Numerical analysis of temperature stratification in a subatmospheric cold helium line

J Fydrych¹, S Pietrowicz²

¹ European Spallation Source ERIC, P.O. Box 176, 221 00 Lund, Sweden
² Wrocław University of Technology, Department of Thermodynamics, Theory of Machines and Thermal Systems, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland

Abstract. In last decades the technology of superfluid helium has become very advantageous for large-scale scientific facilities dedicated to high-energy physics. Superconducting cavities or magnets are usually immersed in helium baths at a temperature of 1.8 to 2.0 K. This temperature is produced by a JT cycle where the return line works at a subatmospheric pressure of 16 to 31 mbar. The subatmospheric line lengths can reach even several thousand meters. The helium flows in the subatmospheric lines are driven by cold compressors or vacuum pumps. Due to a limited pressure drop requirement the line diameters can exceed even 300 mm. Since the thermal conductivity of the line material is very small and the flow rate at some operation conditions can be much lower than at the normal operating conditions, a thermal stratification in the helium flow can appear together with a significant temperature gradient along the pipe circumference. These phenomena can affect the thermo-hydraulic behaviour of the line as well as the operation of the entire cryogenic system. The paper presents the numerical simulations of cold helium vapour flows in a long straight line. The stratification phenomenon is discussed and the potential temperature gradient in the pipe wall is evaluated.

1. Introduction
In last decades the technology of superfluid helium (He II) has become very advantageous for large-scale scientific facilities dedicated to high-energy physics. These facilities usually use an extensive number of superconducting radiofrequency (RF) cavities or magnets for accelerating, conditioning and guiding subatomic particle beams. These superconducting cavities or magnets are usually immersed in helium baths at a temperature of 1.8 to 2.1 K. The production of this temperature on an industrial scale requires complex cryogenic systems. The systems include one or more cryogenic plants and cryogenic transfer lines which connect the cryoplants with the cryogenic users (cryostats housing superconducting magnets and cryomodules with RF cavities). The cryoplants produce cold helium, usually at a temperature and pressure of 4.5 K and 3 bara, respectively. Then, the cold helium is transferred to the cryogenic users, where the He II is produced by isenthalpic expansion. At the cryogenic users the 4.5 K supplied helium is precooled to a temperature of 2.2 K in a counterflow heat exchanger and expanded in a Joule-Thomson (J-T) valve to a sufficiently low pressure. The pressure value depends on the required temperature and varies from 41 mbar for 2.1 K to 16 mbar for 1.8 K. The throttled helium in the J-T valve flows to the He II bath vessel, where it evaporates. In order to maintain the required subatmospheric pressure the cold helium vapour must be constantly evacuated from the He II vessel. The vapour flows via the heat exchanger to a subatmospheric pressure line that returns the helium to the cryogenic plant. In the heat exchanger the cold vapour
absorbs a certain portion of heat from the 4.5K helium stream and slightly increases its temperature (to ca. 3.2 K). In large cryogenic systems the helium flow in the subatmospheric pressure line is driven by cold compressors.

The size of the subatmospheric line results from the maximum required mass flow rate, the acceptable pressure drop, and the highest possible helium density that cold compressors can tolerate. The mass flow rates in the existing He II systems can exceed 100 g/s, the pressure drops are limited to several millibars for the entire process line and the helium density is in the level of 0.2 to 0.3 kg/m³, what for the given nominal operating pressure sets a certain limit for the helium temperature in the level of 3.9 K to 4.6 K. Therefore, the subatmospheric lines of the large He II cryogenic facilities usually have significantly big diameters. For example the LHC cryogenic transfer line QRL, which is 3.3 km in length, includes a DN250 return line (header B) at a pressure of 16 mbar absolute [1]. In currently constructed facilities, such as FRIB or ESS [2, 3], the subatmospheric pressure lines are to be made also of DN250 pipes, but their nominal operation pressures are of 31 mbar absolute. Also, the cryogenic systems of the planned large-scale scientific facilities of International Linear Collider and Future Circular Collider will have to recover cold helium vapours via long and large-size subatmospheric lines [4, 5].

