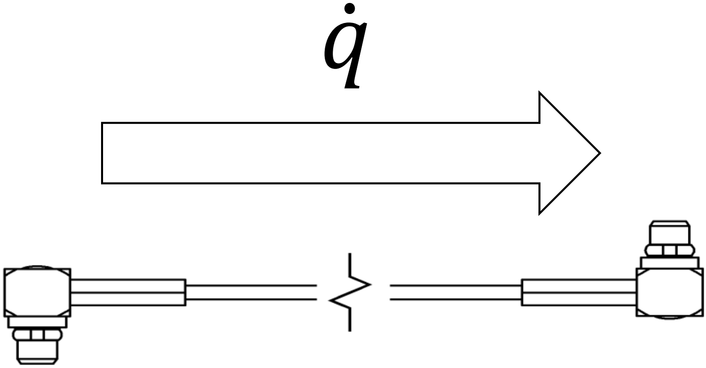
AP004: Heat Flow in Cables



Razorbill Instruments stress and strain cells require relatively high voltages to operate, and integrate capacitance sensors for feedback. This means that the cryostat needs suitably insulated wires for the drive, and coax cables for the readout. But many cryostats do not include this type of wiring, so the researcher may have to retrofit it. There are two other Application Notes AP002 and AP003 which cover drive electronics and capacitance measurement, and have information about types of wire and cable. This Application Note describes thermal conductivity and heat load, which applies to any type of cable.

Note that Razorbill Instruments also sell retrofit kits for some cryostats, which can provide a quicker and easier option than starting from scratch.

Cable material selection

One might image that careful material selection would enable you to have the electrical conductivity but not the thermal conductivity. Unfortunately, almost all materials from which wire can be made follow the Wiedemann–Franz law, which links electrical and thermal conductivities. The main exception is superconductors, which have perfect electrical conductivity and extremely small thermal conductivity. They have substantial downsides however, only working below some critical temperature, being incompatible with magnetic fields, and being generally hard to handle and solder. They are however worth investigating for some cases, in particular for dilution refrigerators and adiabatic demagnetization refrigerators where cooling powers are small and temperatures generally stay low.

The vast majority of customers will stick with metal wiring, and there are several common materials to use. Copper is the simplest, with lots of types available, and it is easy to solder. It also has a large conductivity (electrical and thermal) and that conductivity varies a lot with temperature. While in theory it would be possible to get a higher resistance by using thinner copper wire, it soon becomes impractical, so stainless steel and copper alloys such as manganin, constantan and phosphor bronze are used instead. Wires and cables of reasonable diameter and length for cryostats tend to work out around 10-100 ohms when made from these materials, and that stays nearly constant as the cryostat cools.

Using resistive wire and cables does have some impact on the behaviour of the cell and sensor. The impact of resistive drive wires is usually very small, but resistive coax cables for measuring the capacitance of the sensors can increase noise. For more information see AP002 and AP003 respectively.

Calculating heat loads

For a length L, cross sectional area A and temperature difference ΔT we can start from Fourier's law of conduction:

$$\dot{q} = \frac{A}{L}\lambda\Delta T$$

However, even though the electrical resistance of these materials remains roughly constant, the thermal conductivity λ changes substantially as a function of temperature. Fortunately, we do not need to know the temperature distribution along the wire to calculate the heat flow. We can simply integrate along the wire:

$$\dot{q} = \int_{T_1}^{T_2} \frac{A}{L}\lambda(T)\mathrm{d}T$$

And, for convenience, we can re-write that as:

$$\dot{q} = \frac{A}{L}\left(\int_{4\mathrm{K}}^{T_2}\lambda(T)\mathrm{d}T - \int_{4\mathrm{K}}^{T_1}\lambda(T)\mathrm{d}T\right)$$

Where the integrals are both more useful and easier to measure than $\lambda(T)$. They can be found tabulated in several places, but *Experimental Techniques for Low-temperature Measurements* by Jack Ekin is an excellent source for most cryostat materials. The tables are in the appendix (section A2), which the author has published online at:

> www.researchmeasurements.com/figures/ExpTechLTMeas_Apdx_English.pdf

Worked examples

Let us consider the fitting of 1 metre of Ultra Miniature Cryogenic Coax Type C supplied by Lake Shore Cryotronics. The core wire is 0.203 mm diameter copper and the outer consists of aluminised polyester layer incorporating a second 0.203 mm diameter copper drain wire. Because the majority of the heat will be conducted through the two copper wires, a good approximation for the heat conducted into the cryostat can be considered by assuming that the cabling is solid copper with a cross-section equal to the combined cross section of the core and drain wires: $A = 6.4 \times 10^{-8}$ square meters. Using the tables in Ekin:

$$\int_{4\mathrm{K}}^{300\mathrm{K}} \lambda(T)\mathrm{d}T = 162\mathrm{kW/m}$$

Plugging in the numbers gives 10.4 mW thermal load for 1 meter of Lake Shore C miniature cryogenic coax cable one end of which is held at 300K and the other at 4K.

10.4 mW is tolerable for many cryostats operating from 4K upwards, especially those with a continuous flow of cold helium gas or based on a reasonably large modern cryocooler. A bundle of half a dozen such cables would probably also be OK in most systems.

On the other hand some cryostats will not have the spare capacity to soak up this thermal load, so steps will have to be taken to reduce it. If only small currents need be carried by the cable, then a higher resistance stainless steel coax such as Lakeshore type SS may be used. Repeating the calculation for the 64 strands of 50 AWG plus 44 strands of 44AWG that make up that cable, and using the value of 3.06kW/m from Ekin gives a heat load of around 0.38mW, which would be suitable for almost all cryostats operating over 1K.

Thermal anchoring

A few tens of milliwatts delivered to the cryostat may be acceptable, but the same heat delivered directly to the cell and sample may cause problems. So it is important that the heat flow is intercepted by the cryostat before it reaches the cell. This is achieved my thermally anchoring, (aka thermalizing or heatsinking) the wire or cable at the cryostat before it goes on to the cell. There are several different approaches, suitable for different cable or wire constructions and temperature ranges.

The commonest and probably best method is to wrap the wire or cable tightly around a metal cylinder. For small probes or cryostats, this is usually the body of the probe, whereas for larger systems it might be a specially made copper post. The radius of the post must be larger than the minimum bend radius of the cable. The wire or cable can be reversibly secured to the post with e.g. GE varnish (also known as IMI 7031), or permanently with e.g. stycast 2850. One refinement is to take a loop of wire to wind round the post rather than an end, which results in half the winding being clockwise and half anticlockwise. Called “Bifilar winding” this reduces the crosstalk between different wires wound on the same post and reduces pick-up from the environment.

An alternative method for heatsinking wire is to use a piece of flexible PCB glued to a copper plate. The flex PCB substrate is typically only a hundred microns thick, so the tracks on top are in good thermal contact with the copper plate. Both wire and cable can also be clamped between two metal plates, though it is easy to accidentally damage the insulation when clamping. This is especially true with the FEP and PTFE insulation on the cables supplied by Razorbill, so in general this method is not recommended.

Finally, if low conductivity cables are combined with helium exchange gas, at temperatures over 1K, then the gas may provide adequate heatsinking without any of the techniques described above. This is particularly the case in cryostats where cold helium circulates over the sample then flows up over the cables to a pump at room temperature, as this helium flow has substantial cooling power.

Further reducing heat flow

Thermal anchoring at intermediate points in the cryostat can also be used to reduce the heat flow into the cold plate or cold finger. If we return to the example of stainless steel coax from above, it introduced a heat load of 0.38mW per cable. If instead we consider two 50cm lengths, one from 300K to a cryocooler first stage at 50K, and one from there on to 4K, we can calculate two heat flows:

$$\begin{aligned}\dot{q}_{50\mathrm{K}} &= \frac{A}{L}\left(\int_{4\mathrm{K}}^{300\mathrm{K}} \lambda(T)\mathrm{d}T - \int_{4\mathrm{K}}^{50\mathrm{K}} \lambda(T)\mathrm{d}T\right) \\ &= 0.72\mathrm{mW}\end{aligned}$$

$$\begin{aligned}\dot{q}_{4\mathrm{K}} &= \frac{A}{L}\left(\int_{4\mathrm{K}}^{50\mathrm{K}} \lambda(T)\mathrm{d}T\right) \\ &= 0.033\mathrm{mW}\end{aligned}$$

So by heatsinking the cable at the 50K plate it is possible to reduce the heat load on the 4K plate tenfold, at the cost of dissipating 720µW at the 50K plate. Given the cooling capabilities of most refrigeration systems, this is well worth the trade-off.