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A CLOSED CYCLE CASCADE JOULE THOMSON REFRIGERATOR
FOR
COOLING JOSEPHSON JUNCTION DEVICES

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A closed cycle cascade Joule Thomson refrigerator designed to cool Josephson Junction magnetometers to liquid helium temperatures is being developed. The refrigerator incorporates 4 stages of cooling using the working fluids CF_4, N_2, H_2 and He. The high pressure gases are provided by a small compressor designed for this purpose. The upper three stages have been operated and performance will be described.

Key words: Cascade Joule Thomson refrigerator; cryocooler.

1. Introduction

The problem of cooling of Josephson junction devices to liquid helium temperatures is becoming increasingly important as systems incorporating such devices are becoming more widespread. Traditionally, experimentalists have preferred the use of liquid helium dewars since, in a laboratory setting where liquid helium is readily available, they are convenient to use. Devices can be cooled and warmed quickly and tests can be made with little attention to the cooler other than replenishment of the liquid helium cryogen. However, once devices are integrated into a system and are to be used for extended periods of time, the use of liquid helium dewars often becomes inconvenient, especially if the system is to be operated remotely from a readily available liquid helium supply or if the system is inaccessible by service personnel.

Under these circumstances, it would be preferable to use a cryocooler. The ideal cryocooler would be one that is convenient to operate (i.e., flick the switch to turn on the power) and it does the job. In addition, the cooler should be efficient, occupy a small volume, be adaptable to cool a wide range of instruments, and have minimal interaction with the instrument (other than cooling it). This latter requirement is especially important for the cooling of Josephson junction magnetometers which are very sensitive to electromagnetic interference (EMI) and to vibration.

Because of this constraint almost all magnetometers are cooled in liquid helium dewars. All commercially available cryocoolers use expansion engines and hence act as sources of both EMI and vibration. Therefore, all such coolers are generally unsuitable for the most demanding applications, unless the instrument is contained in a liquid helium dewar and is being continuously cooled by a remotely sited refrigerator. Such a refrigerator could be coupled to the instrument, for example, through a continuously flowing liquid helium transfer line. It is often the case that the cooling power required is much less than one watt. The smallest commercially available coolers have cooling powers greater than one watt. In this sense they are also ove-designed for the small cooling power applications.

Attempts have been made to build low cooling power Stirling cycle cryocoolers [1]. These machines incorporate plastic materials in order to reduce EMI from moving conducting materials and require mechanical balancing in order to reduce vibration. In our view, a far better approach is to construct a refrigerator with no cold moving parts. This has been implemented through the use of the cascade Joule Thomson process [2]. Since Joule Thomson refrigerators require a source of very pure high pressure gas, suitable low flow rate large compression ratio compressors are required. We have taken two approaches to this problem. For very long life refrigerators, chiefly for space applications in which no servicing is possible, we have developed non-mechanical adsorption compressors which are thermally driven and incorporate no moving parts [3]. In the second approach we have designed and built a small mechanical compressor which provides very clean high pressure gas to the refrigerator. The compressor can be remotely sited from the refrigerator and connected to it only through long capillaries through which the high pressure room temperature gases are brought to the JT refrigerators and the low pressure room temperature return gases are returned to be recompressed. In this way, EMI is reduced by distance and vibration is greatly reduced because of the weak mechanical coupling to the cold (business) end of the refrigerator.

2. Cascade Joule Thomson refrigerators

The Joule Thomson process is in wide use for cryogenic coolers. For small cooling powers its major application is in the cooling of IR sensors typically to liquid nitrogen temperatures and above. For small cooling powers the JT refrigerators (heat exchanger plus expansion valve) can be implemented in a variety of ways [4, 5]. In our case we have used parallel metal tube heat exchangers with a constricted tube as the expansion valve.

The Joule Thomson process is conceptually simple. High pressure gas of enthalpy H_h enters the inlet of heat exchanger, expands and cools at the JT orifice and returns through the low pressure side of the heat exchanger in order to precool the incoming pressure gas. At the outlet of the heat exchanger the low pressure gas has an enthalpy H_L. The cooling power of the device is given by

$$\dot{Q} = \dot{m}(H_L - H_h) ,$$

where $\dot{m}$ is the mass flow rate. The JT process produces cooling (rather than heating) only if $H_L > H_h$ for the particular gas at the inlet temperature of the heat exchanger. The temperature above which H_L is always less than H_h is called the inversion temperature. Therefore, in order to reach liquid helium temperatures a minimum of three different gases in three cooling loops are required. In the cascade process an upper temperature refrigerator precools the inlet gas to a lower stage refrigerator to a temperature below the inversion temperature of the gas in the lower stage.

