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Author
Green, Michael A.

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M. A. Green,
Lawrence Berkeley National Laboratory, Berkeley CA, USA

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The Integration of Cryogenic Cooling Systems With Superconducting Electronic Systems*

Michael A. Green

Abstract— **The need for cryogenic cooling has been critical issue that has kept superconducting electronic devices from reaching the market place. Even though the performance of the superconducting circuit is superior to silicon electronics, the requirement for cryogenic cooling has put the superconducting devices at a disadvantage. This report will talk about the various methods for refrigerating superconducting devices. Cryocooler types will be compared for vibration, efficiency, and cost. Some solutions to specific problems of integrating cryocoolers to superconducting devices are presented.**

I. INTRODUCTION

THE various options for cooling superconducting electronic systems include; 1) boiling liquid cryosgen cooling sing either liquid helium or liquid nitrogen (For some liquid hydrogen or liquid neon may be an option, but liquid hydrogen is flammable and liquid neon is expensive to use as a throw away coolant.), 2) cooling with relatively small cryocoolers, and 3) cooling electronic devices with a more conventional liquid helium or liquid nitrogen refrigerator. This report will deal only with the first two options, because most electronics applications for superconductivity have low heat loads in a limited space. Electronic systems that require larger refrigerators will have to be individually tailored to the load.

Connecting the cooling to the load is often the biggest technical issue when one looks at integrating cooling with superconducting electronics systems. Laboratory electronic systems are often cooled in a pool of liquid helium (LTS systems) or liquid nitrogen (HTS systems). The element is often immersed in the liquid cryogen so heat transfer from the device to the boiling cryogenic coolant is often not an issue.

When one uses a cryocooler as the method for cooling the electronic device, a number of issues come into play. They are; 1) the vibration characteristics of the cryocooler and the method used to isolate the cooler from the device, 2) The temperature difference between the electron device and the cryocooler cold head, 3) the reliability of the cryocooler, and 4) the cost of purchasing and running the cryocooler. One of the approaches that has been used for connecting cryogenic devices to a cryocooler is to use a liquid cryogen interface. If this is not done correctly, the results can be bad.

II. COOLING WITH LIQUID CRYOGENS

Table 1 presents various parameters for cryogenic fluids that might be used to cool superconducting electronics components. The fluids shown in Table 1 include helium, hydrogen, neon, and nitrogen. Only liquid helium or liquid nitrogen would be used to cool an electronic component directly, but the other two fluids may be used as an interface fluid between the cold head of cryocooler and the electronic component being cooled.

TABLE 1. Parameters of Cryogenic Fluids [1]

Fluid	He	H_2	Ne	N_2
Triple Point T (K)	2.17	13.81	24.57	63.14
Triple Point P (bar)	0.051	0.070	0.423	0.128
Boiling T at 1 bar (K)	4.22	20.4	27.2	77.3
Liquid Density at T_b (kg m^{-3})	125	70.8	1212	808
Critical T (K)	5.19	32.3	44.4	126.1
Critical P (K)	2.21	12.92	27.10	33.82
Heat of Vaporization (J g^{-1})	20.9	442	86.0	199.7
C_p liquid (J g^{-1} K^{-1})	~2.5	~9.8	~0.44	~2.04
C_p gas (J g^{-1} K^{-1})	5.2	14.2	1.03	1.04
Enthalpy to 300 K (j g^{-1})	~1500	~4400	~367	~432
k_f liquid at T_b (W m^{-1} K^{-1})	0.027	0.119	<0.04	0.140
k_f gas at T_b (W m^{-1} K^{-1})	0.011	0.021	0.014	~0.0075
Max Boiling Q (W m^{-2})	~8000	~60000	<10000	~80000
Max Condensation Q (W m^{-2})	~1000	~4000	<1000	~3500
Liquid Expansivity (T^{-1})	~0.21	~0.02	~0.014	~0.003

When one uses a boiling fluid to cool an electronic device, the operating temperature is close to the normal boiling point at 1 bar. One would normally use liquid helium or liquid nitrogen as a coolant. On most spacecraft, one would use helium as a liquid cryogen of choice (regardless of the device operating temperature) because the total enthalpy available from the boiling temperature to 300 K is highest for any fluid (except for hydrogen). Hydrogen is a special case. It has good heat transfer properties and the largest total enthalpy of any fluid. In space, solid hydrogen can be used for cryogenic cooling (above 14 K) on satellites launched using expendable rockets. NASA space shuttle safety regulations do not permit the launch of any satellite carrying liquid hydrogen.

