EDMS Number 2065408

Fluid-dynamic modelling of pressure distribution in a helium-gas transmission line during transient conditions

tomas.stephen.northam.de.la.fuente@cern.ch / tom.northam@gmail.com

TE-MSC-SCD, CERN, Route Zeeman, 01630 Saint-Genis-Pouilly, France

Abstract. A high current superconducting flexible line called the SC-Link will be built at CERN to hold a 91 mm diameter MgB_2 cable used to transport power to the new magnets for the LHC Hi-Lumi upgrade. In this report, loss of vacuum accidents on a 64 m SC-Link with an inner diameter of 110 mm were studied using a hydraulic network simulator program called FLOWER. The results were compared with an experimentally validated model in which the entire line is uniformly heated at 6 kW/m^2 and 3 kW/m^2. In addition, it was found that the pressures were smallest when the hydraulic diameter of the SC-Link was equal to the diameter of the burst disk. A model of a localised heat leak was also developed to simulate more realistic accidents. With this, a 124 m and 134 m SC-Link were studied by comparing the effect on the pressure when increasing the inner tube dimeters from 110 mm to 135 mm. There was a significant reduction in pressure when the larger diameter was used.

1. Introduction

CERN (European Organization for Nuclear Research) is the largest research facility in particle physics in the world. There are multiple on going experiments, with the biggest one called the LHC (Large Hadron Collider), consisting of a 27-kilometre ring of superconducting magnets used to accelerate beams of particles [1]. In this ring, two beams of particles of 1 mm in diameter are accelerated in opposite directions to velocities of over 99% the speed of light [1].

These beams of particles collide at 4 different locations on the ring. These points have a set of magnets at either side used to compress the particle beams before entering the impact point, so as to ensure a larger number of particles per unit area, resulting in a larger probability of collisions. The LHC will be undergoing an upgrade called the High Luminosity upgrade (HL-LHC), in which new, more powerful niobium-tin magnets will be installed at 2 of the 4 impact points. These magnets will produce much stronger magnetic fields, compressing further the beams of particles resulting in an increased number of collisions.

As a result of this, the background radiation produced by the collisions will increase and will degrade any nearby electronic equipment, such as the magnet power supply unit (PSU). Thus, the PSU will need to be positioned a certain distance away from the impact points. For this reason, a high current transfer line called the Superconducting Link (SC-Link) is being built to supply current to the magnets. The SC-Link is effectively a cryostat with a large length to diameter ratio.

The SC-Link consists of two concentric corrugated stainless steel tubes of 120 m to 130 m in length separated by a vacuum of 10^{-6} mbar to reduce the static heat load. As figure 1 (a) shows, the inner tube will house the 91 mm diameter magnesium diboride (MgB_2) cable, formed by 7 smaller cables in a 6-around-1 configuration, used to transmit the current, as well as supercritical gas helium (GHe) at less than 20 K used to cool down the cable to its superconducting state. There is no need to use liquid helium (LHe) as the cable becomes superconducting below 39 K. Due to the presence of

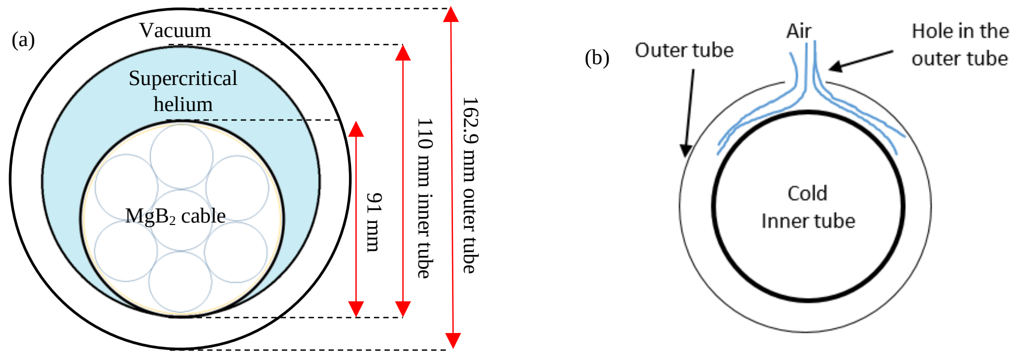

Figure 1. (a) Cross section of the SC-Link. (b) Schematic loss of vacuum accident on the SC-Link.

corrugations, the inner tube will have an inner and outer diameters of 100 mm and 120 mm. For the purposes of these calculations, an average diameter of 110 mm was used.

Finally, this inner tube will be covered with 30 layers of insulating material and inserted in a larger corrugated vacuum tube with an average diameter of 162.9 mm that will be used as a vacuum jacket for insulation. The reason why the tubes are corrugated is to make them flexible so that they can be bent, as the tunnel installation of the SC-Link involves two 90º bends. The main drawback is that, due to the need for this flexibility, the walls of the tubes are much thinner than a non-flexible transmission line. As such, the cables will be potentially more vulnerable against accidents such as puncturing of the outer tube.

At each end of the SC-Link, a burst disk (BD) and relief valve (RV) will be installed to protect the inner pipe against over pressure arising from loss of vacuum (LoV) accidents. A LoV accident would consist of a rupture of the outer tube, as shown in figure 1 (b). This would result in the incoming air being deposited on the cold surface of the inner tube, heating the helium and producing an increase in pressure. LoV accidents are one of the most damaging accidents in cryogenic systems, and thus have to be carefully considered and evaluated.

Before the installation of the final SC-Link, two tests will be made. Demo 1, in which a 64 meter long SC-Link will be tested with helium gas and only 2 out of the 7 cables that form the MgB_2 cable, and Demo 2, where the same 64 meter pipe will be tested but with the full 6-arround-1 MgB_2 cable.

In this report, a detailed explanation is given of the methods and results of simulations made to study the pressure development inside the Demo 2 SC-Link in a sudden LoV accident. Multiple forms of the heat flux on the helium pipe were studied and compared.

Events concerning the cable reverting to normal state and heating the inner tube internally were not considered. This is due to the fact that the voltage drop along a superconducting cable is constantly monitored and any voltage increase beyond a certain threshold automatically causes a current run-down.

2. Methodology

2.1 Simple model

The model that was used was published by Miller et al. [2] in their work on cable-in-conduit conductors (CICCs). The reasons why this model was used is because it was validated by comparing the theoretical predictions with a set of experimental measurements. Their theoretical results match within 1 bar with those from experiment with large changes in pressure ($\Delta P \approx 10$ to 100 bar). This means that this is an experimentally verified theory, and could be used to validate the main computational model use to simulate more realistic scenarios.