In our system we have implemented each JT loop in similar fashion. A schematic of the upper stage loop and the components incorporated is shown in figure 1. The loop incorporates both warm and cold filters as a precaution against contamination resulting in clogging of the refrigerator. The cascaded JT refrigerator which we are reporting on has been implemented with four stages using the working fluids CF_4, N_2, H_2, He. The four stages (rather than three) were used because of increased thermodynamic efficiency and because lower pressures are required from the compressor for the upper stages. The four independent fluid loops are configured as shown in figure 2.

Because of the low gas flows, the eight gas lines to the refrigerator (2 per stage) can be long enough for the compressor to be far from the refrigerator (we have used 3.2 meter lengths) and can be of small diameter (smallest diameter 0.16 cm OD). This provides a very flexible interface to the sensor cryogenics. The refrigerator operates in any orientation which should make the device much easier to use than sensors using liquid helium dewars. The prototype refrigerator shown in figure 3 was specifically designed to cool a SHE biomagnetic probe [6] with a 2nd order gradiometer input coil. A schematic of the cryostat is shown in figure 4. To date, only three of the four stages have been operated. Figures 5 and 6 show cool down curves for the various stages. The longer than necessary cool down times are due to the fact that these measurements were taken with a leak in one of the loops which resulted in excessive heat leak through the inadequately maintained dewar vacuum. The temperature reached at each stage is determined by the pressure at the liquid reservoir which is in turn determined by the impedance of the J-T orifice, the pressure drop in the low side heat exchanger and the inlet pressure to the compressor. In the experiments to date, gas flows through each of the loops have been in the range of 50 STP cc/sec and are chiefly determined by the impedance of the J-T orifice. With lower gas flows we expect smaller pressure drop in the low side heat exchangers, smaller compressor inlet pressures and hence lower operating temperatures at each stage. The design goal was for flow rates of 15 STP cc/sec in each loop. Once all four stages are operating we intend to reduce the flow rates (and cooling powers) to each stage so that the lowest possible temperatures can be achieved.

3. Conclusions

Closed cycle Joule Thomson coolers appear to be an attractive solution to the problem of cooling low power devices to low temperatures. Their small size, orientation independent performance, and absence of cold moving parts make them particularly useful for application where EMI and vibration are a problem.

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4. References

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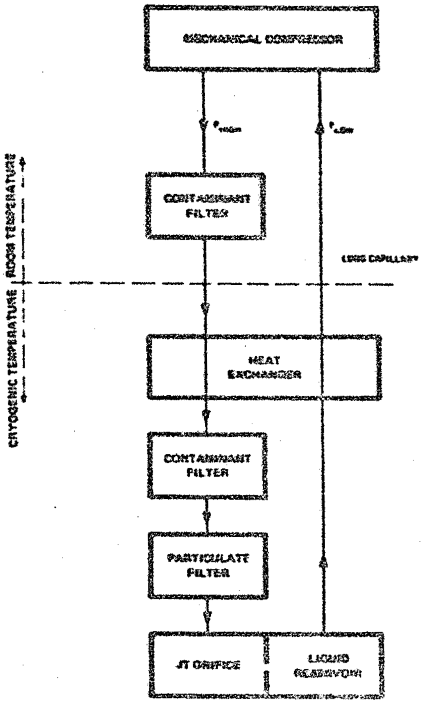

Fig. 1. Schematic of a single stage J-T cooler.

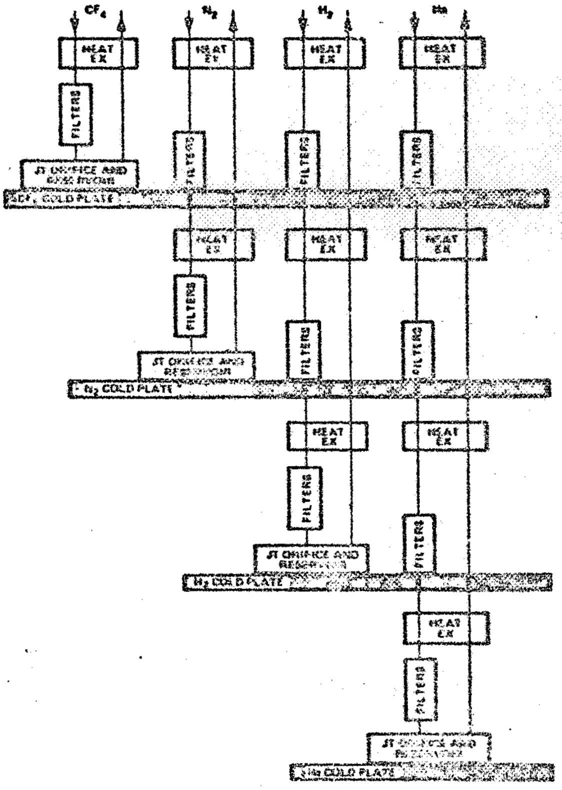

Fig. 2. Schematic of a cascaded four stage J-T cooler.

