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Numerical simulation of cold helium safety discharges into a long relief line

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Abstract

All existing and currently constructed large superconducting particle accelerators use liquid or supercritical helium for transferring cooling power from the cryogenic plant to the accelerator magnets and cavities. These accelerators have extremely elongated structures and therefore require widespread cryogenic distribution systems as well as advanced gas management systems. The design and operation of their cryogenic system are strongly affected by the requirements of high reliability and operating cost minimization. This strongly influences pressure equipment safety strategies. Because accidental helium discharges from the accelerator cryostats and cryomodules cannot be excluded, possibilities of recovering helium releases from safety devices are taken into consideration. Collecting discharged helium and transferring it back to the cryoplant via a long recovery line is not only an option, but also a must. Usually the baseline design choice for the helium recovery system is a set of safety valves connected to a bare relief line that ends in a gas bag. However, rapid and fast discharges of cold helium into warm relief lines can result in significantly unsteady, compressible and thermal flows. Therefore the proper designing and sizing of the recovery system have to be supported by detailed analyses of all expected fluid dynamics and thermodynamics phenomena.

This paper describes the numerical simulations of cold helium discharges into a long, warm safety relief line. The simulations have been done for the helium recovery system of the superconducting proton accelerator that is under construction at ESS in Lund, Sweden. The paper discusses the model assumptions and presents some example results.

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Keywords: helium discharge; safety relief; ESS

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1. Introduction

Helium cryogenics is currently the most developed technology for the thermal conditioning of large superconducting particle accelerators, both for existing (e.g. LHC at CERN and SNS in ORNL) and for those under construction, such as the European XFEL at DESY or the European Spallation Source (ESS) in Lund, Sweden. All these accelerators have elongated structures and require transport of cold helium over very long distances, from the helium refrigeration units to the users of the cryogenic cooling powers. These users consist mainly of superconducting cavities and magnets, whose nominal operation temperatures are at the level of liquid or even superfluid helium. The design and operation of the superconducting accelerators must usually fulfill the requirements of high reliability and limited operational costs. These requirements strongly influence the design choices for their cryogenic systems, including cryogenic gas management and pressure equipment safety strategies. Due to high helium prices, the cryogenic systems must be designed and operated to minimize all possible helium losses, whereas to reach high reliability, the cryogenic gas management system must allow for fast recovery to the nominal operating conditions after a number of possible failures.

As accidental helium discharges from the cryostats and cryomodules cannot be excluded, possibilities of recovering released helium from safety devices should be taken into consideration in order to avoid economic and environmental damages. One possible option is to collect the discharged helium and then transfer it back to the cryoplant via a recovery system. Such a system must include a long line connecting the safety relief valves with a helium recovery tank. A number of design choices for the recovery system are strongly affected by the technical features of the accelerator components.

An example helium recovery system is currently under conceptual design at ESS. ESS itself is going to be the world's most powerful neutron source using a superconducting proton linac [1]. The ESS linac will consist of 43 cryomodules [2] that will be connected to the accelerator cryoplant by an extensive cryogenic distribution system (CDS). The CDS will, apart from the cryogenic transfer and distribution lines with 43 valve boxes, comprise four auxiliary process lines, including the safety valve relief line (SV relief line) [3]. The ESS helium recovery system will consist of the SV relief line and a helium tank connected to the cryoplant warm compressor station. The system is dedicated for collecting all potential helium safety discharges from the cryomodules. The baseline design of the recovery system considers a 400 m long bare relief line connecting the cryomodule safety valves to a gas bag.

The ESS cavities are characterized by low acceptable pressure loads, and the set pressure of the relief valves is therefore considered to be at the level of 1.4 bar only. Nonetheless the discharges of cold helium into this relief line can result in significantly unsteady, compressible and thermal flows. Therefore, the proper designing and sizing of the relief line have to be supported by detailed numerical analyses of all expected flow and thermal phenomena.

This paper presents the numerical simulations of the expected flows of cold helium in a non-isolated, long relief line. These simulations will then be used for sizing the SV relief line.