In their case, a 69 m long 4.4 mm diameter pipe housed a 3.2 mm diameter copper cable cooled by static LHe. A pulse of current was applied to the cable to simulate the cable reverting to normal state and heating up the entirety of the pipe due to the resistance. This means that their system would heat up internally, while our system would heat up externally from gas deposition on the pipe. Nevertheless, these two forms of heating are analogous to a first approximation.

The equations used to predict how the temperature T and the change in pressure ΔP evolved when heat was applied were derived using the equation of continuity, Euler's equation with frictional drag and the energy equation. This resulted in a set of differential equations of the form

$$\frac{d(\Delta P)}{dt} = \frac{\beta c^2}{C_p}(\rho \dot{q}) - \frac{\rho c^2}{l}\left(\frac{3D_h \Delta P}{2f\rho l}\right)^{\frac{1}{2}} \quad (a) \qquad \frac{dT}{dt} = \frac{(\rho \dot{q})}{\rho C_p} + \frac{\beta T}{\rho C_p}\frac{d(\Delta P)}{dt} \quad (b), \tag{1}$$

where β is the thermal expansion, C_p is the specific heat, ρ is the helium density, c is the velocity of sound in helium, $\dot{q}$ is the specific power input, l is have the length of the pipe, f is the fanning friction and D_h is the hydraulic diameter given by

$$D_h = \frac{4A_{flow}}{P_{wett}}, \tag{2}$$

where A_{flow} (flow area) is the difference between the area of the pipe and the area of the cable and P_{wett} (wetted perimeter) is the sum of the perimeter of the cable and the pipe. Equation 1(a) was modified to find the maximum pressure the system reached by using $\Delta P = P_{max} - P_{init}$ and $Q = \rho \dot{q}$, where P_{init} is the starting pressure and Q is the power density input. In addition, Miller et al. [2] further modified equation 1(a) by assuming $\beta^2/\rho C_p^2 \approx 0.45P^{-1.8}$. This gives an implicit equation of the form

$$P_{max} = 0.65\left(\frac{fl^3Q^2}{D_h}\right)^{0.36}\left(1 - \frac{P_{init}}{P_{max}}\right)^{-0.36}. \tag{3}$$

While this model is not very realistic, as it would correspond to the case of removing the entire vacuum jacket instantaneously, it provides a worst case maximum pressure in the system.

2.2 FLOWER model

To model more realistic scenarios, a hydraulic network simulator program called FLOWER developed by Bottura et al. [3] was used. This program is based on the assumption that a cryogenic system can be modelled as a hydraulic network composed of junctions, comprising of pipes and valves, and volumes representing reservoirs of helium used to connect the junctions. The FLOWER program uses a 1D model of flow to simulate the junctions, and assumes perfect mixing of fluids at different P and T at the volumes. To simulate the flow of helium, the non-conventional form of the compressible flow equations are used. These are used in fluid dynamics when the density changes significantly with small fluctuations of P and T. A limitation of the program is that it only considers single-phase helium flow, this is either LHe or GHe only.

The way the SC-Link was modelled in FLOWER, shown in figure 2, was by representing as much as possible the cryogenic system that will be used in DEMO 2. For this, a closed system was constructed by using a long junction (J1), representing the inner tube of the SC-Link and where the static leak heat and LoV heat will be deposited, a pump (J2), use to provide the constant 5 g/s mass flow to the entirety of the loop, and a shorter junction (J3) thermally in contact with a cold reservoir of helium (V4) used as a heat exchanger to return the helium into the SC-Link at 5K. This thermal exchanger was used due the increase in temperature experience by the helium when flowing from V1 to V2 due to a background heat of 1.5 W/m even before a LoV event, as well as the heat deposited by the pump when flowing through J2. The value of the background heat has been measured previously in experiments at CERN. The function of volumes V1, V2 and V3 was to connect all these components. This loop represents the cooling system that will be use in the real installation to re-circulate the helium into the pipe. The pump was set so that the pumping rate would decrease by a factor of 10^3 when a sudden pressure rise above 1.5 bar was detected, so as to simulate the pump turning off.

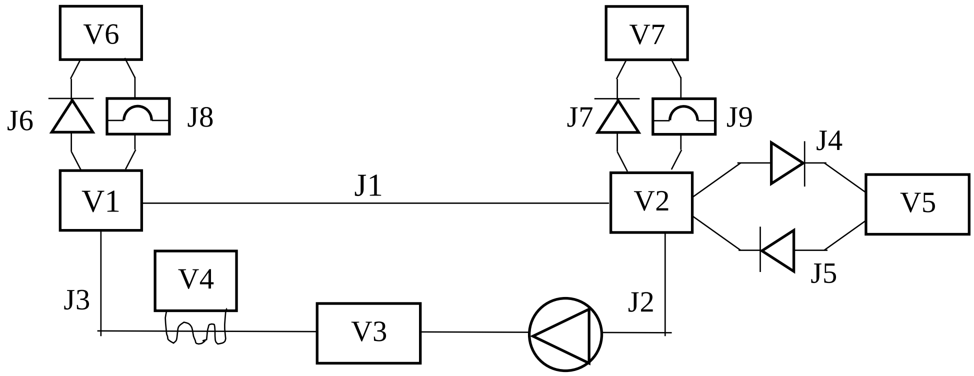

Figure 2. Representation of the SC-Link in the FLOWER program. J1 is the power supply pipe, J2 is the pump and J3 and V4 represent the heat exchanger. J4, J5 and V5 are the RV and reservoir for the pressure control system. J6 and J7 are the check valves of the pressure relief system with the burst disks J8 and J9, and V6 and V7 represent the atmosphere where the helium is vented in case of an accident.

The volumes at each end (V1 and V2) of the main junction also had the pressure relief system (PRS) formed by a RV (J6 and J7) set to open when V1 and V2 reach 1.7 bar and a BD (J8 and J9) set to break when V1 and V2 reach 2 bar. The BD had a much larger A_{flow} than the RV. This is because, while the BD is the main component used to relieve the helium in case of a large pressure increase due to a LoV accident, the RV is used as a pressure regulator.

Finally, a "pressure stabilizer" was added to V2. This consisted of two RV (J4 and J5) that provided helium from V2 to a reservoir (V5) and vice versa when the difference in pressure between these two volumes is of the order of 1 mbar. This pressure stabilizer was used to control and stabilize the pressure of the closed system before LoV. In real systems, due to the heat of all the machinery used, the pressure will slowly drift over time. As such, cryogenic networks have pressure regulator systems to charge or discharge helium from the network according to a pressure threshold.

