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Fluid dynamics analysis of the discharge of cold helium into the storage vessel following a fast discharge of the JT-60SA superconducting coils☆

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ABSTRACT

The cold gaseous helium, exhausted from the superconducting toroidal field coils of JT60-SA following a fast discharge will be released through a quench line into a 250 m^3 storage vessel. An analysis has been performed to compute the transient mass flow, the temperature and pressure along the quench line and in the helium gas storage vessel in order to assess if the vessel, made from carbon steel, is always above its allowed minimum temperature.

1. Introduction

In the case of a fast discharge of the JT-60SA toroidal field coils (TFC), eddy currents mostly in the steel casing will increase the helium temperature (T). The pressure (P) in the He lines/manifolds will consequently increase until a control relief valve will discharge the cold He through manifolds into a quench line (QL). This line is connected with one of six 250 m^3 storage vessels which is kept during operation at about 120 kPa (a). The vessel is made in carbon steel. It is therefore important to assess if the cold He jet could result in vessel areas where the T is below the minimum allowable for the material (233 K).

The analysis was made in two steps. First the transient mass flow, T, P and the He velocity along the QL have been computed using an analytical model. Due to the complexity of the CFD equations some simplifications have been considered, namely:

- In the QL only the turbulent gas flow is considered (no buoyancy, velocities below sonic).
- The pipe is modelled as straight.
- No temperature gradient across the pipe wall.
- Pressure drop in the quench line is caused by friction only. Pressure drop caused by acceleration of the fluid is not considered.

Next the resulting He conditions at the outlet of the quench line are used as input to a FEM CFD analysis of the He storage vessel.

2. Input data

After the opening of the relief valve at ~1.6 MPa, the transient mass flow and the T of the cold He entering the QL have been taken from Ref. [1]. The input data are shown in Table 1. Temperature dependent material properties, except steel density, are used.

2.1. Initial conditions

Before the fast discharge the QL and the storage vessel are assumed to be at the minimum environment temperature of 260 K. The amount of He is 55.51 kg in the vessel and 0.32 kg in the QL. At each time step a He mass-flow $\dot{m}_o(t)$ computed with Eq. (2) is injected at T = 15 K in the first QL element.

3. Analyses of the quench line

A sketch of the analytical model is shown in Fig. 1. The pipe is divided in finite elements and the event in finite time steps. Since the gradients of the relevant variables are changing considerably

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Table 1
Input Data.

Material properties		
Steel specific heat [J/kg/K] with T in K:		
$c_{cs}(T) = \mathrm{Min}\left\| \begin{array}{c} \left(173.72\tanh((T/70) - 1.081) + 0.7666\right) + 0.562T \\ 0.4463T + 0.000589T^3 \end{array} \right\|$		(1)
Steel density (ρ_{cs}) [kg/m^3]:	7850	
Pipe geometry		
Length (Lp) [m]:	100	
Inner diameter (Dpi) [m]:	0.136	
Wall thickness (thp) [m]:	0.0028	
Helium		
Inlet temperature [K]:	15	
Inlet mass-flow rate [kg/s] with time t in [s]:		
$\dot{m}_0(t) = 4.419e^{-t/114} - 3.252e^{-t/77}$		(2)
Heat transfer coefficient to QL [W/K/m^2]:	15	
Heat transfer coeffic. to vessel [W/K/m^2]:	10	
Vessel		
Wall thickness th_V [m]:	0.03	
Inner diameter [m]:	3.94	
Equivalent length of cylindrical part [m]:	20.4	
Volume of the vessel VV [m^3]:	250	
Mass of vessel [kg]:	64,400	

during the event, an adaptive time step dt, dependent on the gas velocity, is used (shorter for higher velocity).

In a first QL analysis all the external surfaces are considered adiabatic (conservative assumption). One hundred He elements have been used (for an adequately accurate solution). The mass balance at each time step has been considered using an iteration method.

For each time step it each element ix receives a He mass-flow $\dot{m}_{in}(it, ix-1)$ with a temperature $T_{He\dot{m}}(it, ix-1)$ injected from the previous element $ix-1$. The corresponding He velocity is computed with the following equation:

$$u(it, ix-1) = \frac{\dot{m}_{in}(it, ix-1)}{\rho_{He}(it, ix-1) \times A_{pc}}$$

where: $\rho_{He}(it, ix-1)$ = He density at $T_{He}(it, ix-1)$, $P_{He}(it, ix-1)$; A_{pc} = internal QL cross-section; $P_{He}(it, ix-1)$ = pressure at time step it of the element $ix-1$; ne = number of elements.

The injected He flow entering element ix fills an axial length equal to $dex = u(it, ix-1)dt$ and exchanges heat with the QL wall; the Dittus Boelter equation has been used for the heat transfer coefficient. Depending on dex there can be two main cases.