2. Model of the ESS helium recovery system

Each cryomodule and valve box pair will have four safety valves linked to the SV relief line [3]. Thus, the line will connect 172 safety valves with the gas bag. All these valves will be distributed along a distance of 305 m, being the superconducting part of the linac. The remaining section of the line, of 95 m in length, will run from the linac tunnel to the cryoplant warm compressor station, where the gas bag will be located. The SV relief line will be filled with helium at ambient temperature, under the pressure of 1.05 bar. Each cryomodule will hold 45 kg of helium, mainly at saturated 2 K helium phase. However, as the safety valve set pressure is equal to 1.4 bar, the discharged helium temperature will be above 4.6 K.

The numerical model of the ESS helium recovery system is presented in Fig. 1. The lengths of the model SV relief line are the same as in the real line, but each cryomodule is connected to the line via one safety valve only. As the simulations were focused on the estimation of maximum available mass flow rates of the discharged helium for a given limit of the maximum pressure downstream the safety valve, the taken simplifications describe the worst case of all possible discharge scenarios.

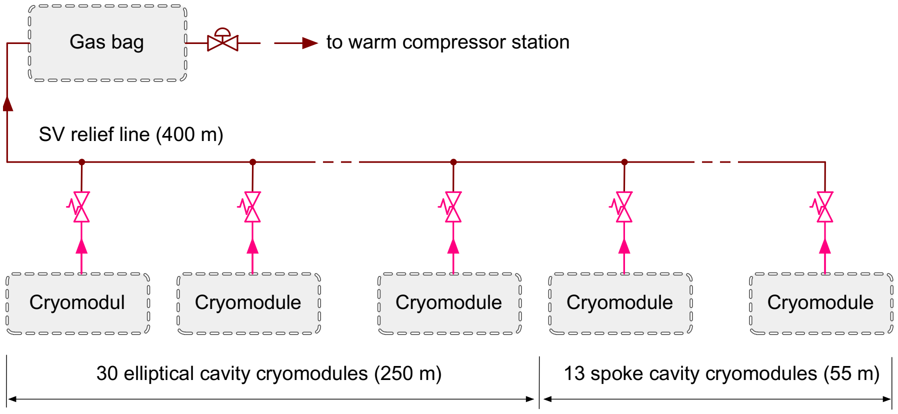

Fig. 1. The model design of the ESS helium recovery system.

The model allows for altering the relief line inner diameter, making it possible to adjust the diameter based on the arising helium mass flow rates and for given pressure limits in the line. The material of the model SV relief line wall is stainless steel 304L and the thickness of the pipe is kept constant at 3 mm for all analysed diameters.

3. Numerical modelling of the helium discharge

The numerical modeling and simulations were done in the Dymola modeling and simulation environment, which is based on the Modelica language [4,5]. As an object-oriented, declarative, and acausal language, Modelica allows to run the simulations with the order of equations and structure of events determined by the evolution of the processes [5].

The flow in the SV relief line was modeled as one-dimensional, using the Darcy-Weisbach friction-adjusted Bernoulli equation. As the line has a very high length-to-diameter ratio and significantly low pressure gradients, this approach can be applied to model the expected flows [6,7]. The heat transfer between the pipe wall and the flowing helium was described by the Dittus-Bölter equation [8]. The heat flux on the outside of the pipe is modeled as purely diffusive, and the surrounding air is kept constant at 300 K. The model did not take into account any heat transfer along the pipe walls, as well as any condensation and frosting on the outer surface of the line.

4. Simulation results

The simulations were focused on the estimation of maximum allowable mass flow rates as a function of pipe diameter and maximum pressure in the line. They were made for helium discharges at different cryomodule locations. The size of the line and the maximum acceptable pressure of helium downstream the relief valves were changed in the ranges of [DN150, DN200, DN250] and [1.10, 1.15, 1.20 bar], respectively.