The boundary conditions of the system were defined in terms of the starting conditions of the network. The volumes were simply defined in terms of their volume size, their starting pressure and starting temperature. While V1-V5 were set to $P = 1.3$ bar and $T = 5$ K, the initial pressures and temperatures of the real system, V6-V7 were set at the atmospheric conditions of $P = 1$ bar and $T = 290$ K. For the size, V1-V3 were set at 10^{-3} m^3, small enough that the did not impact on P_{max}, and V4-V7 were set at 10^3 m^3, big enough to have P and T constant while not limiting the program run time

For the junctions, several parameters were needed depending on the type of junction. For the main pipe (J1) and the heat exchanger pipe (J3) the length, A_{flow}, D_h, P_{wett} and friction factor were defined. In addition, the form of the heat function deposited on the main pipe was also defined. For the pump, only the length and A_{flow} were defined alongside the pumping rate. Finally, for the RV and BD, not only the length and A_{flow} were needed, but two other parameters were defined: the ΔP at which they open or break and the impedance ξ. The ΔP refers to the difference in pressure between the two volumes that they connect. Thus, for J6 and J7, a ΔP of 0.7 bar was used, so that it would open when V1 and V2 reach 1.7 bar. Similarly, J8 and J9 a ΔP of 1 bar was used, so that the BD would break when V1 and V2 reach 2 bar. ξ is a unitless parameter defined by the approximation [3]

$$\xi \approx 6.48 \times 10^8 \left(\frac{A_{flow}}{K_v}\right)^2 \tag{4}$$

where K_v is the flow coefficient. While one of the defining parameters of K_v is A_{flow}, the relation between these two changes depending on the type of valve as well as its characteristics, which are provided by the manufacturer's specifications. ξ determines how easy it is for helium to flow through a valve or how much the valve is open. The RVs used in the pressure regulator had a high ξ, of the order of 10^4, while the RV and BD of the PRS had a much smaller ξ, of the order of 1 and 0.1

respectively. This way, when the pressure increased due to heat deposition on the pipe, helium would flow primarily through the PRS and not through the pressure regulator.

To simplify the system, the same A_{flow} and D_h calculated for the SC-Link was used for J1 to J5. For the RVs of the PRS, the dimensions of the real RV that will be used in Demo 2 were used. The A_{flow} and ξ of the BDs were changed to see their effect on the maximum pressure. Finally, the pump, the RVs and the BDs were all set with a length of 1 m, while the heat exchanger and main pipe were set with the same length and P_{wett}.

The program initializes the system by having all pipes and volumes filled with helium at the pressures and temperatures above, as well as with a 1.5 W/m background heat applied to the SC-Link (J1). As such, the system took an amount of time to set everything in motion and reach a steady state flow. Immediately after this flow was reached the LoV heat function was activated. The amount of time the system took to reach steady state depended mainly in the length of J1 and its A_{flow}, being around 600 seconds for the dimensions and diameters of Demo 2. All the times referred in this report are with reference to the time when the LoV heat function was activated.

The method used to simulate a LoV accident on the SC-Link (J1) was by depositing a certain amount of power (W/m) on the pipe with a certain space and time envelope. This was to simulate a realistic leak which would lead to air condensing over the surface of the pipe due to the low pressures and temperatures. The power produced due to the condensation process would transfer to the helium increasing the pressure and temperature. The values of the heat used in all simulations where values from past LoV experiments. An assumption made was that the heat was entirely absorbed by the helium, ignoring the C_p of the cable and stainless steel.

To test the validity of this model, a heat function similar to the one used by Miller et al. [1] in his experiment was used. The maximum pressure resulting from this heat function was compared to the P_{max} predicted by equation 3. In addition, how the predicted maximum pressure changed with parameters such as the pipe diameter and burst disk diameter were examined. With this, more physical heat functions were used to determine a more realistic maximum pressure. This gave insight into the range of possible pressures the SC-Link could reach in a LoV accident.

3. Results and discussion

3.1 FLOWER comparison and tests

The first heat function used was a top hat-like function in time, shown as the red curve in figure 3 (a), with the entirety of the pipe being heated uniformly. This is not a realistic heat function, as in a LoV accident the incoming air would gradually deposit on the cold surface of the cryostat, and thus the heat would increase gradually. Nevertheless, this function was used because it is very similar to the heat function used in Miller et al. [2] and the result could be compared to the P_{max} predicted by equation 3. In addition this also simulated the absolute worst-case scenario, producing an upper bound to the pressures this system will experience.

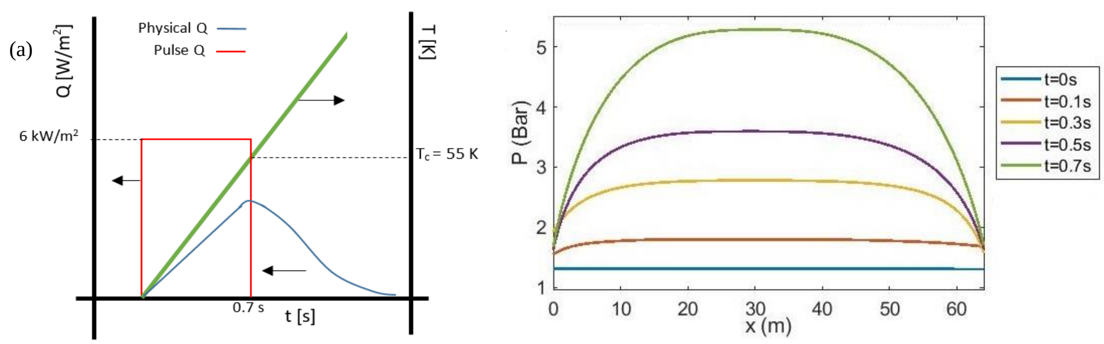

Figure 3. (a) How the multiple heat functions tested in FLOWER evolve in time and decrease according to the condensation temperature T_c. (b) Evolution of the pressure along the pipe after the LoV heat is activated.