III. CRYOGENIC COOLERS

Cryogenic refrigerators come in two general forms; 1) open cycle coolers where the working fluid in the cooler comes is direct contact with the object being cooled, and 2) closed cycle

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M. A. Green, Lawrence Berkeley Laboratory, Berkley CA 94720, USA

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coolers where the refrigerator working fluid does not come in contact with the load. When the word cryocooler is used in this report, the author is referring to the second type of cooler [2],[3]. Cryocoolers typically have one or more cold heads that must be connected to the object being cooled.

Open cycle machines are generally designed for larger heat loads than are commonly found in superconducting electronics applications. Open cycle machines permit one to cool electrical leads with gas from the cooling circuit, which can reduce the refrigeration needed for lead cooling by nearly an order of magnitude.

A modified cryocooler may have a separate stream from the compressor that connects the cold heads to the load through extra heat exchanges. There usually is a final stage of J-T expansion. In this case, the cooler working fluid can be in direct contact with the load. The modified cryocooler system is usually not as reliable as the cryocooler itself.

Cryocoolers come in three general types: 1) the most common cryocoolers use the Gifford McMahon (GM) cycle. Single stage GM machines can be used down to 30 to 40 K; two stage machines can be used down to temperatures as low as 2.5 K. GM machines have regeneration and pistons in the cold heads. The moving pistons are a source of vibration and machine failure. 2) Pulse tube coolers have recently become commercial cryocoolers. Single stage pulse tube machines can go down to 30 or 40 K; two stage machines can go down to 2.5 K. Pulse tube machines have no moving parts in the cold head. As a result, pulse tube machines produce much less vibration and are more reliable than GM machines. 3) Stirling cycle machines are characterized by their high thermal dynamic efficiency (up to five times less input power than a comparable GM or pulse tube machine). The cold head and compressor are often built into a single unit. The cold head contains both moving pistons and regeneration materials. Because of the moving pistons, Stirling units are usually not vibration free. At least on manufacturer produces a two-piston machine with a linear motor drive and brake. By electronically controlling the phase of the motion of the two pistons, vibration levels for this machine are greatly reduced. Stirling machines appear to have the same inherent reliability as a GM machine. In recent years, steps have been taken to increase the mean time between failures of virtually all types of cryocoolers.

Cooler orientation with respect to gravity may be an issue (particularly with the pulse tube coolers). One should check with the cooler manufacturer to see what the effect of orientation on refrigeration is for the cooler of interest.

IV. CONNECTION OF THE COOLER TO THE LOAD

One of the biggest problems in cooling superconducting electronics devices is connecting the cold head of the cooler to the device being cooled. Many electronic applications require very low vibration. Since electronic devices are usually low-mass devices, they are subject to the same level of acceleration seen by the cold head of the cooler.

Vibration isolation is a key element in the integration of the cooler with the electronic device. In general, the device should be mounted onto a stiff substrate that conducts heat well. This substrate should be connected to room temperature through stiff cold mass supports. Vibration isolation from the cold head can be accomplished by flexible connections from the cold heat to the load or through flexible tubes that connect the cold head to a volume of liquid cryogen that surrounds the component being cooled. The problem with both methods of vibration isolation is the temperature drop between the cold head and the electronic component being cooled. The temperature drop problem is further complicated by heat leaks down the leads to go from room temperature (or the first stage temperature of the cooler when a two stage cooler is used) to the electronic component being cooled.

One approach to eliminating the effects of heat leaks down the leads into the electronic device is to immerse the device in a cryogenic fluid. Any of the four fluids in Table 1 can be used (including hydrogen, which has very good thermal properties) provided one does cryogenic design correctly. A device that operates in a cryogen bath can be operated almost any temperature in the range from just above the triple point to near the critical point for the selected fluid. The vessel containing the load and surrounding cryogenic fluid must be vacuum leak tight and it must be designed for the expected range of operating pressures.

The key to connecting the cooler cold head with the load immersed in a cryogenic fluid is creating a condenser that causes the cryogen that the cools through the load to circulate [4]. Simply immersing the cold head of the cooler into a bath of liquid cryogen does not work if one wants a low temperature drop between the load and the cold head. The difference between making the connection from the cold head to the load correctly and not making the connection correctly is a factor of 10 to 1000 (depending on the case) difference in the effective heat transfer coefficient between the cooled load and the cryocooler cold head.

The expansivity of the liquid cryogen used as a medium to transfer heat from the device to the cooler cold head may be an issue (particularly for systems using liquid helium as a coolant). Most cryogenic systems use the liquid level as a means of monitoring the performance of the cooling system. This can be the wrong thing to do, because the liquid level in a device can rise as it gets warmer. Liquid level should not be used to monitor or control the cooling process. The temperature of the cryocooler cold head and the temperature of the load (the pressure in the liquid container if the load is surrounded by liquid cryogen) should be used to monitor the performance of the cooling system.

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