Fig. 2 presents the results for the two extremes of the cryomodule locations, i.e. at 95 m and 400 m from the gas bag. The results show that the analysed flows are very unsteady in the first seconds. Due to high temperature differences, the discharged helium experiences a temperature rise, causing a significant pressure increase. The pressure rises to the highest values in the inlets to the relief line just after the beginning of the flow. Then, within a couple of seconds, it significantly decreases. The distributions of the mass flow rates along the SV relief line in the first seconds of the flow indicate the high unsteadiness. Later, the variations of the mass flow rate disappear and its distributions are uniform, which means that the flow becomes steady. In spite of this, the helium temperatures still vary strongly along the length of the line. However, due to heat loads from the external surroundings to the external surface of the line, the distribution profile does not change after reaching steady flow.

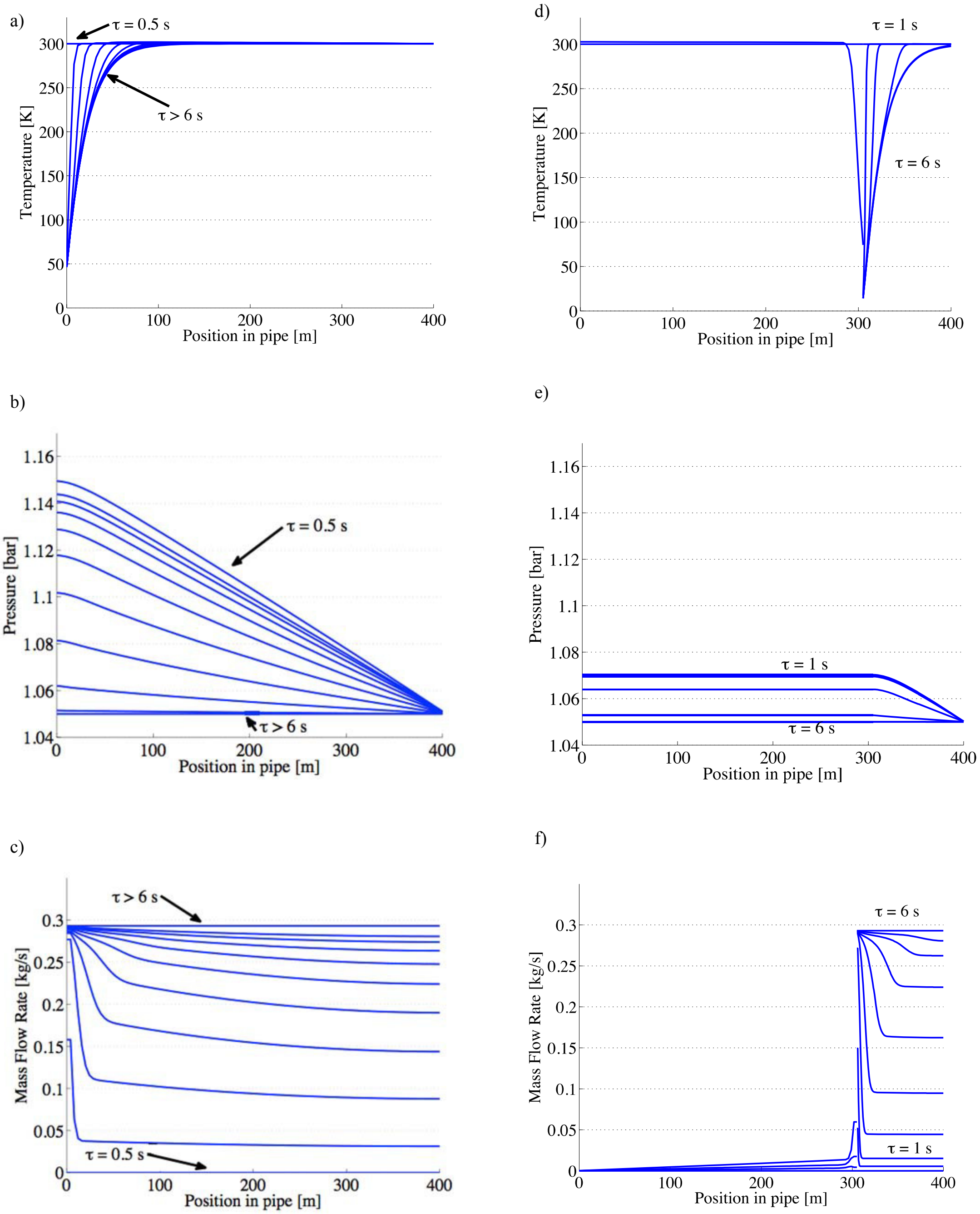

Fig. 2. Evolutions of temperature, pressure, and mass flow rate over the length of the SV relief line for cold helium discharge at 400 m (a, b c) and 95 m (d, e, f) from the gas bag. Here, the input value of initial mass flow rate is kept at 0.293 kg/s for both cases.

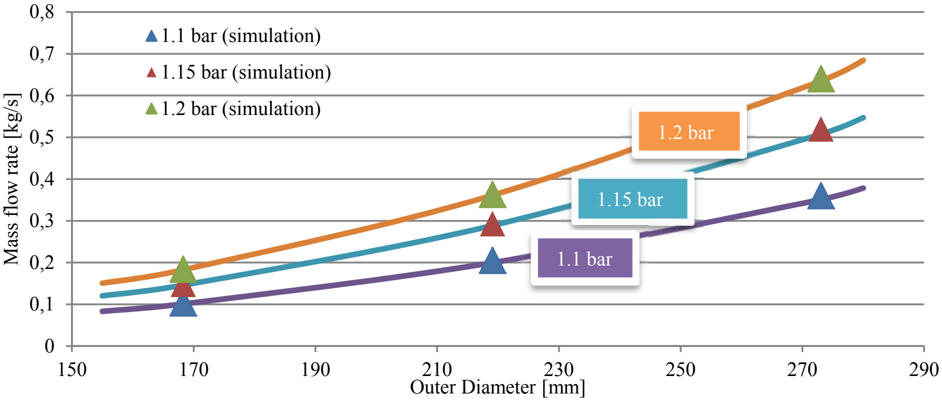

Fig. 3. Mass flow rates as a function of pipe diameters for the chosen maximum available pressures at the outlet of the safety relief valve, and for a pressure in the gas bag of 1.05 bar. Triangles represent the values obtained from numerical simulations of unsteady flows, whilst lines denote the characteristics of steady flows of helium at ambient temperatures.