The heat loads of the cryogenic users can significantly vary for different operation modes. In consequence, the mass flow rate of in the subatmospheric pressure line can drop extensively in respect to the nominal one. For example in the ESS cryogenic system the mass flow rate at the return varies from 111 g/s to 42 g/s [6]. Since the thermal conductivity of the line material (usually SS 304L) is very small, a certain thermal stratification in the subatmospheric helium flow can appear together with a significant temperature gradient along the pipe circumference.

This temperature gradient can impact the measurements of the flowing helium temperature. In order to assess this effect from quantitatively point of view we decided to analysed numerically some chosen flows of cold low-density helium vapour in a long straight line of large diameter. The paper presents the developed numerical model and discusses the obtained results of the temperature stratification phenomenon.

2. Numerical modelling of the temperature stratification

In order to investigate the presumable temperature stratification in a cold helium vapour flow inside a subatmospheric process line we developed a numerical model of steady, incompressible, turbulent, gravity and thermal flow in a long, straight and horizontal axisymmetric tube. The model takes into account steady-state three-dimensional convection processes in the fluid region as well as steady-state three-dimensional conduction in the solid tube. In the calculations, the helium is considered as ideal, incompressible gas. Taking into account these assumptions for the fluid region the set of governing equations describing the thermal-flow processes is composed of the transport equations of mass (eqn.1), momentum (eqn. 2) and total energy (eqn. 3), which can be written in the following form [7]:

\[
\nabla (\rho \ U) = 0 ,
\]

\[
\nabla \cdot (\rho \ U \otimes U) = -\nabla p + \nabla \cdot \tau + S_M
\]

where the stress tensor, \( \tau \), is related to the strain rate as follows:

\[
\tau = \mu \left( \nabla U + (\nabla U)^T - \frac{2}{3} \delta \nabla \cdot U \right),
\]

\[
\nabla \cdot (\rho \ U \ h_{tot}) = \nabla \cdot (k \nabla T) + \nabla \cdot (U \cdot \tau) + U \cdot S_M + S_E .
\]

Additionally, for the solid region the three dimensional steady heat conduction equation is applied:
\[ \nabla \cdot (k_S \nabla T) = 0 , \]  
\[ (4) \]

where \( k_S \) is the thermal conductivity of the pipe materials. It is a function of temperature: \( k_S(T) \).

2.1. Model geometry and boundary conditions
The numerical model consists of two domains, namely fluid and solid domains. The fluid domain is a straight horizontal cylinder which has a length of 40 m and an inner diameter of 267.2 mm. This region is surrounded by the solid tube made of stainless steel 304L with a wall thickness of 2.9 mm. During the numerical calculations the set of equations (1) to (4) is discretized and solved in three-dimensional space with a structural mesh. Figure 1 shows the modelling of the system, the boundary conditions and the applied numerical mesh. The fluid and solid domains are composed of more than 10E6 and 10E5 hexahedra elements, respectively. Near the wall, the nodes distribution is significantly finer, because in these areas the highest gradients of velocity and temperature are expected. The numerical algorithm applies the element-based Finite Volume Method. In the calculations of advection terms (fluxes) the High Resolution Scheme (HRS) is used, whilst for solving the pressure and velocity fields the Shear-Stress-Transport (SST) turbulence model is applied. Both the HRS and SST turbulent model assure a sufficiently high accuracy calculation procedure. The maximum Root-Mean-Square residual target of 10E-5 was chosen to guarantee a sufficient convergence. Usually the calculations reached the chosen RMS value after about 1000 iterations.

Figure 1. Applied boundary conditions and the numerical mesh

The calculations were carried out for five values of mass flow rate: 5, 10, 20, 30 and 40 kg/s and two values of average static inlet temperature: 3.2 K and 4 K. For all analysed cases the average static pressure of 27 mbar was applied in the pipe outlet cross section. This pressure is an optimum one for a medium-length subatmospheric line intended for cryogenic systems using He II at 2 K. Simultaneously, the chosen values of mass flow rate and static temperature were imposed onto the pipe inlet cross section. In the numerical calculations helium was treated as an ideal gas and the equation of an ideal gas was implemented in the software. For the analyzed cases the compressibility factor is equal to 0.988 for 3.2 K and 0.993 for 4.0 K.