The maximum power reached was 6 kW/m^2. This value was taken from Lehman et al. [4] on his work on LoV events in conventional cryostats. While the SC-Link has very different dimensions compared to a conventional cryostat container, as it has a large length to diameter ratio, the evolution of heat in time at a given point is assumed to be similar for both cryostats. In addition, the SC-Link is insulated due to the presence of multi-layer insulation (MLI). This is a thermal insulator set in between the two concentric tubes formed by a reflective film, such as aluminum foil, and an insulating spacer, usually fibre papers. Experiments [4] have shown that the presence of MLI drastically reduces the heat flux from 38 kW/m^2 with no MLI to 6 kW/m^2 with 10 layers of MLI. In reality, this maximum heat flux will be much smaller, due to the fact that this measurement are made for cryostats with 10 layers of MLI, while the inner tube will be insulated with 30 layers of MLI. Nevertheless 6 kW/m^2 was still used as an absolute worst case scenario. However, as the program uses heat in the form of W/m, the heat deposition was computed by multiplying the 6 kW/m^2 by the perimeter of the pipe πD_p, where D_p is the diameter of the inner tube, resulting in a heat deposition of 2.1 kW/m.

Finally, the heat function was further modified so that it was maintained at 2.1 kW/m until the pipe reached the condensation temperature of air (T_c=55K [5]). At this point the heat function reduced to zero. This is because, when such temperature is reached, a layer of solid air would have formed on the pipe, increasing the distance between the helium and new air molecules, and drastically decreasing the heat transfer. In addition, as the temperature would be above the T_c of air, new incoming molecules would not be able to condensate, reducing further the heat deposition.

With this heat function applied to the entirety of the pipe and the dimensions of the inner tube from figure 1 (a), a simulation was made with the parameters from table 1. The friction factor was determined using data from experiments previously made at CERN with a corrugated pipes and a cable of similar dimensions. For the RV, the dimensions chosen were the same as the dimensions of the real RV. Finally, the burst disk was set to have the same ξ as that of the real burst disk, however the A_{flow} was computed assuming a circulate BD with diameter equal to the D_h of the main pipe. The resulting pressure evolution after the heat function was activated is shown in figure 3 (b), with a predicted maximum pressure of 5.3 bar. The pressure initially increase homogeneously along the pipe in the first 0.2 s after LoV, until it reached 2 bar and the BD opened. At this point, the ends were "clamped" just below 2 bar while the middle continued to increase. The pressure rose very rapidly, reaching the maximum pressure and T_c simultaneously, 0.7 seconds after LoV. With the BD open, the helium started to flow to the ventilation volumes (V6 and V7) and the entire system depressurized to 1 bar. This depressurization was much slower, at 2.8 seconds after reaching maximum pressure. This P_{max} predicted for the absolute worst case scenario of 5.3 bar indicates that more realistic heat fluxes will produce more realistic maximum pressures.

The maximum pressure from figure 3 (b) was compared to the P_{max} predicted by equation 3. For this, an initial pressure of 1.3 bar, the full 6 kW/m^2 to calculate Q, and the D_h and f form table 1 were used, producing a $P_{max} = 9.49$ bar, 1.8 times larger than the FLOWER prediction. Another simulation was made with the same parameters but using a reduced heat flux of 3 kW/m^2. The pressure profile was very similar to that from figure 3 (b), but reaching $P_{max} = 3.7$ bar in 3.6 s. Using the same parameters as before but with the 3 kW/m^2, equation 3 predicted a $P_{max} = 5.97$ bar, 1.6 times larger than the FLOWER prediction. The reason for such discrepancies is due to the assumption made by Miller when deriving equation 1. Miller assumed a constant helium density along the pipe. In reality, due to the presence of the background heat, there will be a temperature gradient along the SC-Link of 3.5 K, being colder at the V1 end. As the density of helium changes rapidly with temperature, this T-gradient will result in there also being a gradient in density, as opposed to having a constant density

Table 1: Parameters used to validate the FLOWER model.

Junction	L (m)	A_{flow} (mm^2)	D_h (mm)	P_{wett} (mm)	f	ξ
SC-Link (J1)	64	2999.5	19	631.5	0.1392	-
RV (J6-J7)	1	273.7	-	-	-	2.33
BD (J8-J9)	1	283.5	-	-	-	0.139

along the pipe like in Miller's experiment. This assumption was tested by repeating the simulations but with no background heat, resulting in a $P_{max} = 5.95$ bar for the 6 kW/m^2 and a $P_{max} = 4.14$ bar for the 3 kW/m^2. While this decreased the difference between the two models, the discrepancy was still large. However, the biggest assumption that Miller made was the use of $\beta^2/\rho C_p^2 \approx 0.45P^{-1.8}$. As shown in Miller's paper [2], this approximation holds for pressure above 10 bar and cases where the change in pressure is larger ($\Delta P \sim 10$ to 100 bar). However, as the pressure decreases below 10 bar and ΔP becomes small, the equality no longer becomes valid. A simulation was performed with the same parameters and heat function as before but with a larger $P_{init} = 13$ bar and opening pressures of 13.7 bar and 14 bar for the RV and BD respectively. This resulted in not only both FLOWER and equation 3 predicting a pressure increase of more than 10 bar, but the difference between both results being less than 4%, much smaller than the previous simulations. This confirms that $\beta^2/\rho C_p^2 \approx 0.45P^{-1.8}$ is only valid for pressures above 10 bar and large pressure changes. Nevertheless, the parabolic pressure profile along the pipe is very similar to the pressure profile along the pipe from Miller's experiment.

To further test this model and to determine an appropriate diameter of the BD, a series of simulations were made with the same dimensions and heat function (with maximum heat flux of 6 kW/m^2) as described above, but changing the diameter of the BD while maintaining a fixed ξ. The evolution of the resulting maximum pressure as a function of BD diameter is shown in figure 4 (a). As expected, a smaller BD diameter results in a higher P_{max}. This is because the area through which the helium can be evacuated is smaller, therefore choking the flow of helium, and thus increasing P_{max}.

A more surprising result was the dip in the P_{max} curve of 5.3 bar when the BD diameter equaled the D_h of the main pipe, followed by a slow convergence back to 5.3 bar. It was found that this effect was due to the helium experiencing a sudden pipe expansion. When a sudden increase of diameter occurs, a set of recirculating turbulent flow zones form at the sides of the expansion joint [6]. This produces mechanical energy losses that result in a reduction in flow rate due to mass conservation [6]. As such, there is a reduction of momentum, producing a drop in the velocity of evacuation, as well as a pressure drop given by the Borda-Carnot equation [6]. This explains why there is a minimum in the maximum pressure when the diameter of the BD is equal to the D_h of the pipe, as the opened BD will simply act as an extension of the main pipe. As the diameter increases the area of the expansions increases until it reaches open space, equivalent to having an infinite area. At this point, turbulent flows cannot form resulting in no mechanical losses and no pressure drop. Simulations with BD diameters of 63 mm and 100 mm were performed, resulting in maximum pressure of 5.4 bar and 5.39 bar respectively. This confirms the assumption of the slow convergence to the minimum 5.3 bar.

