He II Heat transfer through a Corrugated Tube - Test Report

Authors: Ch. Darve, Y. Huang, T. Nicol, T. Peterson

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Abstract

The LHC inner triplet is cooled with pressurized He II at a temperature of around 1.9 K. The total heat load (beam induced heat load plus static heat load for the inner triplet) at nominal luminosity is around 180 W. The beam induced heat load distributed within the magnet coil is carried away by the static pressurized He II filling inside of the cold mass. A heat exchanger is needed to absorb the heat load within the pressurized He II to maintain the low temperature. The heat exchanger is located outside and parallel to the magnet cold mass. The saturated, two-phase He II flows inside the corrugated pipe and the static, pressurized He II surrounds the corrugated pipe. A full-sized Heat Exchanger Test Unit has been designed to simulate the LHC inner triplet cooling scheme. The test will be carried out at CERN in 2000.

A small scale corrugated pipe He II heat exchanger was designed, built and tested at Fermilab. The goal of the test was to measure the thermal performance of the same corrugated pipe used for the full-sized He II Heat Exchanger Test Unit. The test sample is a closed test sample and consists of a corrugated pipe, a thick-wall stainless blank flange, detachable stainless steel flange and a matching flange. The corrugated pipe length in contact with the liquid helium is 100 mm.

From the experimental data, including heat load to the test sample and temperatures inside and outside, the total heat transfer coefficient of the corrugated pipe can be determined. The test results show that the Kapitza thermal conductance is in good agreement with the results from other experiments. One more test will be carried out in the near future using the same test sample with some treatment of the corrugated pipe surface.

1 Introduction

The LHC inner triplet operates in a pressurized He II bath at 1.9 K and 0.1 MPa. The heat load absorbed by the coils must be carried away by saturated He II via a heat exchanger to maintain the temperature of the pressurized He II at 1.9 K. The temperature drop across the heat exchanger may be estimated by using the Kapitza thermal resistance between the He II and copper surface. The Kapitza thermal resistance is strongly dependent on the surface material and surface treatment. Some measurements were needed to more accurately predict the total heat transfer coefficient of the proposed heat exchanger pipe.

A first heat transfer model was developed in order to give dimensions to the Heat Exchanger Test Unit [1]. The initial value for overall conductance through the corrugated pipe in the heat transfer model considered up to now was scaled from very early CERN measurements of a corrugated pipe [2]. In order to measure the thermal performance of the corrugated pipe, a piece of corrugated pipe was cut from extra material purchased for the full-sized He II Heat Exchanger Test Unit and tested.

The pressurized He II was contained inside the test sample and saturated He II was outside the test sample. The temperature differences between the pressurized He II (inside the test sample) and the saturated He II baths were measured at different heat loads.

2 Heat transfer model

2.1 Scheme of the thermal transfer

The LHC inner triplet cooling scheme is based on heat exchange between the static pressurized He II and the saturated He II. Figure 1 illustrates heat transfer from the pressurized He II (T1: inside test sample) and saturated (T3: outside the test sample). The total thermal resistance is equal to the sum of the two Kapitza resistances at the interface, plus the resistance of the copper wall. Considering that both surfaces of the tube are wetted over their full length, the applied electrical load, Qelec, to the pressurized He II will generate a difference of temperature, T1-T3, across the copper wall.

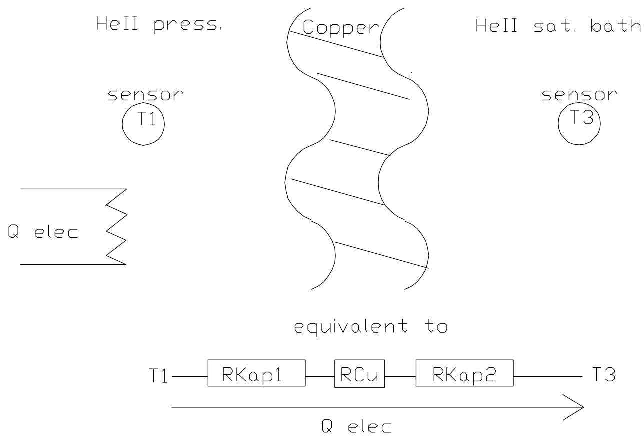

Figure 1. Scheme of the heat transfer

2.2 Method of calculation

When the heat exchanger tube is wetted, the temperature difference between the pressurized helium and the saturated liquid, T1-T3, is minimal. This temperature difference depends only on the heat load, Qelec, and the total transverse thermal resistance, Rthtotal, which can be expressed as shown:

$$\text{Rthtotal} = \lim_{\Delta T \to 0} \frac{\Delta T}{Q} \qquad \text{or} \qquad \text{Rthtotal} = \frac{(T1 - T3)}{\text{Qelec}}$$