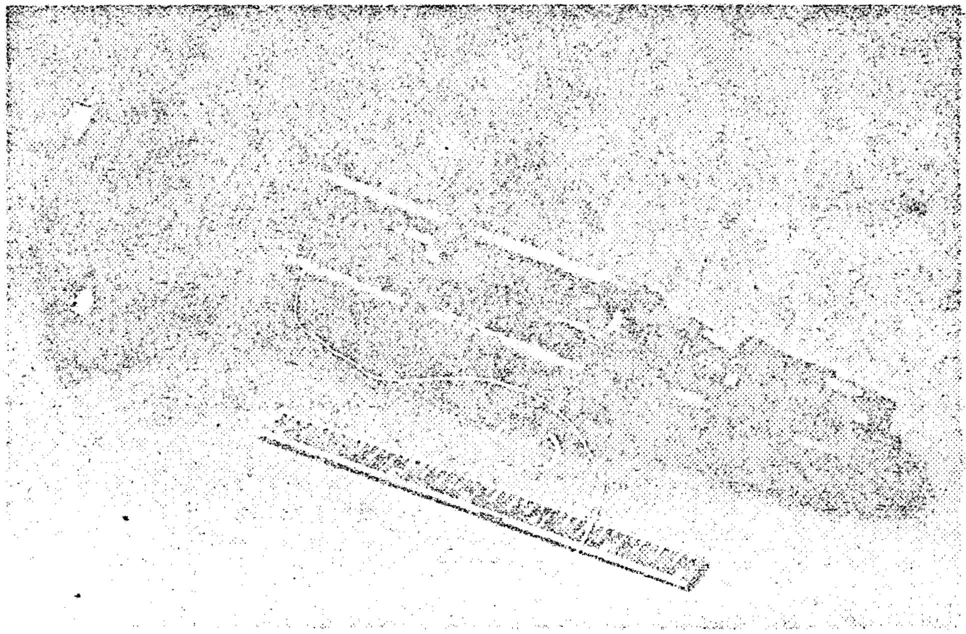

Fig. 3. Four stage cascaded J-T cooler designed to cool biomagnetic probe.

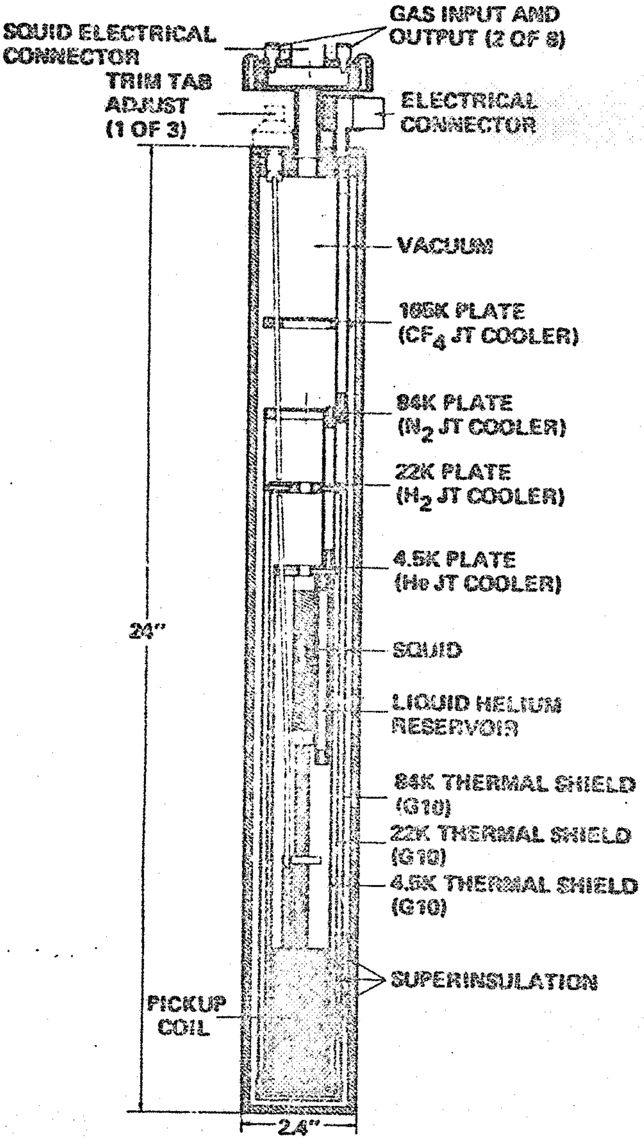

Fig. 4. Schematic of single sensor neuromagnetometer incorporating closed J-T cooler.