To further test the effect of the BD on the system, several simulations were made with a fix BD diameter and using the same heat function and parameters as before, but changing the breaking pressure from 1.4 bar to 2.5 bar. However, this did not change significantly the maximum pressure. When the BD diameter equaled the D_h, the P_{max} for breaking pressures smaller than 2 bar was constant at 5.3 bar and increased up to 5.32 bar when the breaking pressure was 2.5 bar. For much smaller and larger diameters, the P_{max} also did not vary much, with a difference of 0.07 bar between the largest and smallest breaking pressure for a BD diameter of 10 mm, and a difference of 0.1 bar for BD diameters larger than 30 mm. Such a small change in P_{max} is explained by the rapid initial pressure increase, reaching 1.4 bars in 0.23 s for the breaking pressure of 1.4 bar and 2.5 bars in 0.35 s for the breaking pressure of 2.5 bar. Due to such rapid increase, the evolution of the pressure in the middle of the SC-Link, where the pressure is maximum, is independent of the evolution at the ends of the SC-Link. Nevertheless, this is a good indication that decreasing the breaking pressure in the real test will not have a noticeable effect when a LoV accident occurs.

Finally, the effect of the pipe diameter (D_p) on the maximum pressure was studied. For this, a set of simulations were made by keeping the cable diameter constant but changing D_p. Every time the D_p increased, the A_{flow}, P_{wett}, D_h and maximum heat deposition (using 6 kW/m^2) were recalculated using the new D_p, and the new D_h was used as the diameter of the BD. However, the parameters of the RV, the friction and ξ of the BD were left constant throughout all the simulations. This was done to

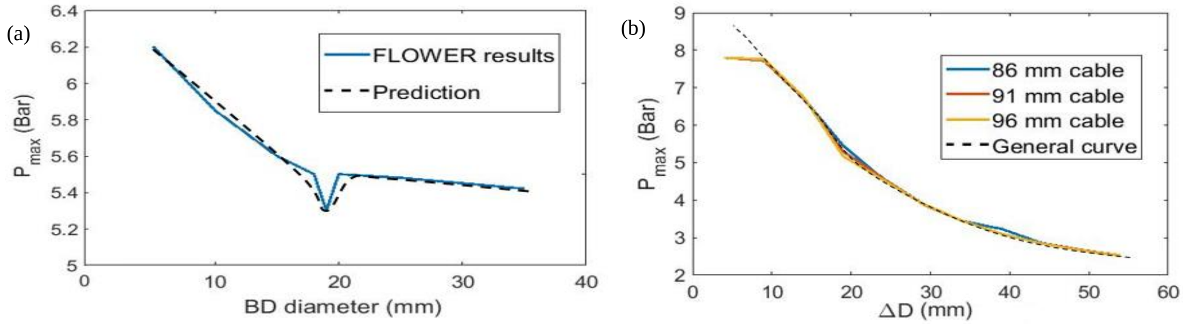

Figure 4. (a) Evolution of the maximum pressure predicted by FLOWER as a function of BD diameter. (b) Evolution of maximum pressure as a function of the difference in diameter between the pipe and the cable.

find a general curve of maximum pressure as a function of difference in diameter between the cable and the pipe (ΔD). As such, when future systems are made with a similar geometry, this curve can be used to determine what would be the maximum pressure for this non-physical absolute worst case scenario and design the system accordingly. To find such curve, three sets of simulations were made with cable diameters of 86 mm, 91 mm and 96 mm, and ΔD ranging from 4 mm to 54 mm in steps of 5 mm. The resulting curve is shown in figure 4 (b).

The gradual decrease in maximum pressure with increasing ΔD was expected, as a larger ΔD indicates a larger A_{flow} and thus a larger mas of helium stored in the pipe to distribute the heat. It was assumed that as the ΔD increased, the maximum pressure would slowly converge to the starting pressure of 1.3 bar, as at large enough ΔD the amount of helium in the pipe is so large that it acts as a reservoir at constant pressure and temperature. Similarly, as the ΔD decrease, the amount of helium in the pipe also decreased, resulting in a much smaller mass of helium to distribute the heat and thus a much higher pressure increase. The results at the smallest ΔD were not considered, as physically the A_{flow} would be so small that there would problems inserting the cable into the inner tube.

To further validate this curve and to determine the effect of the impedance of the BD and the heat on the maximum pressure, two set of simulations were made with the 91 mm cable constant while changing D_p. In the first set the heat flux was left constant at the 2.1 kW/m used for the 110 mm diameter pipe, and in the second set the impedance of the BD was changed accordingly with the new burst disk diameter. The end results where very similar to the general curve from figure 4 (b). The maximum pressures predicted when the impedance changed differed by less than 0.15 bar from those predicted by the general curve from figure 4 (b). The pressures predicted when the heat was constant were very similar to the general curve at small ΔD, but the difference started to be more noticeable as ΔD increased, always producing smaller maximum pressures. This was expected, as the heat used in simulations where the D_p >110 mm was smaller than the heat that the real pipe would experience due to the equation used to convert from W/m^2 to W/m. These results however were not considered due to them not being physical, as the heat in a real system would evolve accordingly to the size.

3.2 Realistic heat flux

With an upper absolute worst case scenario P_{max} of 5.3 bar, and the model tested, more realistic localised heat functions were developed and studied. The main challenge with this was the large number of variables that needed to be taken into account. However, the system was simplified by neglecting factors such as the size of the hole and considering 3 main parameters. These were the probability of the air molecules sticking on the surface of the inner tube, known as the sticking coefficient (C), the velocity of propagation of the air front, and the time it takes for the entirety of the vacuum jacket to re-pressurize back to 1 bar after LoV.

