text{ [m/s]} \qquad (16)$$

where R_0 denotes effective radius of the orifice (of around 3 mm) and R denotes the crown radius.

3.2 Calculation of the heat flux to the tank wall

The heat transfer coefficient α to the tank wall is given by Eq. (13). For a uniform velocity profile $u_\infty = 1.93$ m/s, helium temperature 12 K and pressure 2 MPa, and assuming that the properties of the gas forming the boundary layer change in a negligible way in the vicinity of the stagnation point, we get $\alpha =$ 170 W/m^{2}K. An average temperature difference of 250 K between the helium and the tank wall is assumed and a spot heat flux to the wall of 43 kW/m^2 is computed.
The residual heat flux outside the jet crown is estimated on basis of the overall heat balance of the system and is about 2 kW/m^2.

3.3 Simulation of thermo-mechanical stresses and strains in the tank wall

A 0.8 m long tank wall segment of ±45.8 degree angular length has been considered. The FE mesh is based on 8 divisions in the longitudinal and 14 divisions in the circumferential direction, respectively. The boundary conditions of symmetry were imposed at the edges z=0 as well as θ=±45.8 degree.
The segment was pressurised up to 1 MPa inner pressure and was subjected to a heat flux. The heat flux intensities given in the previous chapter are redistributed over 2 central elements (covering the zone of jet crown of 0.38 m in diameter) and the rest of the segment to represent the effect of the residual heat flux.
The thermal conductivity of the carbon steel was input as a function of temperature for the temperature range 25-300 K.
The time scale necessary for the helium injection into the storage tank (being the time of exposure of the tank wall to highly localised thermal fields) is estimated at 70 seconds. In the transient process of heat transfer, the initial uniform temperature (273 K) of the tank wall changes and a localisation of thermal gradients is observed. The isotherms on the inner and outer face of the wall are shown in Figs 5 and 6, respectively. A maximum local temperature decrease down to 226 K is observed at the impact spot on the inner face of the tank. Thus, the minimum admissible temperature of 223 K (-50 °C) for the carbon steel grade P355NL2 is not exceeded.
The localisation of temperature gradients results in similar localisation of thermo-mechanical stresses and deformations. Since the evaluation of computed stresses according to Section C10 of CODAP[6] requires the Tresca representation of the equivalent stresses (conservative approach) - this stress function is shown in Figs 7 and 8 for the inner and the outer faces, respectively. It turns out that the maximum total equivalent stress (based on membrane and flexural components) is of the order of 120 MPa.
The admissible stress for a carbon steel (that depends on the type of reception of the product) is in the worst case (CODAP 90 - C1/23) equal to:

$$\sigma_{ad} = \min\left\{\left(\frac{R^t_{0.002}}{1.6}\right),\left(\frac{R}{3}\right)\right\} \tag{17}$$

where $R^t_{0.002}$ denotes the yield stress at the temperature t and R denotes the ultimate stress at room temperature. Since these values guaranteed by the manufacturer are equal to 330 MPa and 490 MPa, respectively[7] , the admissible stress is of 163 MPa. The admissible stress for a local zone may be 50% higher which leads to the value of

245 MPa. Also, the stresses that were computed are a combination of the primary (mechanical) and secondary (thermal) stresses. Variation of the total equivalent combined stresses should satisfy the inequality:

$$\Delta\sigma_{eq} \leq 3\sigma_{ad} \tag{18}$$

in order to avoid a progressive deformation and to achieve the state of plastic adaptation to the possible cyclic loads.
All of the above presented conditions are satisfied for the discussed case.