If we consider the total resistance as a function of the Kapitza resistance, Rkap1 and Rkap2, and the copper conductance, Rcu, we can write:

$$\text{Rthtotal} = \text{Rkap1} + \text{Rcu} + \text{Rkap2}$$

Within the tested low temperature range, we can consider that the bulk thermal resistance of the copper is constant. According to acoustic mistmatch theory, the Kapitza resistance should vary as T^{-3} [3]. We can make the hypothesis that both Kapitza resistances at each interface of the copper pipe and the He II pressurized and saturated, are equal to Rkapitza.

In the current report we introduce the Kapitza coefficient Ckapitza which has units [$WK^{-4}m^{-2}$].

The total thermal resistance can be expressed with the following formulas:

$$\text{Rthtotal} = 2 \cdot \text{Rkapitza} + \text{Rcu} \qquad \text{or} \qquad \text{Rthtotal} = \alpha \cdot \left(\frac{1}{T3^3}\right) + \beta$$

If we consider that:

$$\alpha = \frac{2}{\text{Ckapitza} \cdot S}$$

$$\beta = \frac{e}{S \cdot \text{Ccu}}$$

Then, it yields the equation (eq $_1$):

$$Rthtotal = \frac{2}{Ckapitza \cdot S} \cdot \frac{1}{T3^3} + \frac{e}{S \cdot Ccu} \qquad (eq_1)$$

where e is the wall thickness, S the interface surface, Ccu the copper thermal conductance and Ckapitza the Kapitza coefficient characterizing the interface.

Thus, if we plot Rthtotal versus T^{-3}, we obtain a straight line. Consequently, from the temperature difference, T1-T3, measured for a given T3 and various electrical load, Qelec, we can interpret the Kapitza coefficient, Ckapitza, and the thermal conductance of the copper, Ccu.

Previous tests performed at CERN were also dedicated to the measurement of the Kapitza resistance and used this standard approach [4] [5].

3 Small scale heat exchanger design

The test sample, as shown in Figure 2, is composed of the same corrugated tube used in the Heat Exchanger Test Unit. The corrugated tube is made of industrial copper. The effective length of the corrugated tube is 100 mm and its outer diameter is 96 mm. The wall thickness is 0.7 mm. The corrugated tube surface area is 415.6 cm^2 (one side).

The corrugated tube was soldered into the grooves of the thick-wall stainless steel flanges at both ends. Due to the lower thermal conductivity of soft solder in the grooves and thick-wall stainless steel flanges, the heat leak through the end flanges was estimated to be less than 3% of the total heat load applied to the heater.

The Kapitza thermal resistance depends strongly on the surface material and conditions. The corrugated tube tested in our experiment has no chemical treatment, the same as that in the Heat Exchanger Test Unit.