With this, 2 distinct forms for the heat flux in space and time were chosen. For the evolution of heat flux in space along the pipe an exponential decay was chosen with the peak at the location where

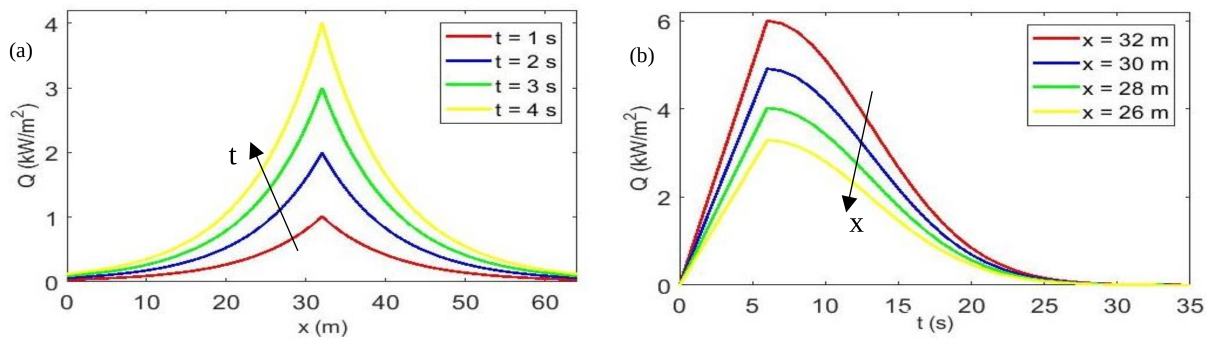

Figure 5. (a) Evolution of the heat flux along the SC-Link at several times. (b) Evolution of the heat flux in time at several locations along the pipe. In both cases, the LoV accident occurs at the midpoint between the two ends of the SC-Link.

LoV occurs, as figure 5 (a) shows. This form was chosen due to the decay of the air front velocity as it propagates along the vacuum. This was shown by Dhuley et al. [5] in a LoV experiment performed on a 32 mm diameter, 1.5 m long uninsulated vacuum copper tube submerged into a tank of LHe. One of the ends of the tube was blocked, while the other was connected to a tank of gas nitrogen at room temperature and 1 bar through a closed valve. At a given time, the valve opened and nitrogen started to flow into the cold vacuum and condense onto the copper tube. Dhuley found that the velocity of the gas front decreased exponentially. The reason behind this decay is due to mass conservation. The mass of the gas front can be divided in 3 terms: "*the mass that accumulates at the beginning of the tube, the mass that condensates on the walls of the tube and the mass that is carried by the front*" [5]. Thus, as the gas propagates more mass condensates on the walls and the mass carried by the front decreases rapidly, reducing the propagation velocity. Experiments of LoV on cold vacuum tubes of 1.5 m [5], 2 m [7] and 6 m [8] have yield measured λs of 0.63 m, 0.8 m and 2.7 m respectively. While these results seem to indicate that λ increases with length, there are many other factors that λ might depend on such as the diameter of the pipe, the entrance velocity of air and the amount of surface.

For the heat evolution in time, an initial gradual linear increase (buildup time) was chosen until it reached 55 K. At this point, the heat would decay like a Gaussian function. An example is shown I figure 5 (b). The gradual increase was chosen because of the experiments made by Lehman et al. [4] in a LoV accidents on an insulated cryostat tanks. These experiments showed how initially the heat flux increased linearly in around 6 seconds until it reached the maximum heat flux, followed by a very slow decay in time. However, multiple simulations made with this gradual increase showed that this system reaches 55 K before the 6 seconds passed, thus never reaching 6 kW/m^2. As such, the heat was set to increase linearly to 6 kW/m^2 until 55 K were reached. At this point, the increase was terminated and the decay initialized. The Gaussian decrease was chosen because of the sticking probability C and the amount of time for the vacuum to re-pressurize to 1 bar. As explained in Garceau et al. [7], one of the main factors that determines the efficiency of the heat flux is the C of air molecules on the pipe. Several experiments have shown how the C of nitrogen on solid nitrogen and metals evolves with temperature, pressure and surface coverage of condensed molecules [8,9].

For pressures and temperatures similar to the ones of the vacuum jacket from the SC-Link, the C on solid nitrogen has been shown to be close to 100% [10], however, as the pressure and temperature increase, C decreases rapidly. This explains the importance of the re-pressurization time. In addition, C drastically decays with surface coverage, meaning that as more air molecules condense on the surface, the C of the new molecules diminishes rapidly and drastically reduces the efficiency of heat transfer. However, it has been shown that while the decay of C is more drastic with pressure and surface coverage [9], almost like a step function, the decrease of C with temperature is more gradual and Gaussian-like [8]. Thus, a Gaussian decay was chosen for the evolution of the heat function in time.

With these functions, the main challenge was to find a proper decay constant in space (λ) and time (τ), as well as a proper build up time. For this, multiple simulations were made using the findings of the effect of the BD diameter and breaking pressure on P_{max} from before, using the same parameters from table 1 and using a buildup times of 6 s. However, in each simulation the values of λ and τ where changed. τ was varied between 5 s and 35 s, and λ was varied between 2.7 m, the value measure by Garceau et al. [8], and 385 m, a large enough λ that the difference between the heat at the LoV point and the ends is small.

It was found that, for a given λ, the decay rate in time did not have a significant impact on the final P_{max}. For the smallest λ of 2.7 m, the P_{max} changed from 1.872 bar for $\tau = 5$ s to 1.932 bar for $\tau = 35$ s. However, as λ increased, this difference decreased significantly until a $\lambda = 9$ m was reached, after which the P_{max} was independent of τ. Thus, due to the small effect of τ on P_{max}, the study of the effect of this parameter was stopped at 35 s. Nevertheless, τ did have an effect on the temperatures reached by the system, increasing as τ increased. This was expected because as τ increases, the heat decay is slower. This would result in a larger total deposited power, and thus a higher temperature. To determine the effect of λ on P_{max} using the above, the rest of the simulations were made with a fix $\tau = 10$ s for convenience. The resulting evolution of P_{max} is shown in figure 6 (a). As expected, a larger λ resulted in a larger P_{max} because the decay in space is slower and a larger average heat flux is deposited on the pipe.

Furthermore, if the decrease in velocity due to mass condensation is ignored, the velocity of the front would be approximately constant. It has been shown by Takiya et al. [11] that for pressures of 10^{-6} mbar, the velocity of entry is of the order of 2000 m/s for an aperture to pipe diameter ratio of 0.1 or larger. If the LoV hole in the SC-Link would occur at the midpoint, the air front would reach the ends in milliseconds. This can be approximated by considering the entire pipe heating up simultaneously, like in the Miller et al. [2] experiment, while keeping the same form of the heat flux in time. Thus, a simulation was made with the entire pipe heating homogeneously but with the heat flux increasing linearly in 6 seconds and a $\tau = 10\,s$. This resulted in a $P_{max} = 3.957$ bar, similar to the converging pressure of the red curve from figure 6 (a). This was expected because, as λ converges to infinity the exponential decay slows down so much that the change of heat flux between the point of air leak and the end of the pipe is negligible.

