Numerical study of a consequence of a vacuum insulation degradation in a cryogenic system

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Abstract. Vacuum is the primary method for a thermal insulation of cold elements in cryogenic systems, tanks and other cryogenic equipment. A dangerous situation arise in the case of vacuum envelope failure when a 300 K air enters the vacuum and the cold elements of cryogenics equipment are exposed to a potentially intense heat fluxes and air velocity. Depending on a mass flow of the air (equivalent to size of an insulation rapture), a different rate of the temperature and pressure growth in the vacuum chamber can promote various mechanisms of the heat transfer to the cold elements. Additionally, it can be limited by the air deposition, condensation and cryosorption. In the present work a simplified numerical model of a typical cryogenics system is developed and different scenarios of vacuum degradation are considered. The current studies aim to identify the development of the different thermal conditions in the cryogenics system in the function of the mass flow of the ventilating air. The present work presents numerical studies of vacuum degradation for various sizes of a rapture hole. Additionally, the work proposes a simplified zero-dimensional model, which includes a deposition of air and its influence on pressure buildup and heat transfer.

1. Introduction
Cryogenic systems containing liquefied gases must be equipped with safety devices, to protect them against over-pressure in case of system failure. An important risk to be considered is a degradation of a vacuum insulation [1, 2]. A typical cryogenics process line contains a helium pipe and a radiation screen. Generally the systems characterized by an excessive pressure are covered by the EN13458 and ISO 21009 norms, however helium cryostats which require additional components are not. Currently, some works are focused on preparation of a holistic helium standard [3]. The standard mentions the loss of vacuum insulation as one of possible sources of the excessive pressure. The works [1, 4, 5] concern a heat transfer to the helium cryogenic vessel as a consequence of vacuum degradation. However, they neglect a deposition of a solidified air layers on the cryogenics elements and its influence on a pressure buildup.

The present work is focused on a numerical investigation of a flow and heat transfer in a cryogenics process line as a consequence of a vacuum degradation. The work considers various intensities of the vacuum degradation in a function of a size of a rapture hole. Additionally, the work proposes a simplified zero-dimensional (0D) model of a deposition of solidified air and its influence on pressure buildup and heat transfer in the considered process line. Finally, a functional form of a heat transfer to the helium pipe is defined, which can be used as a boundary condition in similar problems.
2. Numerical model of cryogenic process line

The current studies are based on a geometry of a cryogenic process line test stand proposed
in [2]. A typical cryogenic system can be illustrated as a series of nodes consisted of a cold
cryogenic tank protected with a radiation screen and kept in a process line [6]. The figure 1
shows the two-dimensional (2D) numerical model used in this work. The proposed numerical
geometry can be seen as a cross-section of a typical cryogenics process line. The blue color
marks the inside of the process line, where a vacuum is established, and the red color depicts
the surrounding environment with constant pressure $p_{\text{out}} = 1$ bar and $T_{\text{out}} = 300\text{K}$. The most
inner pipe (white color) is a helium pipe with $T_{\text{he}} = 4\text{K}$ and diameter $d_{11} = 11\text{cm}$. The
inner ring with a gap, which surrounds the helium pipe, represents a permable radiation screen
with constant temperature $T_{\text{N2}} = 77\text{K}$ and diameter $d_{20} = 20\text{cm}$. It is assumed that the gap
occupies 5\% of the radiation screen circumference. The process line has diameter $d_{32} = 32\text{cm}$
and the rapture hole is located on top of it. For simplicity it is assumed that walls of the helium
pipe and radiation screen are not insulated.

In the course of the current investigation five different sizes of the holes were considered:
$0.003\%$, $0.05\%$, $0.1\%$, $0.5\%$, and $1\%$ of the circumference of the process line, corresponding to
the area of $10053$, $5026$, $1005$, $503$, and $30\text{mm}^2$, assuming $1\text{m}$ long computational domain. The
smallest one corresponds to the size of an emergency valve which would be needed in the
considered process line according to the norm EN ISO 4126-1.

![Figure 1. Left: Numerical model of the considered cryogenic process line, points 1 –
6 correspond to locations where numerical measurements were taken; Right: Zoom of the
numerical mesh with the 0.05\% rupture hole.](image)

The points 1 – 6 shown on the figure 1 depicts the reading locations where numerical
measurements where taken. It is assumed that an initial pressure and temperature of the
process line are $p_0 = 10\text{Pa}$ and $T_0 = 77\text{K}$. The value of $p_0 = 10\text{Pa}$, as representation of a
vacuum, is dictated by a numerical stability of a continuous Navier-Stokes model used in the
current studies. It is going to be shown later that this assumption was justified and gave a good
agreement with the developed 0D theoretical model considered in the present work.

