Numerical analysis of free convection in cold helium vapor flows in a long sloped pipe

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Abstract. The cryogenic systems of large scientific facilities using superfluid helium technologies include a cold helium circuit composed of a subcooled liquid helium supply line and a low-pressure return line. Due to long distances between the cryogenic plant and cryogenic users the line lengths can reach hundreds or even thousands of meters. Usually the low-pressure return line is a large size pipe, which inner diameter can exceed 300 mm. In some cases the accelerators and also the cold helium circuit lines are sloped. In some transient modes there is a risk of a counter flow in the low-pressure return line. This counter flow phenomenon can be driven mainly by free convection and it can disturb the cool down dynamics or affect the performance characteristic of some cryogenic devices, which are sensitive to cool down rates. This paper presents a numerical analysis of free convection in cold helium vapor flows in a long straight and sloped line. The methodology of numerical modeling of the thermo-hydraulic phenomena is described in detail. The results of the numerical simulations performed for various pipe lengths, slopes and mass flow rates are compiled and discussed.

1. Introduction

The cryogenic systems of large scientific facilities using superfluid helium technologies, such as LHC, SNS, CEBAF, XFEL, ESS and LCLS-II, include a cold helium circuit composed of a subcooled liquid helium supply line and a low-pressure return line. The superfluid helium provides indispensable cooling power to the particle accelerators superconducting components (cavities and magnets). The superfluid helium is produced from the subcooled liquid helium at 4.5 to 5 K and 3 bar(a) by precooling in a heat exchanger and throttling in a Joule-Thomson valve. From a thermodynamic point of view, it is profitable to produce superfluid helium just at or in the cryostats of superconducting components. For very long machines, there is a need for a large number of heat exchangers and JT valves. This architecture, which is used in LHC and SNS [1, 2], results in lower heat loads to the supplied helium but requires higher capital costs. Precooling the 4.5 K helium to 2.2 K in one large heat exchanger and distributing the 2.2 K helium to the JT valves located near the final users of superfluid helium can lower the cost. However, it can result in higher heat loads to the transferred helium. This layout, with one common heat exchanger, can be found in the XFEL and LCLS-II cryogenic systems [3, 4]. In both solutions the JT valves throttle the helium to a sub-atmospheric pressure of 16 mbar(a) to 31 mbar(a). This low sub-atmospheric pressure is generated by cold compressors, which are located at the cold box. Therefore, there is a need for transferring low-pressure
helium vapors at a temperature of 4 K in case of many small heat exchangers, or around 2 K in case of one big heat exchanger.

The cryogenic distribution systems of the mentioned facilities include also a thermal shield circuit, which transfers supercritical helium at a temperature of 40 K to 80 K and a pressure of 12 bar(a) to 20 bar(a). Its function is to collect the heat from the cryogenic user thermal shields and from the cryodistribution line.

Because of long distances between the cryogenic plant and cryogenic users, which can exceed even 3 km [1], as well as strict requirements for allowable pressure drops, the process lines of the cold helium and thermal shield circuits have significantly big diameters. The sizes of the cold helium supply lines and thermal shield lines vary from DN40 to DN80 to provide sufficiently high flow capacity for cooling down the machine in a reasonable period of time. The sub-atmospheric line, however, needs DN200 to DN300 pipes [1, 3, 4]. This need is imposed by a very high volumetric flow of cold helium vapor during nominal operation conditions. Then the density of the helium vapor is in the range of 0.2 to 0.4 kg/m³ and the available pressure drop is of a few millibars only. Whereas the mass flow rate is of 60 to 120 g/s.

In some cases, (e.g. LHC and LCLS-II) the accelerators and their cryogenic supply and return lines are slanted up or down from a horizontal line. Such slopes do not disturb significantly the helium flows in the process lines at nominal operation conditions. However, in some transient modes, there is a risk of a counter flow in the low-pressure return line. This counter flow can significantly disturb the cool down of the cryogenic users. In case of the sequential cool down of cryogenic devices it can lead to an uncontrollable cool-down of the next device due to some convectional flows of cold helium vapor via the sub-atmospheric line. Then the device can stay at unwanted temperature range for a long time, which can cause a significant decrease of its performance properties.

