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Design and thermal calculations of FRESCA2 heat exchangers for pressurised superfluid helium baths temperature controlling

J. Polinski[1], M. Grabowski[1], M. Chorowski[1], A.V. Crean[2], V. Parma[2]

[1] WUST Wroclaw University of Science and Technology, Wroclaw, Poland
[2] CERN Organisation Europeen pour la Recherche Nucleaire, Geneva, Switzerland

jaroslaw.polinski@pwr.edu.pl

Abstract. In order to characterise and qualify superconducting cables at currents up to 70 kA, at background magnetic fields up to 13 T and at 1.9 K or 4.3 K temperature levels the Facility for Reception of Superconducting Cable (FRESCA2) is currently under design in collaboration between CERN and WUST. The FRESCA2 design using the double cryostat concept, with superconducting magnet external cryostat and a cable sample insert internal cryostat. The magnet and the cable sample are held in the pressurised superfluid helium bath of the particular cryostat, whose temperature is controlled by a heat exchanger (HX), where the saturated superfluid helium (HeIIs) is used as the cooling medium. The paper presents the design and the thermal model of the HXs as well as the calculation of their minimum area necessary to cool - down the particular bath from 4.3 K to 1.9 K in the required time in respect to an available pumping speed of warm compressors.

1. Introduction

Future circular accelerator superconducting (SC) magnets will be supplied with currents and will work at magnetic fields that are much higher than today's standards. Before the magnet design process the structure of a cable for the magnet coil need to be optimized and characterized, while before the magnet production the cable need to be tested in final operation conditions. In order to perform such a tests the Facility for Reception of Superconducting Cable (FRESCA2) is currently under design in collaboration between CERN and WUST and in the near future it will be installed and operated at CERN. FRESCA2 will offer tests of the cable sample in magnetic fields up to 13 T, in the temperature range between 1.9 K and 4.3 K and supplied current up to 70 kA. The magnetic field will be generated by the Nb_3Sn superconductor-based magnet [1] with the 100 mm diameter aperture for the cable sample.

As the cable sample is required to be replaced once per week and magnet cold - down/warm - up process is taking weeks it is decided to keep the FRESCA2 magnet in the one, outer cryostat, while an insert with the sample holder will be placed in an independent, inner cryostat. Such a solution allows cool - down and warm - up the cable sample in a few hours while the magnet will be continuously kept in the cold.

The design of both FRESCA2 cryostats is based on Claudet's principle, where the pressurized superfluid helium (HeIIp) bath is thermally separated from the saturated normal helium (HeI) bath with the lambda plate. A control of the particular HeIIp bath temperature at the required level is realized with

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the liquid – liquid heat exchanger (L-L HX) where the superfluid saturated helium (HeIIs) is used as the coolant. Each heat exchanger is made of a number of U-tube shaped, high purity copper pipes, connected to the manifold where the helium saturation pressure, thus, its temperature, is controlled by the external warm compressor. A view of the inner cryostat heat exchanger design is presented in figure 1.

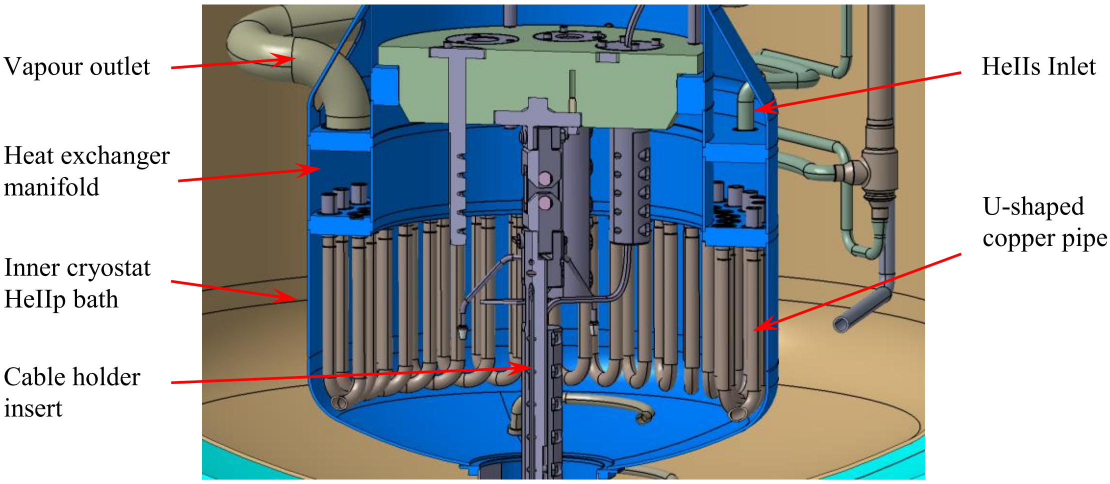

Figure 1. View of the inner cryostat liquid – liquid heat exchanger

2. Liquid – liquid heat exchangers sizing requirements

The heat transfer area (size) of the particular L-L HXs shall be determined in view of the following requirements and limitations:

- the cool down time of the helium from 4.3 K to 1.9 K in the inner and outer cryostat HeIIp bath shall be lower than 1 hour and 12 hours respectively,
- the temperature difference between the HeIIp and HeIIs baths at the steady state operation shall be of 20 mK and of 10 mK for the inner and the outer cryostat respectively,
- the maximum heat flux to each of the HeIIp baths is 20W,
- maximum pumping capacity of the warm compressor destined for each L-L HX is of 1370 Nm^3/h, what is equivalent of 1.0 g/s mass flow of the helium at 1.8 K saturation pressure.

In an addition, the height of the heat exchanger should be as small as possible in order to reduce the volume of the HeIIp baths.

3. Mathematical model

The energy balance for the HeIIs bath of the L-L HX can be expressed as:

$$V_{HeIIs}\rho_{He_{IIs}}\frac{dh_{HeIIs}}{dt} = Q_{HX} - Q_{pump} \qquad (1)$$

where: V_{HeIIs} is the volume of the HeIIs bath, m^3; ρ_{HeIIs} is the HeIIs density, kg/m^3; h_{HeIIs} is HeIIs enthalpy, J/kg; Q_{HX} is the heat flow through the heat exchanger, W and Q_{pump} is the heat taken with the He vapors to the warm compressor, W.

The heat taken with He vapors to the warm compressor can be calculated from:

$$Q_{pump} = S \cdot \rho\left(p_{HeIIs}, T_{300K}\right) \cdot r_{HeIIs} \qquad (2)$$

where: S is the pumping speed of the warm compressor, m^3/s; ρ (p_{HeIIs}, T_{300K}) is the helium density at inlet to the warm compressor at room temperature and HeIIs saturation pressure, kg/m^3; r_{HeIIs} is the HeIIs heat of evaporation, J/kg.

For the HeIIp side of the HX the energy balance can be written as:

$$V_{HeIIp}\rho_{HeIIp}\frac{dh_{HeIIp}}{dt} = Q_{HeIIp} - Q_{HX} \tag{3}$$

where: V_{HeIIp} is the volume of the HeIIp liquid, m^3; ρ_{HeIIp} is the HeIIp density, kg/m^3; h_{HeIIp} is the HeIIp enthalpy, J/kg; Q_{HeIIp} is the total heat flux to the HeIIp bath, W.

It is consider that the heat flow to the HeIIp bath is a result of the superfluid leak thought the microchannels between the λ-plate and all openings created in the plate, such as: the λ-valve or mechanical feedthrough for the IC vacuum vessel, as well as due to heat transfer though the λ-plate gaskets. Thus:

$$Q_{He_{IIp}} = \begin{cases} 0\,W & if \;\; T_{HeIIp} \geq T_{\lambda} \\ Q_{\lambda\ plate} & if \;\; T_{HeIIp} < T_{\lambda} \end{cases} \tag{4}$$

Heat transferred through the heat exchanger pipes can be calculated from:

$$Q_{HX} = \frac{\pi \cdot n \cdot L \cdot \left(T_{HeIIp} - T_{HeIIs}\right)}{\dfrac{1}{d_{in}\alpha_{in}} + \dfrac{1}{2\lambda_{Cu}}\ln\dfrac{d_{out}}{d_{in}} + \dfrac{1}{d_{out}\alpha_{out}}} \tag{5}$$

where: n is the number of HX pipes, L is the total length of the HX pipe, m; α_{in}, α_{out} are the convective heat transfer coefficient for HeIIs and HeIIp side of the HX, respectively, W/m^{2}K; and d_{in}, d_{out} are the inner and outer diameter of the HX pipe, respectively, m.

The convective heat transfer coefficients need to be considered for two separate cases: for helium temperature above and below T_{λ}, separately.