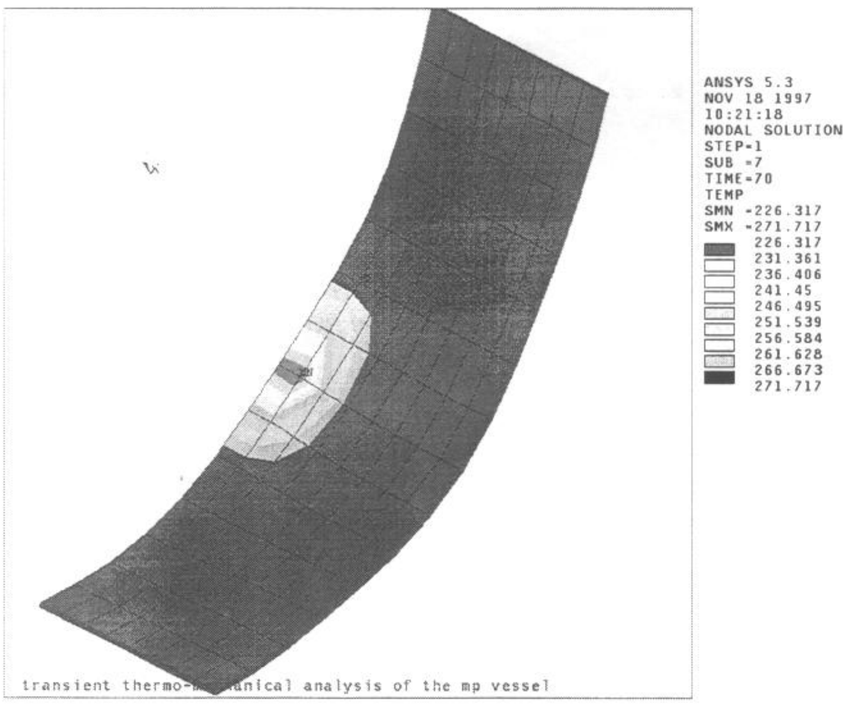

Fig.5 Isotherms on the inner face of the helium storage tank (after jet decay).

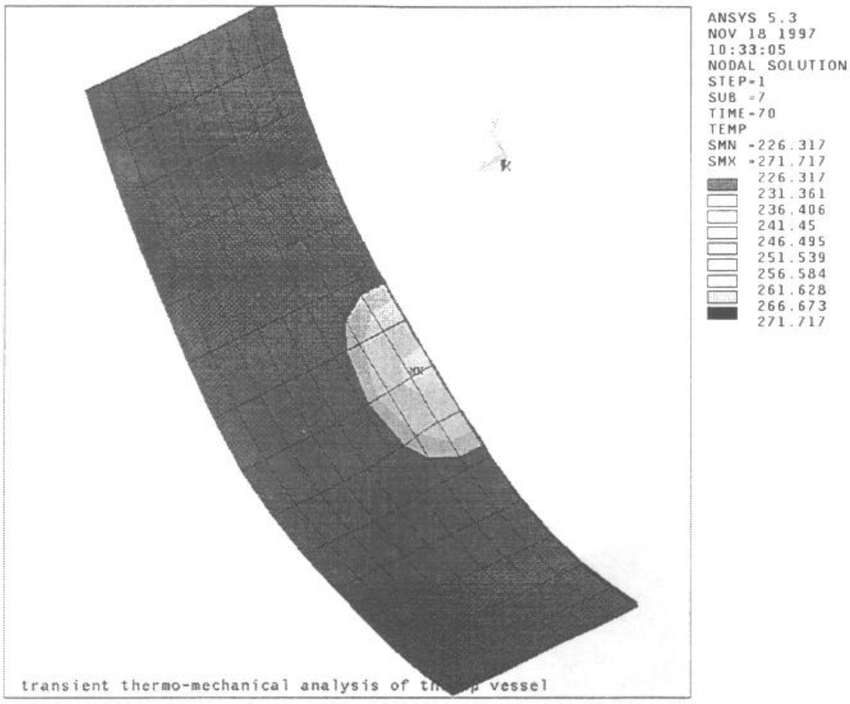

Fig.6 Isotherms on the outer face of the helium storage tank (after jet decay).

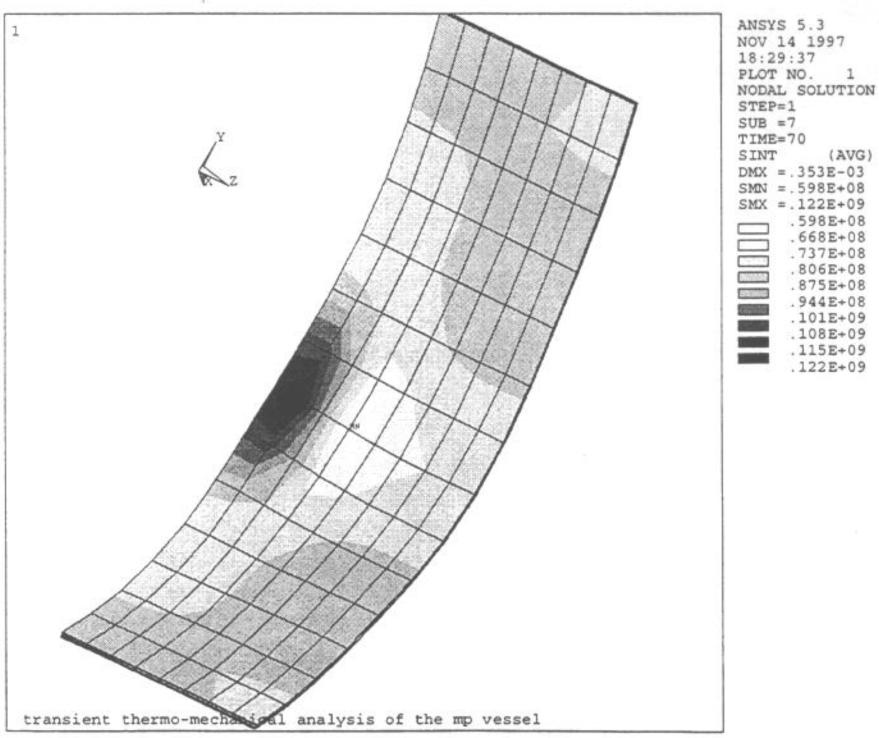

Fig.7 Tresca equivalent stress on the inner face of the tank (after jet decay).