The paper presents the results of numerical analysis of natural convection in cold helium vapor flows in a long straight and sloped line.

2. Cold helium flows in cryogenic helium lines and free convection phenomenon

All the cryogenic distribution systems of the mentioned scientific facilities require at least four main cryogenic process lines. The helium supply and low-pressure return lines form a cold helium circuit, which provides cooling power at 2K. The two other lines, namely the TS supply and TS return, form a 40-80 K thermal shield circuit. The typical sizes of these four lines and the thermodynamic and hydraulic properties of the transferred helium are presented in table 1.

| Process line            | Size          | T | p | Mass flow rate | Gr  | Re   | Gr/Re² |
|-------------------------|---------------|---|---|----------------|-----|------|--------|
| TS supply               | DN40-DN50    | 35-50 | 12-20 | 60-100       | 1.9E8-3.3E9 | 2.5E5-4.3E5 | < 0.01 |
| TS return               | DN40-DN50    | 50-80 | 12-20 | 60-100       | 4.6E7-8.1E8 | 1.9E5-3.3E5 | < 0.01 |
| He supply               | DN50-DN80    | 4.5-5.0 | 2.5-3.5 | 80-120     | 1.4E10-5.3E11 | 1.9E5-3.3E5 | < 1    |
| LP return at 2K mode    | DN200-DN300  | 2.0-4.0 | 0.016-0.031 | 80-120     | 1.4E10-5.3E11 | 3.2E5-3.2E6 | < 1    |
| LP return at cool down  | DN200-DN300  | 4.5-300 | 1.1-1.3 | 20-120      | 7.4E5-4.6E13 | 4.1E3-3.5E5 | 0.1-77 |

The flows of helium in the TS circuit and the He supply line are driven by the pressure differences created by the warm compressors of the cryogenic plant. In the LP return line at nominal conditions the helium flow is caused by the cold compressors which evacuate the cold vapor from the cryogenic
users and create the required sub-atmospheric pressure. In the cool down mode, however, the helium vapor in the LP return line is at 1.1 to 1.3 bar(a) and its flow is driven by the warm compressors. Since the process line walls are exposed to significant thermal loads from their surroundings the cold helium flows can be affected by natural convection. The ratio of the Grashof number to the square of the Reynolds number reveals the impact of free convection onto the flow pattern. In case of the TS process lines the Grashof number is much smaller than the square of the Reynolds number. Thus free convection is negligible. In case of the cold circuit lines Gr/Re^2 can be close to 1, which shows that the heat transfer in the flowing helium is by combined forced and free convection.

The case looks quite different when it comes to flows in the process pipe in transient modes such as cool downs or warm ups. Then, the ratio Gr/Re^2 can significantly exceed 1, which shows that the natural convection can get much stronger than forced one. A good example is the LP line at cool-down mode. For small mass flow rates, the free convection can strongly surpass the forced one.

3. Problem description and plan for the numerical experiment
Since natural convection can have a strong impact on the flow pattern in cryogenic transfer lines there is a risk that in the sequential cool downs of cryogenic devices a certain significant portion of the cold helium vapor (flowing from a device being cooled down into the LP line) can flow into the further section of the line. This portion can circulate in the dead end of the line and finally return to the cryoplant in the stream of warmer vapor flowing at the upper part of the line. The process of reversal flow can be intensified by the inclination of the process line. Figure 1 illustrates this phenomenon. It shows two cryogenic devices in a sequential cool down mode. Device 1 is being cooled down, while Device 2 is supposed to stay at room temperature. Some portion of cold vapor flowing from Device 1 to the LP line gets into in the dead end. Thus Device 2 can be exposed to cooling by some circulations of the reversal flow.