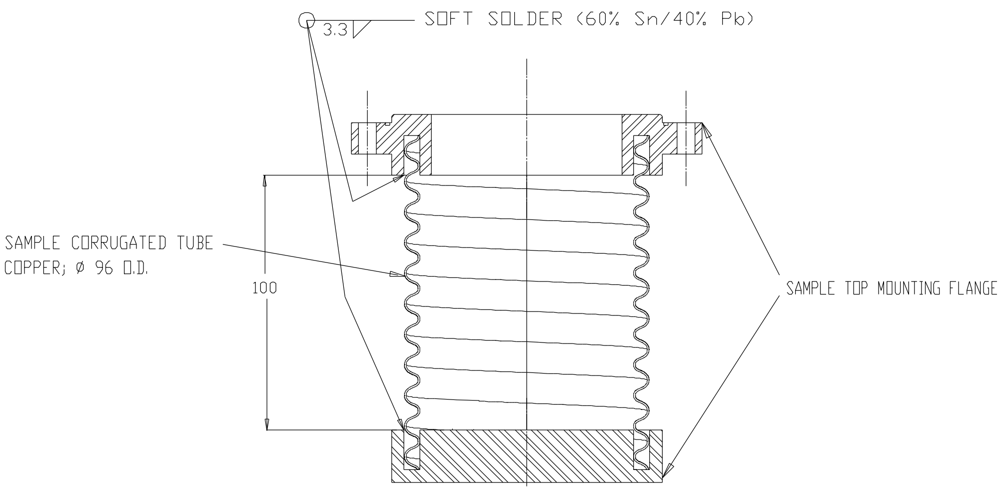

Figure 2. Corrugated tube testing device sample assembly

4 Description of the test setup

The test setup is composed of a test dewar, pumping unit, vacuum pump, helium gas supply, and liquid helium supply. Figure 3 illustrates the schematic of the test system. The test sample is filled with pressurized He II and mounted with a resistive heater, level indicator, thermometer and pressure transducer. The saturated He II bath surrounding the test sample is used to maintain the bath temperature while absorbing any heat load from the test sample. There is also a thermometer on the saturated He II side to measure the bath temperature. The thermal transfer process is the same as in the real LHC heat exchanger.

The dewar is 500 mm long and 500 mm ID. Pipe connections have been designed in order to fill the inner sample assembly with pressurized He II. The system minimizes parasitic leaks due to radiation, solid conduction, and conduction into superfluid helium.

An electrical rack contains power supplies for the instrumentation and control as well as switches from the electronics. The data acquisition and control system was written in QuickBASIC.

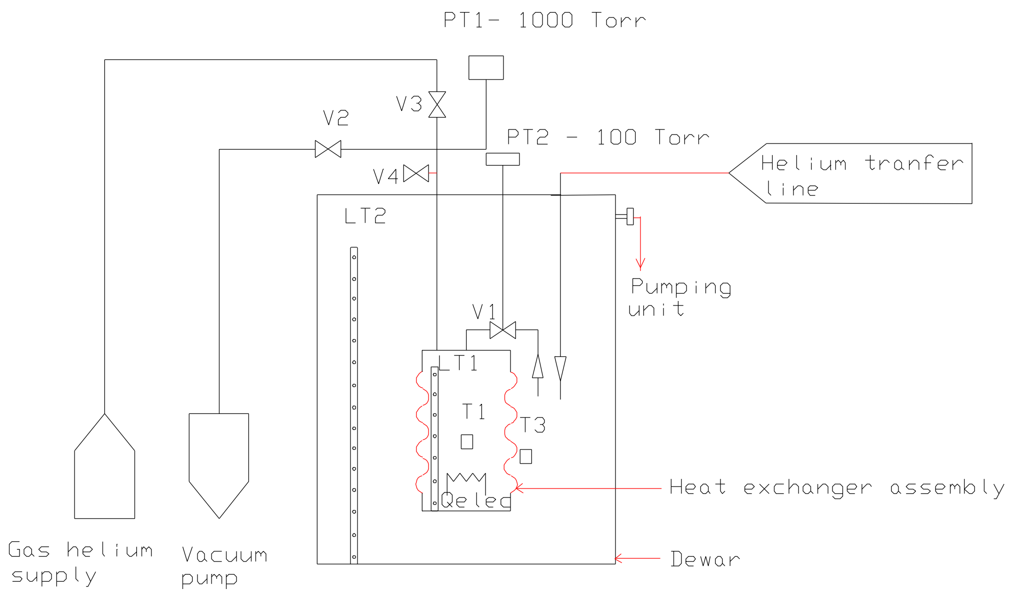

Figure 3. Scheme of the cryogenic system

4.1 Instrumentation

Several valves, indicators and sensors permit precise control of the measurements. The sensors include thermometers, helium level indicators, and pressure transducers, all mounted inside and outside.

Two calibrated Lake-Shore® Germanium thermometers (T1 and T3) are supplied with a 1µA current source. These sensors measure the temperature of the pressurized and the saturated He II. Both T1 and T3 are deduced from their respective Chebychev polynomial algorithms. Two helium level indicators LT1 and LT2 are supplied with a 75 mA current source. The pressure transducers PT1 and PT2 are used to monitor the pressure during the operation and check the bath temperature measurement. A resistive heater is mounted inside the test sample to provide heat load Qelec.

Each set of data consists of ten channels. The signals are read through two digital voltmeters (DVM). Each of the ten devices is powered separately. The two DVMs communicate the read-out voltages to the computer. The data acquisition system enables the recording of five sets of data per minute.

4.2 Test Procedure

The test sample assembly is leak checked and then installed in the dewar. Once the test sample is filled with liquid helium, valve V1 is closed. Then, valve V3 between the gas helium cylinder and test sample is opened to maintain the pressure at above one atmospheric pressure. The test sample is connected to a gas helium cylinder to condense gas helium into liquid and maintain its pressure slightly above atmospheric pressure during the phase transition from He I to He II. Valve V2 connected to the vacuum pump is slowly opened to reduce the pressure PT1 until the bath temperature T3 reaches the required value.