The fact, that the typical process line can be very long and the large pressure difference will
promote a supersonic flow, justifies the necessity of the 2D simplification of the numerical model.
Thanks to this the investigation of the considered parameter space was possible.

2.1. Mathematical model and numerical implementation

The considered flow problem is characterized by a very high pressure difference and consequently
by velocities exceeding a local speed of sound. This promotes the formation of large
gradients and discontinuities characteristic for supersonic flows. It leads to a need to use
dedicated mathematical models suited for such class of flows. In the current study the numerical calculations were made using the OpenFOAM (Open Source Field Operation and Manipulation) CFD toolbox [7]. OpenFOAM offers two mathematical models dedicated for transonic/supersonic flows: sonicFoam and rhoCentralFoam. The first one is a pressure based model and uses the pressure and velocity as dependent variables and couples them through the PISO (Pressure Implicit with Splitting of Operators) algorithm for compressible flows. The rhoCentralFoam is a density-based model for compressible flows and is based on central-upwind schemes of Kurganov and Tadmor. In general, models based on the central-upwind schemes give more accurate solutions and can use coarser mesh and less computational time as compared to the pressure based models.

It motivated the choice of the rhoCentralFoam solver in the current study. The velocity field, \( \mathbf{u} = (u, v, w) \) was calculated by solving the compressible Navier-Stokes equations:

\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u}) - \frac{1}{3} \nabla (\mu \nabla \cdot \mathbf{u})
\]

(1)

which, along with a state equation and the continuity equation constitute a closed system. An ideal gas law was used as the state equation and to calculate the density and the Sutherland approximation was used to calculate the viscosity [7]. The temperature field was calculated using the energy transport equation:

\[
\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho \mathbf{u} e) = \nabla \cdot (k \frac{C_v}{T} \nabla e) + p \nabla \cdot \mathbf{u}
\]

(2)

where \( k \) is heat conductivity and \( e = C_v T \).

3. Simplified 0D model with air solidification

The developed 0D model of vacuum degradation and air deposition is based on the geometry shown in the figure 1 and assumes the same thermal conditions. The air flowing through the rupture hole in the process line cause the pressure increase. However, some part of the entering air is deposited on the wall of the helium pipe. The helium pipe is assumed to be a perfect heat sink. The deposited layer of air grows till its outer temperature reaches a triple point temperature and after that a condensation of air starts. It was assumed that air is a pure mixture of 79% of nitrogen and 21% of oxygen.

3.1. Model of ice layer formation

The first step of the developed 0D model considers a pressure buildup \( p_{in,n} \) inside the process line. The pressure buildup is a function of a mass of air inside the process line and its value in \( n \)-th time step can be expressed as follow:

\[
p_{in,n} = \frac{[m_{n-1} + (\dot{m}_{in} - \dot{m}_{des})t_{step}]R_{air}T_{in}}{V_{top}}
\]

(3)

where \( \dot{m}_{in} \) is the inlet mass flow of air, described by the eq. (4), \( \dot{m}_{des} \) is the mass of air desublimated on the helium pipe, described by the eq. (5), \( t_{step} \) is the value of the time step, \( T_{in} \) is the temperature of the gas inside the process line, \( V_{top} \) is the volume of the considered process line. The mass flow of air \( \dot{m}_{in} \) depends on the pressure inside the process line and can be described by [1]:

\[
\dot{m}_{in} = A_{hole} \sqrt{2p_{out}} \rho_{out} \left\{ \begin{array}{ll}
\left( \frac{2}{\kappa_{air}+1} \right)^{\frac{1}{\kappa_{air}-1}} \sqrt{\frac{\kappa_{air}}{\kappa_{air}+1}} & \text{if } p_{in} < p_{cr} \\
\left( \frac{1}{\kappa_{air}-1} \right)^{\frac{2}{\kappa_{air}}} \left( \frac{p_{in}}{p_{out}} \right)^{\frac{\kappa_{air}+1}{\kappa_{air}}} & \text{if } p_{in} \geq p_{cr}
\end{array} \right.
\]

(4)
where \( A_{\text{hole}} \) is a cross section of the rupture hole, \( \kappa_{\text{air}} \) is an isentropic exponent of air, \( p_{\text{in}} \), \( p_{\text{sat}} \) is internal, external and critical pressure respectively, \( \rho_{\text{in}} \) is density of the entering air. The mass of air desublimated on the wall of the helium pipe can be calculated by [8]:

\[
\dot{m}_{\text{des}} = A_{\delta,n} \alpha_T \left( \frac{1}{\sqrt{2\pi R_{\text{air}}}} \right) (\alpha_c \frac{p_{\text{in}}}{\sqrt{T_{\text{in}}}} - \alpha_e \frac{p_{\text{sat}}}{\sqrt{T_{w,n}}})
\]  