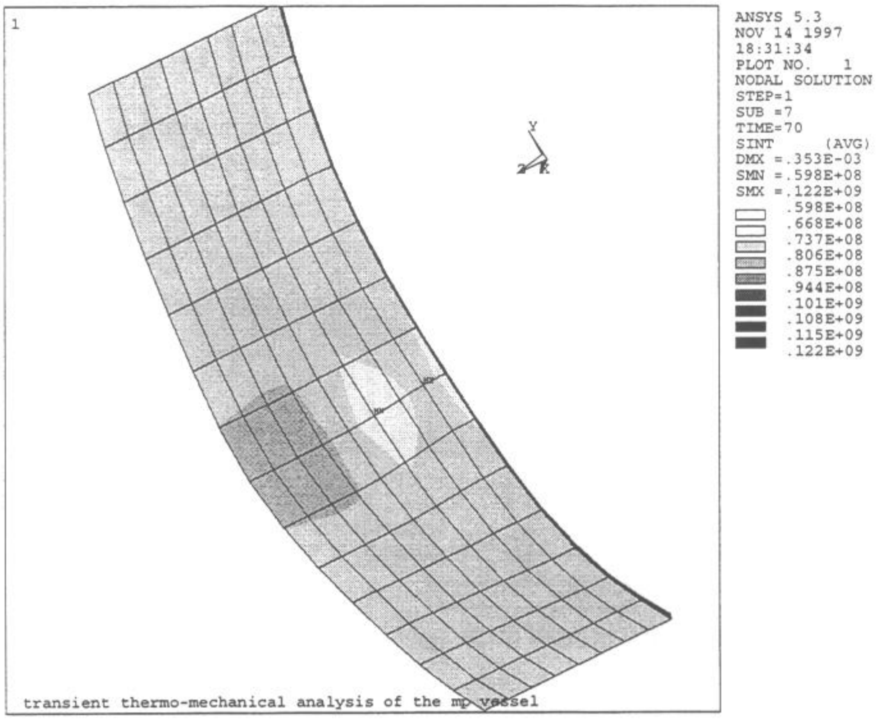

Fig.8 Tresca equivalent stress on the outer face of the tank (after jet decay).

4. Conclusions

- The above presented analysis of thermo-mechanical stresses in the tank wall shows that cold helium injection (following LHC sector quench) through a number of orifices drilled in a dedicated pipe will not provoke a state of strains and stresses in the tank wall that exceed the admissible values calculated according to CODAP 90.
- The temperature of the cold spot will decrease to about 226 K and will stay within the carbon steel operation limit i.e. above -50 °C.
- It is strongly recommended to verify experimentally the presented assessment of the jet crown area, the hypothesis of turbulent mixing of helium in the crown, the velocity profile as well as the heat fluxes to the tank wall. A test rig composed of a tube with a single orifice directed towards a cylindrical steel panel, equipped with a thermo-vision camera is proposed in order to verify the localisation of the thermal gradients as well as the state of stress.

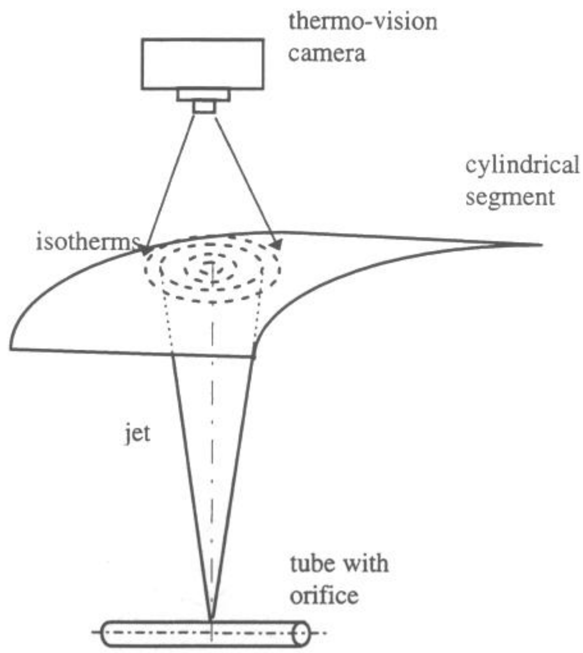

Fig.9 Conceptual schema of the proposed experiment.

- The results can be extrapolated to similar situations associated with a loss of tightness in the LHC cryogenic lines, inside the LHC magnet interconnect zones or elsewhere - where there exists a leak-induced danger of blowing cold gas into a thin walled structure like thermal shield, radiation screen, cryostat etc.

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