As described in (2.2), the test mainly consists of measuring the temperature difference, T1-T3, for various values of T3. This temperature difference provides us with the total thermal resistance. The helium level gage, LT2, indicates that the saturated He II is always above the top flange while the measurement data points are observed. During the measurement, the helium level indicator, LT1, confirms that 100% of the sample length (100 mm) is wetted by the saturated He II.

For each heat load, the temperatures are recorded after bath temperature T3 is stabilized (ΔT <1 mK). The first set of data were always recorded corresponding to zero electrical heat load, then additional Qelec (with an increment of 0.5 W), was applied, step by step, until the vacuum pump was unable to keep the bath pressure constant. The measurements are repeated for bath temperature T3, from 1.75 K to 2.00 K with an increment of 0.05 K.

5 Results and Discussion

5.1 Results

The accuracy of the temperature sensors is 6 1 mK for the observed temperature range. An error of 6 3 % on the measurement is estimated according to the resolution of the various devices and the effect of the soldered thick wall stainless steel flanges at both ends.

If we consider the LHC inner triplet, the worst case for the temperature and pressure drops appear at the interaction point 5 (IP5-left). The temperature at the feedbox on the pumping line was estimated to be 1.851 K [6]. This case is shown in Figure 4. This figure illustrates the equilibrium response of the system once Qelec is increased, step by step, up to 6 W. In order to check the behavior of the system, Qelec is finally reduced to 2.5 W then to zero. The operation is repeated for several values of T3. For each configuration a similar graph is obtained.

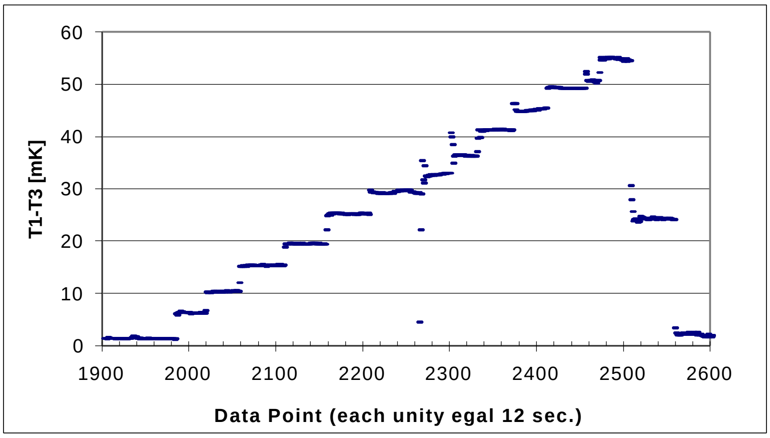

Figure 4. Example of measurement for T3 = 1.85 K

With several T3 configurations, we can show the evolution of T1-T3 versus Qelec. Figure 5 illustrates the curves for the entire range of T3 values. We observed the limitation of our pumping unit capacity, which did not allow us to run the test at a heat load above 5 W when T3 was at 1.75 K.

Furthermore, Figure 5 expresses the heat capacity of the current heat exchanger design for a given temperature difference across the He II heat exchanger wall to the saturated superfluid. An optimal difference of temperature is estimated at 30 mK.

Once we plot our results in the plane (Rthtotal, T^{-3}), we note a linear behavior of the total thermal resistance, Rthtotal, and T^{-3}. Figure 6 gives a calibration for the current heat exchanger. By linear regression on data point, we obtain the equation (eq_2).

$$y = 53.9x + 0.1904 \qquad (eq\ 2)$$

Considering the parameters (slope and intercept) of this line, we can deduce, the value of the Kapitza coefficient (Ckapitza) and the copper thermal conductivity (Kcu).

$$\text{Ckapitza} = 892.8\ WK^{-4}m^{-2}$$
$$\text{Kcu} = 88\ WK^{-1}m^{-1}$$

Thus, the Kapitza conductance at 1.9 K is equal to 0.612 $Wcm^{-2}K^{-1}$.

The test results show that the Kapitza thermal conductance is in good agreement with the results from other experiments [7].