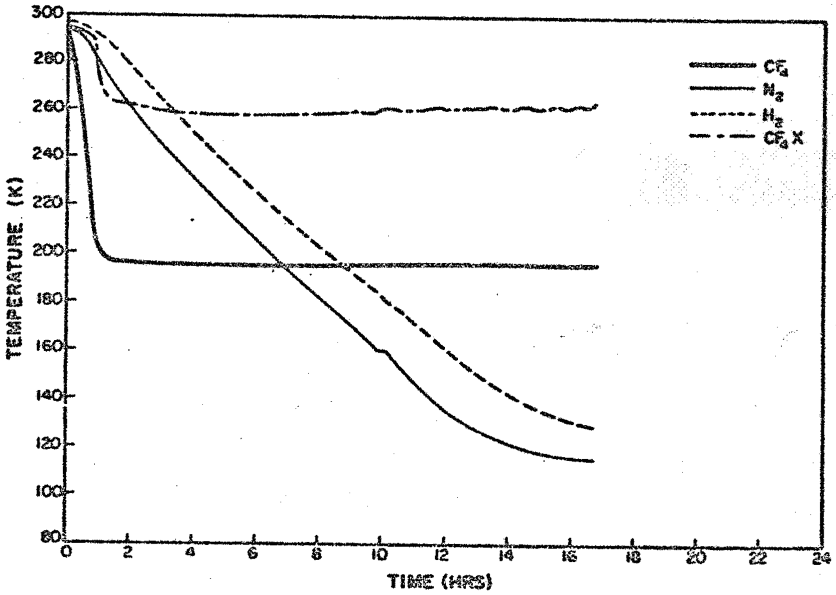

Fig. 5. Cooldown of upper two stages of refrigerator. The H_2 stage is being cooled by conduction. The curve labelled, CF_4X indicates the outlet temperature of the heat exchanger. The low temperature after cooldown is due to excess cooling power.

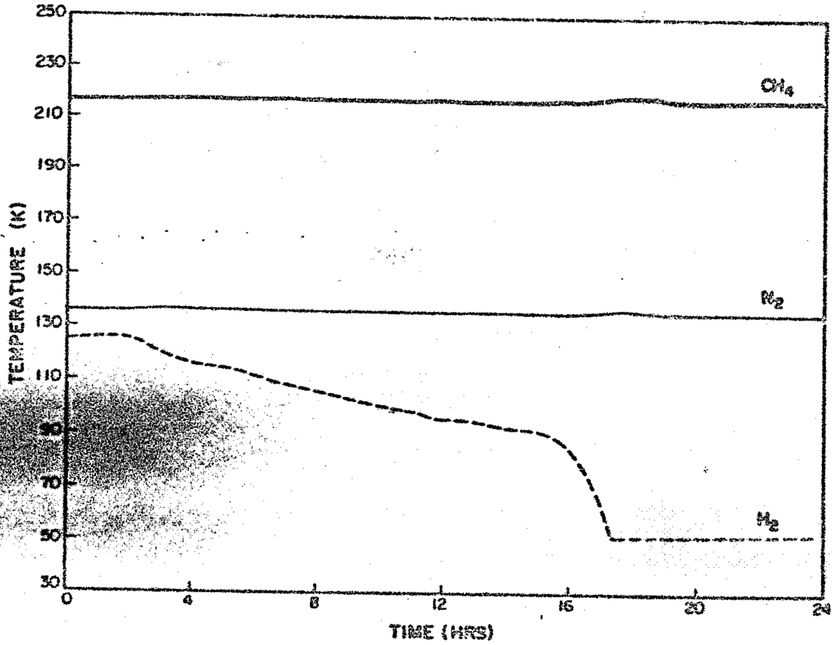

Fig. 6. H_2 stage cool down. Note temperature stability. The rapid cool down below 70 K is due to increased gas flow and cooling power as the impedance of the refrigerator drops with temperature.