The obtained results of the numerical simulations allowed for estimating the maximum available mass flow rates. The found available mass flow rates for chosen pipe sizes and maximum acceptable pressures in the line are shown in Fig. 3. The plotted values are compared to the mass flow rates of steady and isothermal flows of helium at ambient temperature. The comparison shows that the maximum available mass flow rates at unsteady flows are only 2.5% higher than the mass flow rates of steady flows of helium at ambient temperature.

5. Conclusion

The presented simulations consider the worst case scenario for sizing the SV relief line of the ESS linac helium recovery system, being a bare pipe exposed to a cold helium discharge from one safety relief valve only. The mass flow capability of the line is limited by the discharges at 400 m from the gas bag. The system reaches steady state within 6 seconds, after which the temperature, pressure, and mass flow distributions stay constant as long as the discharge lasts. The highest pressures are reached for a helium discharge at the maximum distance from the gas bag, while they are considerably lower at the closer end (see Fig. 2). This means that the closer to the gas bag a discharge appears, the higher the allowed mass flow rate.

A simple model of isothermal, steady helium flow at ambient temperature can be used for initial estimations of the expected maximum flow capacity of a non-insulated long relief line, dedicated for collecting cold helium safety discharges. The results presented in Fig. 3 show that, as long as the flow is not compressible and frosting and condensation on the relief line external surface are not present, an isothermal calculation is a very good approximation, with the differences not exceeding 2.5%.

The modeling of the ESS recovery system is ongoing. The further study will be focused on analyzing the effects of frosting and air condensation on the external surface of the relief line wall. The effects of convective heat transfer will also be included in the detailed model.

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