The heating of the flowing medium is modelled via a constant heat flux \( \dot{q} \) imposed on the entire external surface of the pipe. The calculations were performed for the heat fluxes of 0.1 W/m² and 0.15 W/m². The numerical investigation of the temperature stratification phenomenon consisted of 20 (5x2x2) numerical simulations in total.
2.2. Results and discussion

The obtained numerical simulation results include the three dimensional information of thermal-flow parameters, i.e. temperature, velocity and pressure distributions. However, the present paper is mainly focused on the temperature maps (contours) both in the subatmospheric pressure line material and flowing helium as well. Since the Prandtl number for considered helium is close to 1 (Pr = 0.703 at 3.2 K and Pr=0.698 at 4.0 K) the velocity and thermal boundary layer are getting developed about the same distance [8]. We observed that the obtained temperature and velocity profiles evolve in the first half of the fluid domain. Starting from the middle of the pipe the profiles are almost stable and did not change significantly along almost the entire second half of the pipe. Due to the outlet boundary condition effect there are certain disturbances only in the last meter before the outlet cross section. Taking the above into account we decided to take the cross section located in the distance of 35 m from the pipe inlet as illustrative.

For better comparison of the obtained results the temperature profiles are presented in a dimensionless form defined as:

$$\theta = \frac{T - T_{min}}{T_{max} - T_{min}}$$

where $T_{min}$, $T_{max}$ are the minimum and maximum temperatures in the analysed cross-section, respectively.

The contours of dimensionless temperature in the selected cross-section for different mass flow rates and heat fluxes are presented in tables 1 and 2. In all the analysed flows the temperature profiles are not symmetrical in respect to the pipe centre, which reveals certain stratifications in the flowing helium. The stratification tends to get significantly weaker for higher mass flow rates. From qualitative point of view the distributions of dimensionless temperature have the same structure independently of the applied inlet helium temperature and the heat flux to the pipe external surface. On the contrary the mass flow rate has a very high impact on the temperature contours. As it is intuitively expected much higher temperature differences are observed for lower mass flow rates. The hottest spot is located at the top of the subatmospheric pressure line, whilst the coldest region is in the lower half-region.

Table 1. Dimensionless temperature distributions in the 35 m cross-section of the subatmospheric line for the inlet helium temperature of 3.2 K

| Mass Flow Rate (g/s) | Mass Flow Rate (g/s) | Mass Flow Rate (g/s) | Mass Flow Rate (g/s) |
|---------------------|---------------------|---------------------|---------------------|
| 5 g/s Re = 2.86E4   | 10 g/s Re = 5.71E4  | 20 g/s Re = 1.14E5  | 30 g/s Re = 1.71E5  |
| 0.1 W/m²            | 0.15 W/m²           |                     |                     |

For better comparison of the obtained results the temperature profiles are presented in a dimensionless form defined as:
Table 2. Dimensionless temperature distributions in the 35 m cross-section of the subatmospheric line for the inlet helium temperature of 4.0 K

| Re   | 0.1 W/m² | 0.15 W/m² |
|------|----------|-----------|
| 5 g/s | Re = 2.27E4 | Re = 4.96E4 |
| 10 g/s | Re = 4.55E4 | Re = 4.96E4 |
| 20 g/s | Re = 9.10E4 | Re = 4.96E4 |
| 30 g/s | Re = 1.36E5 | Re = 4.96E4 |
| 40 g/s | Re = 1.82E5 | Re = 4.96E4 |

The longitudinal profiles of dimensionless temperatures along the vertical diameter of the 35 m cross section for the helium inlet temperature of 3.2 K and 4.0 K are presented in figures 2 and 3. In all the cases the warmest helium flows at the top of the line. Then, its temperature decreases gradually and reaches the lowest value somewhere between the line axis and the bottom of the pipe. At the bottom of the pipe the helium dimensionless temperature rises even to 0.8.

