Heat transfer resistances in the measurements of cold helium vapour temperature in a subatmospheric process line

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Abstract. The superfluid helium technology, which is essentially used in particle accelerators, requires complex cryogenic systems that include long lines transferring cold helium vapours at a subatmospheric pressure below 50 mbar. Usually in large systems the subatmospheric pressure is generated by a set of warm and cold compressors. In consequence, the heat loads to the line and especially the helium temperature in the inlet to the cold compressors are crucial parameters. In order to measure the helium temperature the temperature sensors are usually fixed to the external surface of the process lines. However, this technique can lead to unwanted measurement errors and affect the temperature measurement dynamics mainly due to low thermal conductivity of the pipe wall material, large pipe diameters and low helium density. Assembling a temperature sensor in a well (cold finger) reaching the centerline of the flowing helium is a technique that can improve the measurement quality and dynamics (response time). The paper presents the numerical simulations of heat transfers occurring in the both measurement techniques and discusses the impacts of the heat transfer resistances on the temperature measurement dynamics.

1. Introduction

The superfluid helium (HeII) technology has been effectively used in particle accelerators of different sizes. The linacs of the ALICE, S-DALINAC and FLASH facilitates are examples of small size accelerators, which thermal loads at 2 K are around a hundred watts. Whereas, SNS, CEBAF and LHC are the examples of large superconducting accelerators that require cooling power at the level of several kilowatts at superfluid helium temperature (2.4 kW@2.1K, 8.4 kW@2.1K and 8×2.4 kW@1.8K, respectively) [1]. The HeII technology is going to be applied in the currently constructed accelerators such as XFEL, ESS and ICLS-II, as well as in the planned large-scale scientific facilities of International Linear Collider and Future Circular Collider [2, 3]. This technology uses either only saturated HeII or both saturated and pressurized HeII. In both cases the cryogenic systems apply a concept of the Joule-Thomson cycle. The cold helium, usually at 4.5 K and 3 bar absolute, is supplied by a cryogenic plant and transferred to the cryogenic users via a long cryogenic distribution system. Typical cryogenic users are cryomodules with superconducting radiofrequency cavities or cryostats with superconducting magnets that are immersed in superfluid liquid helium. At the cryogenic users the 4.5 K helium is firstly precooled in a counterflow heat exchanger and then throttled in a Joule-Thomson valve to a subatmospheric pressure between 16 and 41 mbar, depending on the required temperature level. The produced liquid HeII absorbs heat from the cryogenic users, evaporates and flows back to the...
cryogenic plant via a dedicated process line. The subatmospheric pressure is generated by vacuum pumps in case of small facilities or by a set of warm and cold compressors in case of large ones. Usually the subatmospheric helium process lines are vacuum insulated, just to keep their sizes in a reasonable limit. In large cryogenic systems the lines are connected to cold compressors, which are characterized by a narrow operation region defined by the inlet temperature, pressure and mass flow rate. If any of these parameters exceeds from the region the cold compressors shall be rapidly turned off and bypassed. Therefore the heat loads to the line and especially the helium temperature in the inlet to the cold compressors are crucial parameters. Therefore, there is a need for monitoring the temperature of the subatmospheric helium at the inlet to the cold compressors with appropriate dynamics. The location of the temperature sensors along the line is also very important. In order to alarm as soon as possible and give reasonable time to open the bypass of the cold compressors, the sensors should be placed significantly far from the cold compressors. In a case where the distance from the cold box to the first cryogenic users is not so long the temperature measurement should have high dynamic response.

In order to measure the subatmospheric helium temperature the temperature sensors can be fixed to the external surface of the process line. This technique, later on called as “saddle” technique, can lead to unwanted measurement errors and affect the temperature measurement dynamics mainly due to low thermal conductivity of the pipe wall material, large pipe diameters and low helium density. Applying a so-called “well” technique (called also as cold-finger technique), in which a temperature sensor is placed in a thin-wall tube (cold finger) reaching the centerline of the flowing helium, can improve the measurement quality and shorten the response time. On the other hand this technique can require higher investment costs and can cause a risk of helium leaks.

Selection of the most appropriate technique should base on a detail comparison of the design and assembly features as well as the expected temperature measurements dynamics for each particular case. For example the two mentioned above techniques are investigated in [4], however, the shown results describe their application for temperature measurements of subcooled liquid helium flowing in a small-size process pipe.

The paper presents the numerical simulations of heat transfers occurring in the both measurement techniques used in a large-size process line designed for transferring helium vapour at subatmospheric pressure. Heat transfer resistances are described and their impacts on the temperature measurement dynamics are discussed.

2. Description of the analysed temperature measurement techniques

There is a number of temperature sensors and measurement techniques that are successfully used for cryogenic process lines. They can differ not only in costs, ranges of use and sensitivities, but also in measurement reproducibility and thermal time responses. Cernox\textsuperscript{TM} resistance thermometers are well suited for high-energy physics accelerators due to their very good performance in magnetic and radiation environments [5, 6].