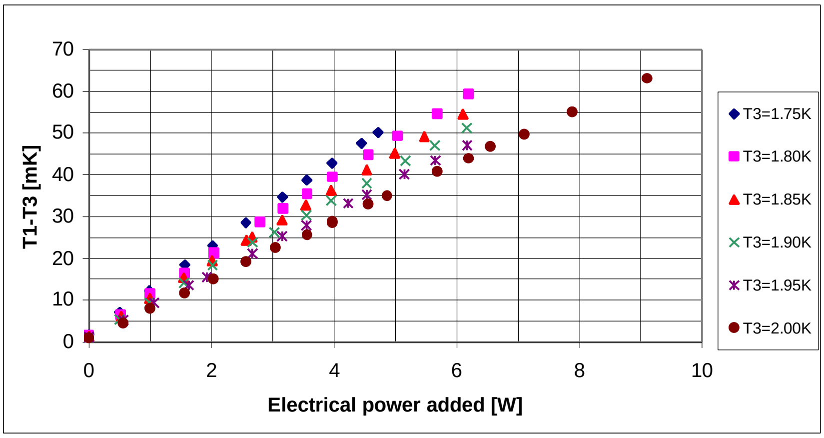

Figure 5. Dependence of the temperature difference versus the applied electrical power

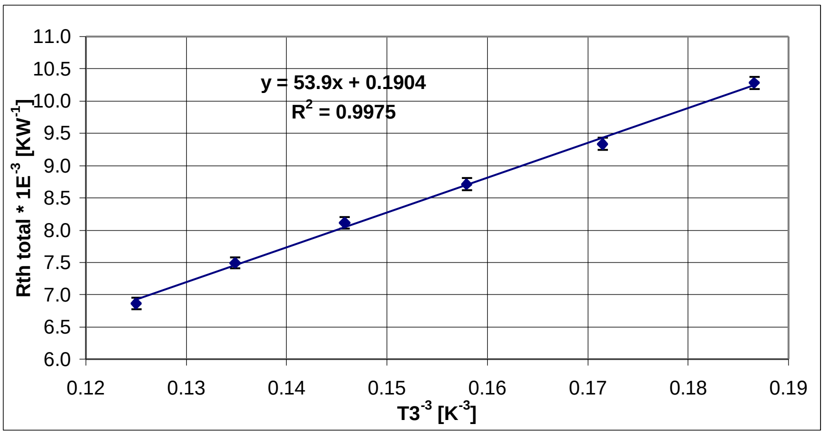

Figure 6. Total transverse thermal resistance

5.2 Discussion

Our initial estimate for overall conductance through the corrugated pipe of the full-sized Heat Exchanger Test Unit, was scaled from early CERN measurements of a corrugated pipe. A test performed at CERN provided an overall heat conductance of 80 to 140 WK^{-1} per meter of length for a 39/43 mm corrugated DHP copper [2]. The test at CERN indicated that the heat exchanger tube was wetted on about 30% of its surface. This implies an overall heat transfer coefficient through the copper wall of about 0.2 $Wcm^{-2}K^{-1}$ of active area at 1.9 K. If we scale the 80 WK^{-1} per meter estimate for the 39/43 mm tube up to the present 85/96 mm corrugated tube, we get 180 WK^{-1}, assuming 30 % is wetted. Initial sizing of the corrugated tube was based on this estimate for conductance.

The results from our small heat exchanger sample provide an overall wall conductance through the active area of 0.295 $Wcm^{-2}K^{-1}$, about 50 % higher than our initial estimates. This higher conductance for the short sample is in good agreement with the higher end of the 80 to 140 WK^{-1} range found in the early CERN tests referenced above. These results imply heat transfer of 265 WK^{-1} per meter of length for our 85/96 mm corrugated tube.

If we compare our results to those obtained for a smooth tube [4], we note that a similar Kapitza coefficient is obtained in the case of a sample without surface treatment. An increase of 30 % of the Kapitza coefficient was observed for a degreased sample. Thus, we might improve the heat transfer of our heat exchanger pipe if we degrease the surface. However, any method of surface treatment should be compatible with the long heat exchanger tube in the LHC inner triplet.

6 Conclusion

The current note reports the measurement of the temperature difference across the LHC inner triplet He II heat exchanger wall to the saturated superfluid. The measured total thermal conductance yields a Kapitza coefficient of $892.8\ WK^{-4}m^{-2}$ 6 3%. Therefore, a Kapitza conductance of $0.612\ Wcm^{-2}K^{-1}$ is estimated for the operating temperature of 1.9 K.

These data show that the delta-T attributable to wall resistance is cut to about 65 % of what we have used to size the Heat Exchanger Test Unit. These results enable us to predict a lower temperature difference across the copper wall, hence to permit a larger margin for the distribution of temperature for the rest of the inner triplet.

Another test is planned with the same test sample but with a surface treatment.

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