For the inner side of the heat exchanger α_{in} and the HeIIp bath temperature (T_{HeIIs}) above the T_{λ}, the nucleate boiling heat transfer is considered, while for T_{HeIIs} below the T_{λ} the α_{in} is equal to the Kapitza conductance between the superfluid liquid and heat exchanger inner surface. Thus the convective heat transfer coefficient for the inner side of the heat exchanger can be express as:

$$\alpha_{in} = \begin{cases} 1.0 \times \Delta T^{1.5}\; W/cm^2K \; [3] & for \;\; T_{HeIIs} \geq T_{\lambda} \\ \dfrac{T_{HeIIs}^{2.28}}{7.65}\; W/cm^2K \; [4] & for \;\; T_{HeIIs} < T_{\lambda} \end{cases} \tag{6}$$

where ΔT is difference between the bulk bath and inner HX surface temperatures, K.

For the outer side of the heat exchanger and the HeIIp bath temperature (T_{HeIIs}) above the T_{λ} heat will be transferred by natural convection while, for T_{HeIIp} below T_{λ}, the Kapitza conductance should be accounted. Thus:

$$\alpha_{out} = \begin{cases} \dfrac{\lambda_{HeIIp}}{d_{out}} 0.726 (Gr\,\mathrm{Pr})^{0.25} \; [5] & for \;\; T_{HeIIp} \geq T_{\lambda} \\ \dfrac{T_{HeIIp}^{2.28}}{7.65}\; W/cm^2K & for \;\; T_{HeIIp} < T_{\lambda} \end{cases} \tag{7}$$

where: λ_{heIIp} - thermal conductivity of the HeI in the HeIIp bath, W/mK; Gr, Pr – He I Grashof and Prandtl number respectively.

4. Calculation results

4.1. Calculation input parameters
The inner cryostat HeIIp bath volume is of about 59.5 dm^3. The cryostat geometry allows using 36 U- tube shaped, 15 mm external diameter and 13 mm inner dimeter copper pipes. The volume of the helium in the HeIIp bath of the outer cryostat is of about 1340 dm^3 and the heat exchanger can be made of 24 U-tube shaped, 30 mm external diameter and 27 mm inner dimeter copper pipes.

The gist of the HXs sizing is finding the area, thus, a length of the HX copper tubes, for which the cool - down time form 4.3 K to 1.9 K is lower than required. In the calculation the heat capacity of the magnet, insert and HX materials is neglected while the heat flow to each HeIIp baths is accounted as $Q_\lambda = 20$ W. The thermodynamic parameters of helium have been taken from HEPAK [6] and an average value of the thermal conductivity for copper in range of 1.9 – 4.5 K is taken as 100 W/m^{2}K [7].

4.2. L-L HX size calculation results
Figures 2 a) and b) present the cool down time for the inner and outer cryostat HeIIp baths respectively.

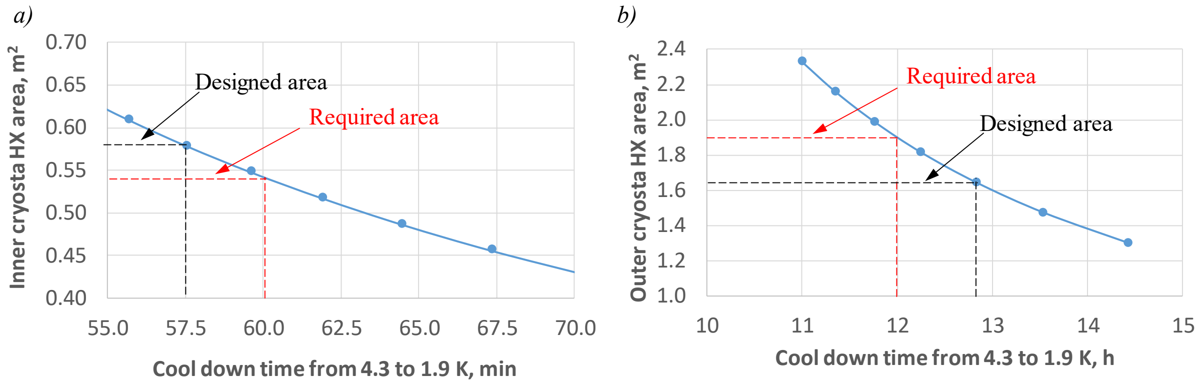

Figure 2. The cool - down time of the FRESCA2 HeIIp baths from 4.3 K t o 1.9 K, a) inner cryostat, b) outer cryostat.