![Figure 1](image.png)

**Figure 1.** Schematic layouts of a) the saddle and b) cold finer techniques
Since subatmospheric helium process lines are usually located inside or along the superconducting magnet cryostats and/or RF cavity cryomodules, they can be exposed to a high magnetic field and radiation. Therefore, we decided to use these sensors in our numerical simulations of the saddle technique as well as in the well technique. In both of these techniques the sensor is located in AA-type copper canister package, described in detail in [7]. The layouts of the two analysed temperature measurement techniques are schematically depicted in figure 1.

In the saddle technique a copper block is soldered to the process pipe external surface and the Cernox package is inserted into a small cave in the block as shown in figure 1a. In order to minimize some unwanted thermal contact resistances the gap between the package and block is filled with some grease that does not get brittle at cryogenic temperature and has good vacuum properties (e.g. Apiezon N). If needed the surface of the block can be machined to fit better to the curvature of the process pipe and to lower the thickness of the filler, which usually is a silver-based brazing alloy. Figure 1b shows a schematic of the well technique. Here the Cernox package is inserted in a thin-wall tube. The tube is slightly longer than the radius of the pipe, so as the sensor is located precisely in the process line centre. At one end the tube is welded to the process pipe wall, whilst its other end is appropriately sealed off in order to keep the process line tight. Thermal contact between the package and tube wall is also improved by using high thermal conductivity grease.

3. Numerical modelling of the temperature measurements

In order to perform numerical simulations of heat flows in the analysed measurement techniques we built a numerical model consisting of fluid and solid domains and applied the element-based Finite Volume Method. The developed numerical models describe the incompressible and thermal flows of cold helium vapour in a large-size process line at the pressure of 27 mbar and temperature of 4 K. The flow is considered as turbulent and k-ε turbulence model is applied. In the saddle technique model the process line is equipped with a copper block on the top of the pipe, whilst in the well technique model there is a think-wall tube that stick into pipe as shown in figure 1. The chosen temperature sensor package was model in detail as shown in figure 2.

![Figure 2](image_url)

**Figure 2.** Numerical model of the selected sensor package a) inner design and b) dimensions

The selected sensor package consists of materials that are characterised by relatively high thermal conductivity at liquid helium temperature. The sensing element (1) consists of a zirconium nitride thin-layer film embedded in a non-conducting zirconium oxide matrix. The sensing element is sputtered onto a 0.2 mm thick sapphire substrate (2), that is placed onto a contact plate (3) made of beryllium oxide [8]. All this components are closed in a copper can (4) that is fulfilled with gaseous helium (5). Thermal contact between the outer surface of the packages and the inner surfaces of the fixing elements (copper block in the saddle and stainless steel tube of the cold finger) was ensured by the appropriate
layer of Apiezon N grease. The selected grease thermal conductivity at 4.2K is taken as equal to 0.005 W/mK [9].

The numerical simulations were performed for the mass flow rate of 30 g/s. The pipe is considered as perfectly insulated, but the inflowing helium suddenly increases its temperature by 0.5 K, 1 K, 2 K and 3 K. Each temperature increase occurs after 10s of simulation, when the velocity profile is fully developed. After the helium temperature rise, the model records the evolutions of temperature maps in the solid domain. The heat is transferred from the flowing helium due to forced convection and in the solid domain due to conduction. In the present model radiation heat transfer is considered as negligible.

The pipe external walls are considered as perfectly insulated.

The investigated subatmospheric process lines are DN250 in size (273 mm x 2.9 mm) and 6 m in length. They are made of stainless steel 304L. The temperature measurement points are located in the middle of the model pipes. In the saddle techniques the copper block model is 15 mm long, 18 mm high and 9 mm thick and has a Ø3 hole (12 mm in length). The sensor package model is placed in the hole. The package model is thermally connected to the block model via a 0.5 mm thick layer of grease, whilst the block is attached to the process pipe external surface by a 0.5 mm-thick layer of silver (solder). The saddle technique numerical model is meshed into 3.7E5 hexahedral and 4.0E4 tetrahedral elements. The fluid domain has a structural mesh with higher density in the region close to the attached sensor and near the inner walls of the process line (see figure 3).

![Figure 3. Mesh of the saddle technique numerical model](image)

![Figure 4. Mesh in cold finger method: a) capillary tube with sensor b) helium inside transfer line](image)
In the well technique the cold finger model is made of a 304L stainless steel pipe (Ø6×1, 143 mm) ended with a spherical end cap. The sensor is located at the bottom of the tube and thermally connected to the inner surface of the tube via a 0.5 mm thick layer of grease. The well technique numerical model is meshed into 6E4 hexahedral and 7E5 tetrahedral elements. In this case, the fluid domain mesh consists mainly of tetrahedral elements (see figure 4).

Thermal properties of all the applied materials are functions of temperature in the range from 3 K to 10 K. The functions of specific heat and thermal conductivity of the solid materials were derived from the data provided in [9, 10], whereas the properties of gaseous helium were determined from [11].