![Figure 1. Schematics of the natural convection in a sloped section of the LP line.](image)

The main purpose of the present study is to assess quantitatively the reversal flow in the dead end of the LP line. Based on the hypothesis that the free convection can significantly drive the reversal flow in the dead-end of the pipe the set of variables (factors) affecting the flow consists of 1) inlet pipe diameter, 2) main pipe diameter, 3) helium inlet temperature, 4) inlet mass flow rate, 5) outlet helium pressure, 6) main pipe wall temperature, 7) pipe slope and 8) dead-end pipe length. Cool down of the cryogenic machines is a transient mode. Because of its significantly high inertia, we considered the helium flows as steady and selected three controllable factors as presented in table 2.
Table 2. Controllable factors and their ranges of variability

| Controllable factors                  | Variability         | Discretization                      |
|--------------------------------------|---------------------|-------------------------------------|
| Helium temperature in the inlet      | from 5 K to 20 K    | 5 K, 10 K and 20 K                  |
| Mass flow rate in the inlet          | from 5 g/s to 10 g/s| 5 g/s and 10 g/s                    |
| Slope of the pipe                    | from -1% to + 1%    | -1.0%, -0.5%, 0%, +0.5% and +1.0%   |

The numbers of controllable factor levels are 3, 2 and 5, respectively. Hence, with the approach of full factorial analysis, 30 separate numerical experiments were required. The $Gr/Re^2$ varies from 0.3 to even 61.4. The largest values are for flows at 5 K, 5 g/s and slopes -0.5%, 0%, +0.5% and +1.0%. 1% of slope is defined as 0.01 radian, which is equal to about 0.573 deg.

4. Numerical modeling

The numerical analysis called Computational Fluid Dynamics (CFD) using the Finite Volume Method (FVM) was performed in Ansys CFX 17.2 software. This method involves the simultaneous calculation of algebraic equations resulting from discretization of the partial differential equations of an incompressible, buoyancy, non-isothermal and laminar flow [5].

4.1. Model geometry

The analyzed geometry is presented in figure 2. The model is composed of two cylinders. The horizontal one represents a section of the LP line. Its length and size are 45 m and DN300, respectively. The vertical cylinder, which represents a DN100 inlet line, is connected to the main one in a distance of 25 meters from the outlet. The symmetrical configuration of the model allowed for employing symmetry along the YZ plane and analyzing numerically one half of the geometry.

The created geometry was discretized using a structured Hexahedra type mesh. In areas where the high pressure and velocity gradients were expected, i.e. near the slope pipe walls and symmetry, the mesh was thickened. The total number of mesh elements was equal to 4.6 million, with approximately 4.7 million nodes.

Figure 2. a) The geometry with the boundary conditions and b) the detail of the mesh and boundary conditions applied during numerical calculation

4.2. Boundary conditions

Inlet type boundary conditions were applied at the inlet to the DN100 pipe, including the specified helium mass flow rate (5 g/s and 10 g/s). The helium inlet temperature was equal to 5, 10 and 20 K. The standard no slip condition was used at the walls and the cylinder external surfaces were exposed.
to a heat flux of 0.138 W/m² [6]. The no-slip and adiabatic conditions were applied at the dead end of the pipe, whilst at the symmetry plane the scalar flux was equal to zero.

4.3. Residual target
The calculation processes were terminated when the RMS residual target of monitoring parameters dropped below $10^{-5}$. In the numerical experiments, the residual target was achieved after about 4000 iterations. The total calculation time for a single numerical experiment was 6 hours for a server with 24 processors and 48 GB of RAM.

5. Results and discussion
In order to visualize the free convection impact on the analyzed flow patterns and evaluate the reversal flow in the dead end of the LP line, results were presented as distributions of streamlines, temperature, velocity contours and vectors. Figure 3 shows example results for helium flows in the LP line at the inlet for 10 g/s helium mass flow rate, 10K inlet temperature and three different slopes: -1%, 0% and +1%. The streamline distributions reveal a strong impact of free convection on the flow pattern. Strong convective structures appearing downstream the inlet reveal a strong impact of natural convection. These structures are visible down to the distance of $2.5D_{LP}$, where $D_{LP}$ is the inner diameter of the LP line (0.318 m). The temperature distributions show significant temperature stratification, especially in the dead end section. The temperature difference of the helium flowing in the bottom and top of the line exceeds 0.6 K.

![Streamlines and velocity contours](image1.png)

**Figure 3.** Streamlines, velocity contours and temperature distributions in the central region of the modeled LP line for $m_{He} = 10$ g/s, $T_{in} = 10$ K and chosen slopes of the pipe.