From the figure 2 a) it can be found that the required area of the inner cryostat L-L HX shall be larger than 0.54 m^2. In the final design, due to available space, the copper pipes with a total length of 378 mm have been used what provides the total area of the L-L HX of 0.578 m^2. In case of the outer cryostat L - L HX, due to cryostat design limitation, it is possible to use the copper pipes with the total length of 764 mm only. This provides the total area of the L-L HX of 1.64 m^2. From the figure 2 b) it can be found, that the required area for the outer cryostat L-L HX is 1.9 m^2, what is of 0.26 m^2 larger than the designed one. Nevertheless, for the designed L-L HX area the cool-down time of the HeIIp bath of the outer cryostat is 12.8 hours, what is only 40 minutes longer than the required time. In the view of the fact that the outer cryostat will be cooled - down a few times over the FRESCA2 lifetime, slightly longer cooling down time can be accepted in this case.

4.3. Temperature difference across L-L HXs
Figure 3 presents the evolution of the temperature in the inner cryostat's HeIIp and HeIIs baths for the designed geometry of the L-L HX during the cool - down from 4.3 K to 1.9 K.

It can be found that the temperature of the inner side of the HX drops very rapidly from 4.3 K down to λ temperature while below the lambda temperature the HeIIs temperature change is much slower. It is because of the nucleate boiling convection heat transfer coefficient value is a magnitude lower than Kapitza heat transfer, therefore, in the first period of the HeIIs bath cool - down the heat transferred through the heat exchanger Q_{HX} is negligible in comparison with the heat taken with the helium vapours transferred to the warm compressor Q_{pump}. As long as the HeIIp bath temperature is above the λ temperature the temperature difference across the HX is large. This results from very low natural convection heat transfer coefficient value. When HeIIp bath temperature reaches the λ temperature the natural convection changes in to Kapitza conductance and heat flow conductance through the HX rapidly increases. As the mass of helium in the HeIIs bath is relatively small, its temperature rapidly increase almost to the λ temperature.

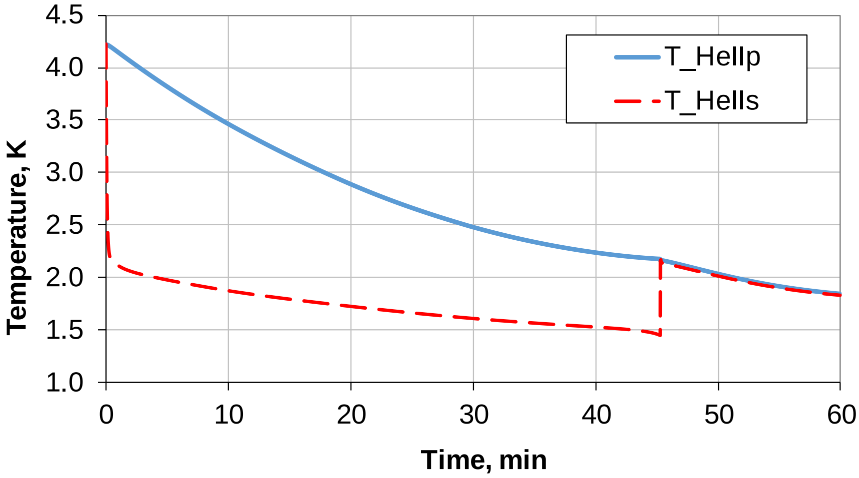

Figure 3. Evolution of the temperature in the HeIIp and HeIIs baths of the inner cryostat for designed geometry of the L-L HX during the cool - down from 4.3 K to 1.9 K

As it is mentioned above, if HeIIp temperature is lower than λ temperature the $Q_\lambda = 20$ W of heat is transferred to the HeIIp bath. From this point the temperature across the HX is of about 20 mK and, with existing Kapitza conductance on both sides of the copper pipe of the heat exchanger, it is sufficient to transfer Q_λ.

As it is resulting from information in the subsection 4.1 the outer cryostat heat exchanger HX area is of 2.83 times larger than the inner cryostat L-L HX. Therefore, the temperature difference across the outer cryostat L-L HX, needed for transferring $Q_\lambda = 20$ W, is $20/2.83 \approx 7$ mK, what is fulfilling the appropriate requirement.

5. Conclusions

The liquid – liquid heat exchangers for the FRESCA2 test stand's inner and outer cryostat HeIIp baths have been designed and sized in view of space available in the particular bath, capacity of the warm compressor that is dedicated for the test stand, required cool - down time and required temperature difference across the heat exchangers. Besides the cooling time of the outer cryostat HeIIp bath, which for the designed HX geometry is 40 min longer than the required 12 hours, all other requirements have been fulfilled. Slightly longer cooling - down time of the outer cryostat HeIIp can be accepted as the cryostat will be cooled - down a few times over the FRESCA2 lifetime.

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