3.2. Results and discussion

The present numerical investigation of the heat transfer resistances in the measurements of cold helium temperature in a subatmospheric process line consisted of 8 transient simulations in total. Their main results were the time evolutions of the temperature maps in the built numerical models. Figures 5 and 6 show several selected temperature fields in the models of the saddle and well techniques, respectively, after the helium temperature rise of 3 K. The inflowing helium temperature increases from 4 to 7 K at 10 sec. In the first 5 seconds after this rise the both temperature sensors are at temperatures close to 4 K, however the temperature of the copper block and cold finger increases to about 4.3 K and 5.6 K, respectively. During next 30 sec the block reaches about 6.3 K and its thermometer is only at 5.3 K. At this time the cold finger is at about 6.8 K, whilst its temperature sensor is at 5.8 K. Later, the temperature of the block and cold finger are getting very close to 7 K. In spite of this the thermometer temperatures are rising much slower, what is caused by significantly low thermal conductivity of Apiezon N.

Figure 5. Temperature field evolution in the copper block of the saddle technique for the helium temperature rise of 3 K

Figure 6. Temperature field evolution in the cold finger of the well technique for the helium temperature rise of 3 K
For the purpose of the present analysis we assume that the required accuracy of temperature measurement is equal to 0.1 K. Thus, the temperature stabilization time is counted to a time instant when the temperature sensor is at \( T_{TS} = T_{He} - 0.1 \) K. In the simulation for the helium temperature rise of 3 K, the sensors in the copper block and cold finger reach 6.9 K at 213 sec and 221 sec, respectively. The obtained temperature evolutions for all the analyzed cases are presented in Figure 7.

![Figure 7](image)

**Figure 7.** Time evolutions of temperature in the sensing elements in a) copper block of the saddle technique and b) cold finger of the well technique

Figure 8 shows the comparison of the temperature stabilisation times for the both analyse measurement techniques. It depicts that the stabilisation times are almost the same. The differences do not exceed 8 K, which is less than 5 % of the related temperature stabilisation time. Nonetheless, the comparison of the temperature evolutions shows that the well technique sees the helium temperature increase significantly faster.

![Figure 8](image)

**Figure 8.** Temperature stabilization time vs. temperature rise - comparison of both techniques

Since the dynamic responses of the both techniques have characteristics similar to a step response of a higher order overdamped system, they can be approximated by First Order Plus Dead Time FOPDT function and characterized by dead time constant \( \theta \) and first order time constant \( \tau \). Figure 9 shows the graphical determination of the time constants for the dynamic responses of the investigated temperature measurement techniques for the helium temperature rise of 3 K. This superposition illustrates how faster the well technique reacts in the initial period in respect to the saddle technique. The slope of its plot in the range from 15 sec to 30 sec is about twice higher. Later, starting from the time instant of 30 sec, this slop tends to decrease faster than the slope of the saddle technique step response. The higher slop in the
first period is mainly due to a certain temperature gradient in the flowing helium. The helium in the
centre line gets warmer much faster than the helium flowing at the pipe wall, which exchanges heat with
the pipe wall material. As soon as the pipe wall gets warm the temperature measured by the saddle
technique sensor gets gradually closer to the temperature in the cold finger thermometer.

Figure 9. Determination of time constants for the dynamic responses of the well and saddle
techniques (ΔT_{He} = 3 K)

Figure 10 presents the comparison of the dead times and first order time constants for all the obtained
dynamic responses. Their dead times are almost the same; the average values are around 4.5 sec and
4.4 sec. Much higher differences are in case of the first order time constants. For the saddle technique τ
tends to increase from 54 sec to 60 sec proportionally to ΔT_{He}, whilst for the well technique it decrease
from 25.7 sec to 23.3 sec. It shows that the higher ΔT_{He}, the longer process of warming up the cooper
bloc and the faster process of warming up the cold finger. The average value of the first order time
constant of well technique is equal to 24.3 sec. It is more than 57 % shorter than the average τ of saddle
technique, which is 56.9 sec.

Figure 10. Time constants of the dynamic behavior of the both temperature measurement techniques:
a) dead times and b) first order time constants
4. Conclusions
The performed numerical simulations investigate the heat transfer resistances in temperature measurements in a large-size cold helium vapour line at subatmospheric pressure. Two measurement techniques are compared, namely so-called saddle (copper block) and well (cold finger) techniques. The obtained results allow for a quantitative comparison of the time responses of the two techniques. In contrary to intuitive predictions, the results show that the stabilization times of the both temperature measurement techniques are very similar to each other. The well technique has shorter response times. For $\Delta T = T_{He} - T_{TS} = 0.1$ K do not exceed 8 sec, which is less than 5% only. Almost the same times can be explained by comparing the thermal properties of the applied materials; precisely by a combination of low thermal capacity and high thermal conductivity. Nevertheless, the well technique initially reacts much faster than the saddle technique. The approximation of their dynamic responses with FOPDT functions shows that the well technique time constant is more than 57 % shorter.

Acknowledgments
The work was partly supported by Wroclaw Centre for Networking and Supercomputing WCSS (http://wcss.pl) in the scope of Grant No. 309. The authors would like to thank for access to the WCSS computational resources.

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