Figure 4 presents the distribution of streamlines in a case of helium flow at lower mass flow rate and temperature. Here the convective structures are much more coherent and regular, especially at the side wall of the pipe. The helium flowing from the inlet pipe into the LP line initially tends to creep at the bottom of the pipe. Then it collects heat from the pipe wall surface and flows along semicircular lines to the upper part of the pipe. Later the streamlines tend to lower their strength and tend to partly turn down and locally direct to the outlet.

In case of a positive slope (pipe sloped to the outlet) the strong and coherent convective structures are located mainly downstream of the inlet zone. If there is no slope the structures are distributed
almost uniformly, whereas, for a negative slope of -1.0%, the strong streamlines are placed in the dead end section in the distance of about 1.0 $D_{LP}$. They form coherent structures at the side wall and further they fall down to the center of the pipe before reaching the very top of the pipe. The density of the streamlines at the top of the pipe is significantly lower, which shows that there is warmer helium flowing from a distant section of the dead end.

The axial velocity vectors distribution shown in figure 5 confirms the existence of this flow of warmer helium. Local axial velocities of helium flowing at the top of the pipe reach even 8 cm/s. The velocities in this region remain significantly strong along the significant length of the dead end. They decrease by half in the distance of 47 $D_{LP}$ (-15 m from the inlet).

What is also very interesting is that the axial velocities reveal significantly strong reversal flows. The velocities directed towards the dead end at the bottom of the pipe initially reach 4 cm down to the -9m cross section. Farther, they drop significantly and become very weak after the -11m cross section.

Based on the axial velocities profiles in the selected cross sections we plotted the distributions of negative mass flow rate ratios along the dead end for chosen flows (see figures 6 and 7). The negative mass flow rate $\dot{m}_- / \dot{m}_{in}$ is a flow rate of the helium flowing backwards to the dead end at the bottom of the pipe $\dot{m}_- / \dot{m}_{in}$ to the mass flow rate in the inlet pipe $\dot{m}_{in}$:

$$R_- = \frac{\dot{m}_-}{\dot{m}_{in}} = \sum \frac{v_i \rho_i A_i}{m_{in}}$$

where: $v_i$, $\rho_i$ and $A_i$ are local velocity, density and cross section of unit helium streams.

The negative mass flow rate ratio distributions show the intensity and active distance of reversal flows in the dead end.

Intensity and distance strongly depend on the temperature of the flowing helium, slope of the pipe and mass flow rate. The highest intensity is for the lowest analyzed temperature. Then the helium density is equal to 16.7 kg/m$^3$, which is almost 2.6 or 5.3 times higher than at 10 K and 20 K, respectively. Simultaneously the helium conductivity at 5K is of 10.6 mW/m-K, which is 40% and 60% lower compared to those at 10 K and 20 K. Higher density together with lower conductivity significantly increase the tendency of keeping stratified flows. The intensity of reversal flow reaches even 160% of the mass flow rate in the inlet of 5 g/s and slope of -1.0%. The lengths of significant reversal flows can exceed even the distance of 12 m in the dead end of the LP line. For higher temperatures the reversal flows get much weaker and they almost disappear for temperatures higher than 10 K.
Figure 5. Velocity vectors at chosen cross sections of the dead end for slope of -1.0%, $m_{He}=5$ g/s and $T_{in}=5K$ ($Gr/Re^2 = 59.1$).

Figure 6. Distributions of the negative mass flow rate ratios in the dead end for $m_{He}=5$ g/s.
6. Conclusions

Numerical analysis presented in the paper showed that natural convection can have a strong impact on the patterns of the cold helium vapor flows in the LP line in the sequential cool-down mode. In the analyzed flows, strong and coherent convective structures appear in the LP line in close proximity to the inlet pipe, to +2.5 m for a positive slope of +1.0 % and to -1.0 m for a negative slope of -1.0%. The phenomenon of reversal flows is most evident for the lowest analyzed temperature and for the highest negative slope of the LP line. Negative flows can reach the intensity of 160 % of the inlet mass flow rate, whilst significant reversal flows at the bottom of the pipe can exceed the distance of $37 \cdot D_{LP}$ (12 m) in the dead end of the LP line.

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