3.1. Case 1

If dex is smaller than the element size de, the He and the QL wall temperature at time step it for the element ix are calculated from the heat transfer balance between the He flow and the pipe wall:

$$T_{He\_dex}(it, ix) = T_{He\dot{m}}(it, ix-1) + \frac{hA_{pl}(T_p(it-1, ix) - T_{He\dot{m}}(it, ix-1))}{c_p \dot{m}_{in}(it, ix-1)} \quad (3)$$

$$T_{p\_dex}(it, ix) = T_p(it-1, ix) - \frac{hA_{pl}dt(T_p(it-1, ix) - T_{He\dot{m}}(it, ix-1))}{c_{cs}\rho_{cs}V_{cs}} \quad (4)$$

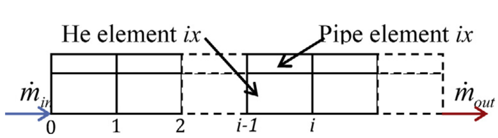

Fig. 1. Sketch of the analytical model.

where $T_{He_{dex}}(it, ix) = T_{He}$ injected for a length dex; $T_{He\dot{m}}(it, ix-1) = T_{He}$ entering from the element $ix-1$; $Tp_{\_dex}(it, ix)$ = QL temperature at it; $Tp(it-1, ix)$ = QL temperature at $it-1$; de = element length; dex = axial length filled by the gas in it; $A_{pl} = \pi D_{pi} dex$ = the lateral surface of the element filled by the gas; c_p = He specific heat at constant P; $V_{cs} = ((\pi((D_{pi} + th_v)^2 - D_{pi}{}^2))/4)dex$; steel volume of the QL which exchange heat in it.

The gas injected in element ix is heated, ref. Eq. (3), and expands. The expansion results in an increase dx in the length occupied by the gas in element ix:

$$dx = dex\left(\frac{T_{He}(it, ix)}{T_{He\dot{m}}(it, ix-1)} - 1\right)$$

The gas mass flow $\dot{m}_{in}(it, ix-1)$ that has entered element ix during the time step it for an axial length dex plus its expansion length dx push out an equivalent amount of the gas that was inside the element ix at the previous time step $it-1$ at temperature $T_{He}(it-1, ix)$. This enters element $ix+1$. If the length $dex+dx$ is smaller than de, the corresponding mass-flow entering the $ix+1$ element is:

$$\dot{m}_{in}(it, ix) = \frac{(dex + dx)A_{pc}\rho_{He}(it-1, ix)}{dt}$$

where: $\rho_{He}(it-1, ix)$ = He density at $T_{He}(it-1, ix)$, $P_{He}(it-1, ix)$.

If the length $dex < de$ and $dex + dx$ are larger than de, the corresponding mass-flow entering the $ix+1$ element is:

$$\dot{m}_{in}(it, ix) = \frac{deA_{pc}\rho_{He}(it-1, ix) + (dex + dx - de)A_{pc}\rho_{He}(it, ix)}{dt}$$

In the case that the length $dex+dx$ is smaller than de, the gas that has entered element ix mixes with the remaining gas in the element ix:

$$T_{He}(it, ix) = \frac{F1\rho_{He}(it, ix)T_{He\_dex}(it, ix) + F2\rho_{He}(it-1, ix)T_{He}(it-1, ix)}{dex\rho_{He}(it, ix) + (de - dex)\rho_{He}(it-1, ix)}$$

where F1 = $dex + dx$; F2 = $de - dex - dx$.

Similarly the steel pipe T in element ix at time step it can be calculated with:

$$T_p(it, ix) = \frac{F1T_{p\_dex}(it, ix) + F2T_p(it-1, ix)}{de}$$

3.2. Case 2

If dex is larger than or equal to de, the gas injected from element $ix-1$ fills the element ix and is passed immediately to the element $ix+1$. As a consequence the length dex is substituted in the equations by de. The mass-flow passing from element ix to element $ix+1$ is in this case (taking also in due account the mass balance):

$$\dot{m}_{in}(it, ix) = \frac{deA_{pc}\rho_{He}(it-1, ix) + dxA_{pc}\rho_{He}(it, ix) + \dot{m}_{in}(it, ix-1)dt(1 - (de/dex))}{dt}$$

The third term in the numerator is the part of the mass which in the time step it, passes through the element ix, and enters the element $ix+1$.

3.3. Pressure evolution in the quench line

At each time step and for each element the pressure drop in the He flow is calculated with:

$$\Delta p(it, ix) = \frac{8\dot{m}_{in}(it, ix-1)^2 de}{(1.74 - 2\,\mathrm{Log}_{10}(2(0.00006/D_{pi}) + (18.7/Re \times fric^{0.5}))^2(\pi^2 D_{pi}{}^5 \rho_{He}(it, ix))}$$

The mass balance for each element and time step is performed with iteration processes.