All this simulations were made assuming a maximum heat flux of 6 kW/m^2, the maximum heat flux measured in a LoV accident of a cryostat with 10 layers of MLI. However, the SC-Link will be insulated with 30 layers of MLI. According to the expression from [12], increasing the layers of MLI from 10 to 30 reduces the heat flux by half. Thus the same set of simulations were made but with a smaller maximum heat flux of 3 kW/m^2. In addition, it was assumed that the effect of adding more layers of MLI would also delay the time it takes to reach the maximum heat flux. This increase time was assumed to be 12 seconds, double the increase time of 10 layers of MLI.

The same set of simulations as before were made with this new heat flux. Just as before, τ had an

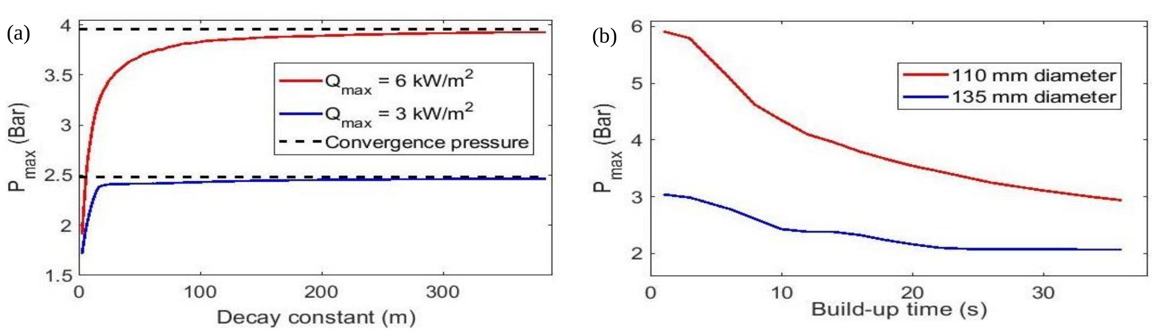

Figure 6. (a) Evolution of the P_{max} with λ for a maximum heat flux of 6 kW/m^2 with a 6 seconds increase rate and a maximum heat flux of 3 kW/m^2 with a 12 seconds increase rate. (b) Evolution of the reasonable worst possible P_{max} with change in the initial buildup time for the 124 m SC-Link with and inner tube average diameter of 110 mm and a provisional inner tube of 135 mm average diameter.

insignificant effect on the P_{max}. On the other hand λ did have an effect on P_{max}, as figure 6 (a) shows, increasing rapidly for small λ before converging to a $P_{max} = 2.479$ bar, significantly lower than the 10 layers of MLI case. This shows the importance of using insulation layers in cryogenics systems. Just as before, the convergence value was computed by assuming no decrease in the air front velocity and approximating the rapid air propagation along the tube as the entire pipe heats up simultaneously. This value was treated as the reasonable worst possible pressure for a realistic LoV accident.

In all of the previous simulations, the aperture responsible for LoV was located in the midpoint between the two ends of the SC-Link, at 32 m from V1 in figure 2. It was assumed that, due to the symmetry of the system, this location is where the pressure would be the largest, decreasing parabolically as the LoV hole moved to the ends of the pipe. To test this assumption, multiple simulations were performed in which both λ and the location where the decay started were changed. While all the resulting P_{max} curves had a parabolic shape, the maximum was not always at 32 m from V1. The location of the largest P_{max} varied between 28 m and 32 m. However, this variation was never larger than 0.05 bar, and treating the LoV hole at 32 meters from V1 as the worst case was still valid. A possible reason for the maximum P_{max} not being in the midpoint of the pipe length is because, even if the pressure stabilizer system is ignored, the system is not completely symmetric. Due to the background heat mentioned before, the helium flowing from V1 to V2 in figure 2 heats up by around 3.5 K, meaning that the V1 end will be colder than the V2 end. Thus, because the P_{max} is highly dependent on the distance to the BDs and the initial temperature, increasing for lower initial temperatures, the largest P_{max} will be shifted a small amount towards the V1 end.

Finally, with these findings, the effect of the initial buildup time of heat flux on the P_{max} was tested by changing this time between 1 s and 36 s. This was done twice, first with a 124 m SC-Link with the inner tube having the mentioned diameter of 110 mm, using the same geometry and dimensions as described before, and then again with the same length and RV but a larger average diameter of 135 mm with a $A_{flow} = 7810\,\text{mm}^2$, a D_h and BD diameter of 44 mm, and a $P_{wett} = 710$ mm. In both cases the cable was fixed at 91 mm. The latter is a provisional pipe diameter in case the final design of the cable is too large to fit through the current cryostat. In addition, because in some cases the buildup time was so small that the system reached 3 kW/m^2 before reaching 55 K, the heat function was modified as follows. If the system reached 3 kW/m^2 before the 55 K, the heat flux would be maintained at that value until the 55 K were reached, at which point the heat would decay like a Gaussian. This would be very similar to top-hat like function used before but with a Gaussian decay. An example of this is shown in figure 7. The resulting curves are shown in figure 6 (b). As expected, both diameters produce a large P_{max} at small buildup times. This is because if the buildup time is slower, when the system has reached 55 K the BD would have opened long ago and most of the helium would have been ventilated, resulting in there being very little helium to heat and thus a small increase in pressure. Conversely, for fast buildup times, the system would reach 3 kW/m^2 shortly after the BDs opened, resulting in a much larger pressure increase. This was confirmed when the simulation with a buildup time of 1 s predicted the BD to open 1 s after LoV while the simulation with a buildup time of 18 s predicted the BD to open 5.78 s after LoV. However, the situation with a

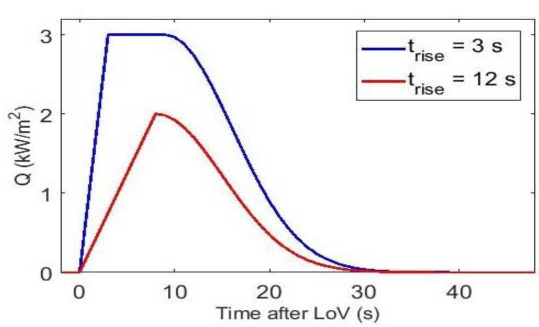

Figure 7. Heat function with time after LoV for a buildup time (t_{rise}) of 3 s, where the system reaches 3 kW/m^2 before reaching 55 K, and a t_{rise} of 12 s, where the system reaches 55 K before reaching 3 kW/m^2.

small buildup time have unrealistic LoV event and therefore not representative of a reasonable physical event. Nevertheless, these curves clearly show the benefits of having a larger inner tube diameter, as not only the P_{max} is more independent of the buildup time, but it also drastically reduces the pressures. This is because the amount of helium stored in the tube at any given time is much larger, resulting in a larger helium mass to distribute the heat, drastically reducing the maximum pressure in a LoV accident. These results are in agreement with the general curve from figure 4 (b) of the decrement of P_{max} with larger inner tube diameter.