![Figure 2. Distributions of the helium dimensionless temperature along the axial vertical line of the analysed cross-section for the inlet temperature of 3.2 K and for the heat flux of a) 0.1 W/m² and b) 0.15 W/m²](image-url)
Figure 3. Distributions of the helium dimensionless temperature along the axial vertical line of the analysed cross-section for the inlet temperature of 4.0 K and for the heat flux of a) 0.1 W/m² and b) 0.15 W/m²

From the practical point of view, it is important to know about the maximum temperature difference between the warmest and coldest parts of the subatmospheric pressure line. This difference creates a temperature gradient that can generate some additional thermo-mechanical stresses in the pipe sections. As it is shown in tables 1 and 2, as well as in figures 2 and 3, the coldest spots are located at the bottom and the hottest at the top of the pipe. The maximum temperature differences between these two spots in the fully developed flows are shown in figure 4. The highest temperature difference of 0.18 K occurs in the helium flow for the lowest analysed mass flow rate (5 g/s) and the highest heat flux (0.15 W/m²). The difference strongly depends on the mass flow rate. For 10 g/s it drops to only 75 mK and decreases then asymptotically.

Figure 4. Comparison of the maximum temperature differences in the analysed flows of cold helium vapour in a subatmospheric pressure line for different heat fluxes and inlet temperatures
The temperature differences cannot be directly transferred to the temperature gradients created in the pipe and have to be studied together with the internal flow of the medium. The obtained results of the temperature gradient in the pipe wall for the lowest and highest analysed mass flow rates are presented in figure 5. In the coldest part of the pipe the temperature gradient is almost the same independently of the mass flow rate. But some significant differences in the temperature gradient values and locations appear in the upper part of the pipe. For the highest analysed mass flow rate (40 g/s) the maximum temperature gradient reaches 0.55 K/m and is located on the very top of the pipe. In the case of the lowest analysed flow the maximum temperature gradient is almost twice higher and is located below the top of the pipe at an angle of ca. 40 deg.

![Figure 5](image_url) - Temperature gradient in subatmospheric process line wall for the helium inlet temperature of 4 K, heat flux of 0.15 W/m² and for the helium mass flow rate of a) 5 g/s and b) 40 g/s

When comparing the distributions of temperature (see table 2) and temperature gradients (see figure 5a) for the lowest analysed flow one observed an offset in the locations of their maximum values. This offset disappears for higher mass flow rates. This phenomenon results from high differences in the velocity fields. Figure 6 shows the velocity contours and streamlines in the chosen cross-section for the lowest and highest analysed flows.

![Figure 6](image_url) - Velocity contours and streamlines in the analysed helium flow for the inlet temperature of 4 K, heat flux of 0.15 W/m² and for the helium mass flow rate of a) 5 g/s, b) 40 g/s
In the lowest analysed flow the helium flows mainly in the bottom half of the pipe (see figure 6a). The longitudinal velocity of helium at the upper half of the pipe above the two additional vortexes is about 4 to 5 times lower than in the bottom half of the cross section. This slow flow leads to a certain uniform temperature distribution at the top of the pipe and shifts the maximum of temperature gradients down. In case of the highest analysed flow (40 g/s) (see figure 6b) there are much smaller differences in the helium velocities in the two halves of the pipe and the helium circulates in two big vortexes, which fill the entire cross section. In consequence, there is no very low velocity layer in the upper part of the pipe and the maximum of temperature gradient is located at the top of the pipe.

3. Conclusions
The paper describes the numerical study of cold helium vapour flows in a large-size (DN250) long straight process line at subatmospheric pressure which is exposed to a uniform thermal loads typical for vacuum-insulated cryogenic process lines. The investigated phenomena reflect the thermo-hydraulic behaviour of subatmospheric process lines used for the helium recovery from the superfluid helium cryostats of large cryogenic facilities. The obtained results revealed a certain temperature stratification in the flowing helium. This stratification is inversely proportional to mass flow rate and can affect the temperature distribution in the process line wall. In the present study the maximum temperature difference reaches 0.18 K for the 4 K helium vapour flow (at 27 mbar) with the mass flow rate of 5 g/s. For higher mass flow rates the temperature difference is much smaller and decreases to only a few mK for 40 g/s. Since the cold helium vapour lines of this size are usually designed for higher mass flow rates the temperature stratification should not appear in the nominal operation conditions. However, in some abnormal operation modes characterised by significantly smaller helium flows, the temperature stratification can affect the thermo-hydraulic behaviour of the line. Then, the temperature sensors, which are usually fixed to the external surface of the line, may not provide the precise information about the real temperature of the flowing helium.

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