(5)

where \( \alpha_T, \alpha_c \) and \( \alpha_e \) are transmission, condensation and evaporation coefficients described by [5], \( p_{\text{sat}} \) is saturation pressure for the temperature \( T_{w,n} \) established on the wall covered with the solidified air and \( T_{in} \) is temperature of the air inside the chamber and \( A_{\delta,n} \) is the increased area of the wall after deposition of the \( n \)-th ice layer. As a consequence of the desublimation a layer of solidified air is formed on the wall. The width of the single ice layer deposited during the \( n \)-th step for 1 m long pipeline can be calculated by:

\[
\delta_{n,\text{step}} = \frac{\sqrt{4 \dot{m}_{\text{des,step}} \pi \rho_{\text{air}}}}{\pi \rho_{\text{air}}} + (d_{11} + 2\delta_{n-1})^2 - (d_{11} + 2\delta_{n-1})
\]

and

\[
\delta_{n,\text{total}} = \sum_{i=1}^{n} \delta_{i,\text{step}}
\]

(6)

Consequently, the total width of the \( n \) layers of the ice is a sum: The ice layers are deposited one on another till the temperature of the outer surface of the \( n \)-th layer reaches the triple point temperature \( T_{TP} = 63 \) K. The temperature of the \( n \)-th layer of the ice on 1 m long pipeline can be calculated by:

\[
T_{w,n} = T_{w,n-1} + \frac{\dot{m}_{\text{des}}(r_{\text{des}} + C_p(T_{in} - T_{\text{TP}}))\ln(\frac{\delta_{n,\text{total}}}{\delta_{n-1,\text{total}}})}{2\pi k_{\text{ice}}}
\]

(7)

where \( r_{\text{des}} \) is the latent heat of desublimation, \( T_{w,n-1} \) is the temperature established on the surface of the ice layer in the previous step and \( k_{\text{ice}} \) is thermal conductivity of solid ice, the wall covered with the solidified air and \( T_{in} \) is temperature of the air inside the chamber and \( C_p \) is a specific heat air.

3.2. Heat flux to the helium pipe

Depending on the temperature established on the helium pipe wall \( T_{w,n} \) a different mechanism of heat transfer should be considered. If \( T_{w,n} \) is lower than a triple point temperature \( T_{TP} \), the heat transfer is govern by solidification of air and is associated with the latent heat \( r_{\text{des}} \). Consequently, assuming an instant solidification \( \dot{m}_{\text{in}} = \dot{m}_{\text{des}} \), the pressure buildup is delayed.

Next, if the \( T_{w,n} \) is grater than \( T_{TP} \) but lower than a boiling temperature of air \( T_{\text{boil}} \), the heat is transferred mostly by forced convection govern by a condensate flowing around the helium pipe covered with the solidified air and \( T_{in} \) is temperature of the air inside the chamber. In this case, even if \( \dot{m}_{\text{in}} = \dot{m}_{\text{des}} \), the pressure inside the process line is building up. It is justified to assume that the condensed liquid evaporates immediately after dropping on warmer elements of the process line. Finally, if the \( T_{w,n} \) is grater than the \( T_{\text{boil}} \) a pure convection govern by the moving air can be assumed. Consequently, a heat transferred to the helium can be expressed as a function of \( T_{w,n} \), the size of rupture hole and time (8):

\[
\dot{Q} = \begin{cases} 
\dot{m}_{\text{des}}(r_{\text{des}} + C_p(T_{in} - T_{\text{TP}})) & \text{if} \quad T_{w,n} \leq T_{\text{TP}} \\
\alpha_{\text{cond}}(T_{in} - T_{w,n}) & \text{if} \quad T_{\text{TP}} < T_{w,n} \leq T_{\text{boil}} \\
\alpha_{\text{conv}}(T_{in} - T_{\text{boil}}) & \text{if} \quad T_{w,n} > T_{\text{boil}}
\end{cases}
\]

(8)

where \( \alpha_{\text{cond}} \) is a heat transfer coefficient related to condensation [9] and \( \alpha_{\text{conv}} \) is a heat transfer coefficient related to convection [10]. To avoid an additional degree of freedom in the both considered models (2D and 0D) a vacuum pumping was not considered.
4. Results

4.1. Results of the 2D numerical model

Figures 2 and 3 show the temperature and velocity fields of the considered flow for the 0.003\% and 0.05\% holes. It can be observed that for very early times a characteristic front of high temperature and high velocity, exceeding 800 m/s is formed. Its existence is very short and after less than 1 second the temperature field is stabilized and velocity drops down significantly. As it could be expected, the inflow gets more violent with an increase of the rapture hole.