4. Conclusion and future work

The LHC will be undergoing an upgrade in which new magnets will be installed at 2 of the 4 colliding locations to increase the number of collisions. A high current transfer line called the Superconducting Link (SC-Link) is being built to transport the power to the magnets. The SC-Link will consist of two concentric corrugated tubes 120 m to 130 m in length separated by vacuum. The inner tube with an average diameter of 110 mm will contain supercritical gas helium at temperatures below 20 K and a pressure of 1.3 bar, as well as a 91 mm diameter superconducting MgB_2 cable assembly used to transport the current. At each end of the SC-Link a pressure relief system comprised of a burst disk (BD) and a relief valve (RV) will be used to protect against overpressure. In this report, multiple simulations were made using the FLOWER program to determine the maximum pressure in the SC-Link in a LoV accident for a reduced 64 meter long SC-Link and a 124 meter long SC-Link.

The P_{max} predicted by the model were compared with the P_{max} predicted by the experimentally verified theory from Miller et al. [2]. For this, a top hat-like heat function in time with a maximum heat flux of 6 kW/m^2 was applied uniformly to the entire of the inner tube. This would be equivalent to entirety of the outer tube suddenly being removed. While FLOWER predicted a peak $P_{max} = 5.3$ bar, Miller's equation predicted a $P_{max} = 9.49$ bar if the full 6 kW/m^2 was used. The measurements were repeated but using a smaller heat flux of 3 kW/m^2, producing a $P_{max} = 5.3$ bar for FLOWER and a $P_{max} = 5.97$ bar with Miller's equations.The reason for such disagreement is the assumptions made by Miller such as having a constant density along the pipe before LoV and using the equality $\beta^2/\rho C_p^2 \approx 0.45P^{-1.8}$. Nevertheless, the parabolic pressure profiles along the pipe predicted by FLOWER were very similar to the pressure profiles of Miller's experiment.

Furthermore, the effect of the BD diameter and breaking pressure on the P_{max} were tested with this same heat function. Results showed that the P_{max} is almost independent of the breaking pressure. However, the P_{max} did change drastically with BD diameter, with a minimum of 5.3 at a BD diameter equal to the hydraulic diameter D_h of the pipe. This is in accordance with the Borda-Carnot equation. Finally, a general curve of the P_{max} as a function of the difference between the cable and pipe diameter (ΔD) was found, resulting in a gradual reduction in P_{max} as ΔD increased.

With this verification, more realistic heat functions were studied. For this, three main factors were considered: the decrease in velocity of the air front, the sticking coefficient, and the re-pressurization of the vacuum jacket. The chosen functions were an exponential decay in space, with a decay constant λ, and a gradual linear build up in time followed by a Gaussian decay, with a decay constant τ, when the condensation temperature of 55 K was reached. The effect of λ and τ were tested with a maximum heat flux of 6 kW/m^2 and a build-up time of 6 seconds (for 10 layers of MLI), and then again with a maximum heat flux of 3 kW/m^2 and a build up time of 12 seconds (for 10 layers of MLI).

While the rate of the decay in time did not change the resulting P_{max} significantly, the rate of decay in space did have an effect, increasing rapidly for small λ and converging to a value of 3.957 bar and 2.479 bar for the 6 kW/m^2 and 3 kW/m^2 case respectively as λ approached infinity. Finally the effect of the build-up time on P_{max} was tested for the full 124 m long SC-Link, first using an inner tube with a 110 mm diameter and then using a 135 mm diameter tube. This showed the benefits of having a larger diameter, as the resulting P_{max} curve were almost independent of the buildup time, and was significantly lower than the P_{max} predicted for the smaller diameter.

Much more work has to be done in refining this model, as there are many parameters that need to be carefully considered, such as the size of the hole producing the LoV, the heat capacity of the cable and the air entrance velocity. Nevertheless, the model can still be used in other similar systems and produce satisfactory results.

Acknowledgment

I would like to acknowledge Luca Bottura, group leader of the "Magnets, Superconductors and Cryostats" group in the "Technology" department, for providing the FLOWER program, the IT team for helping to set up the software needed to run FLOWER, the "Cryogenics" and "Superconductor and devices" team for providing details of the specifications of the SC-Link, the cable and the valves, and my supervisor Patrick William Retz for guiding the project.

References

[1] CERN 2018 The Large Hadron Collider [Online] Available: https://home.cern/science/accelerators/large-hadron-collider
[2] Miller J R, Dresner L, Lue J W, Shen S S and Yeh H T 1980 *Proc. ICEC-8* (Genova) (Guilford: Butterworth) pp 321-9.
[3] Bottura L and Rosso C. 2003 *Cryogenics* **43** 215-23.
[4] Lehmann W and Zahn G 1978 *Proc. Int. Cryogenic Eng. Conf.* (London) vol. 7 (United Kingdom: IPC Science and Technology Press) pp 569–79.
[5] Dhuley R C and Van Sciver S W 2016 *Int. J. Heat Mass Transf.* **96** 573–81.
[6] Chanson H 2004 *The Hydraulics of Open Channel Flow: An Introduction* (London: Elsevier Butterworth-Heinemann).
[7] Dalesandro A A, Dhuley R C, Theilacker J C and Van Sciver S W 2014 *Advances in Cryogenic Engineering* vol 59 ed Weisend II J (New York: AIP Publishing) pp 1822–1828.
[8] Garceau N, Bao S and Guo W 2019 *Int. J. Heat Mass Transf.* **98** 1144-50.
[9] Welch K M 2001 *Capture Pumping Technology* ed Welch K (Amsterdam: Elsevier Science BV).
[10] Deng S H M, Cassidy D B, Greaves R G and Mills Jr A P 2007 *Appl. Surf. Sci.* **253** 9467-69.
[11] Takiya T Higashino F Terada Y and Komura A 1999 *J. Vac. Sci. Technol. A* **17** pp 2059–63.
[12] Giannelli S *Sizing of pressure relief devices for 60 meters long semi-flexible cryostats in the framework of the Superconducting Link project* CERN internal notes EDMS1722630.