Figure 2. Changes of temperature in time. Consecutive rows corresponds to the holes: 0.003\%, 0.05\% respectively.

Figures 4 and 5 present the heat flux to the helium pipe and the radiation screen respectively, for all the considered rapture holes. For better visibility of the process rapidity only an early time is shown. After the pressure of 1 bar was reached the heat flux saturated at (23.43, 1.63, 4.50, 1.19, 1.92) kW/m² for the hole size of (0.5, 0.5 with ice, 0.1, 0.05, 0.05 with ice, 0.003)\%, respectively for the helium process line and at (22.46, 23.79, 27.17, 18.81, 1.72) kW/m² for the hole size of (0.5, 0.5 with ice, 0.1, 0.05, 0.05 with ice, 0.003)\% respectively for the radiation screen. For 0.003\% the computation time was extremely slow with \( \Delta t \sim 10^{-9} \) s but it can be observed that the heat flux reached an approximately steady value for the completed calculations. It should be noted that in the cases with the ice layer the sudden jump of heat flux was not observed. Moreover, in case of the 2D model only the convective heat transfer was modelled.

4.2. Results of the developed 0D model

Figures 6 and 7 show the pressure buildup in time resulting from the developed 0D model. The figures compare the flows without and with the deposition of air mechanism included respectively. The characteristic flat zones visible on the plots from the figure 7 correspond to the air deposition period. During that time the inside pressure does not increase. It is particularly visible for the rapture hole 0.003\%, see figure 10.

Figures 8 and 9 compare the dynamics of the deposited air layer formation on the helium pipe. The figure 8 assumes that all inflowing air is instantaneously solidified till the outside ice
The temperature reaches $T_{TP}$. In this case the ice thickness is independent from the rapture hole size and reaches approx. $0.25 \text{mm}^2$. While the figures 9 and 11 show the ice formation resulting from the 0D model, eq. (6). It can be noticed that the time of air deposition is longer and the final ice thickness changes with the size of rapture hole, being the largest for 0.003% hole.

Figure 12 shows the heat flux to the helium pipe for different sizes of the rapture holes. The initial high values correspond to the period of air solidification, when more heat need to be transferred and dissipated in helium. After the ice formation is finished the heat transfer is constant and limited by the convection mechanism. The values of the heat flux related to the convection compares satisfactorily with the results of the 2D model presented in the figure 4.

Table 1 compares the 2D and 0D models. The consecutive columns show the time after which the pressure inside the process line reaches 1 bar. Satisfactory agreement of the 2D model and 0D model is archived for cases without air solidification mechanism included. Longer times needed
in the 2D model can be related to the realistic simulation of the flow dynamics and the existence of initial pressure of 10 Pa. Moreover, the 0D model assumed a constant temperature inside the process line $T_m = 300$ K. Note that the 2D computations for the 0.003% hole were extremely long and the final time 16.86 s was approximated assuming a linear increase of pressure.
Figure 12. Heat transfer to the helium pipe in time for different sizes of the rupture hole. The higher values correspond to the air solidification process, compare with eg. (8) and the figure 4.

Table 1. Comparison of the 2D model and developed 0D model: time after which the pressure inside the process line reached 1 bar.

| hole       | 2D model | 0D no air deposition | 0D with air deposition |
|------------|----------|----------------------|------------------------|
| 0.003%     | 16.86 s  | 13.31 s              | 341 s                  |
| 0.05%      | 1.61 s   | 0.79 s               | 2.18 s                 |
| 0.1%       | 0.59 s   | 0.39 s               | 0.95 s                 |
| 0.5%       | 0.12 s   | 0.08 s               | 0.44 s                 |
| 1%         | 0.07 s   | 0.02 s               | 0.05 s                 |

5. Conclusions
The proposed 0D model showed that the dynamics of pressure buildup inside a process line can be significantly influenced by deposition of air on cold elements. This influence gets larger for smaller rupture holes. The main simplification of the 0D model was the treatment of helium pipe as a perfect heat sink. In general the heat transfer to the helium would depend on its boiling regime and dynamics of air deposition would depend on a heat dissipated in helium. This two processes are linked together as a feedback loop and should be treated simultaneously. The future development of the proposed 0D model will include this feedback mechanism. Additionally, the model will take into account a cool down process of an ice layer and a heat up of the condensate.

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