A Review of Low Temperature Refrigerator Development

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Abstract-*Refrigeration plays a prominent role in our everyday lives, and cryogenics plays a major role in medical science, space technology and the cooling of low-temperature electronics. This volume contains chapters on basic refrigeration systems, non-compression refrigeration and cooling, and topics related to global environmental issues, alternative refrigerants, optimum refrigerant selection, cost-quality optimization of refrigerants, advanced thermodynamics of reverse-cycle machines, applications in medicine, cryogenics, heat pipes, gas-solid absorption refrigeration, multi salt re-sorption heat pumps, cryo-coolers, thermo acoustic refrigeration, cryogenic heat transfer and enhancement and other topics covering theory, design, and applications, such as pulse tube refrigeration, which is the most efficient of all cryo-coolers and can be used in space missions.*

Keywords:Refrigerator, microgravity, condenser, mixing chamber, demagnetization.

I. INTRODUCTION

Research at low temperatures is an extremely fruitful field because of the many phenomena that occur only there. Unusual phases of matter such as superconductors and super fluids occur at low temperatures and many subtle behaviors that are obscured by thermal motion at higher temperature can be studied in great detail at low temperatures. To carry out research at low temperatures it is necessary to have a refrigerator that 1) cools to the required temperature, 2) is reliable and, 3) if possible, operates continuously for the duration of the experiment, whether that is hours or days. On the ground the need for temperatures below 0.3 K is almost universally met by the He-3-He-4 dilution refrigerator. Its usefulness arises from the fact that it operates continuously, it can provide a substantial cooling power at temperatures from around 1.0 K down to 0.010 K and below and it can run uninterrupted for as long as several months.

There are many very interesting physics experiments that need the unique microgravity environment of space but which also need lower temperatures than are currently available. In order to investigate phenomena that occur at very low temperatures, particularly in super fluid He-3, the capability for extending research to temperatures of 0.001 K in space needs to be developed. On the ground, temperatures to 0.001 K and below are reached with adiabatic demagnetization systems that are pre-cooled with helium dilution refrigerators. Similar temperatures can be achieved in space if the dilution refrigerator can be adapted to work in microgravity.

II. SINGLE-CYCLE DILUTION REFRIGERATOR

Figure 1 shows how such a refrigerator operates. The lowest temperatures occur in the mixing chamber where there is a phase boundary between liquid He-3 and liquid He-4. Cooling is produce when He-3 crosses this boundary into the He-4. From the mixing chamber this dilute He-3 flows through the He-4 to a higher temperature chamber where it is fractionally distilled from the He-4. The resulting He-3 gas is collected by the charcoal pump. The cooling cycle ends when all the He-3 is in the charcoal pump. Because the refrigerator uses adsorption onto charcoal for its pumping, all operations can be controlled by heaters and, as a consequence, there are no moving parts in the refrigerator.

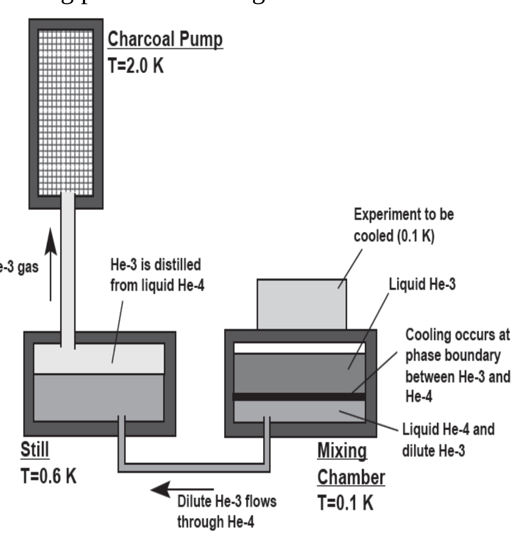

Figure 1. Operation of compact single-cycle dilution refrigerator using a charcoal pump.

We have built a shallow version of the dilution refrigerator that has a mixing chamber and still that are only 0.5 cm high; this allows us to use sinter with rather large pores (40 □m to 200 □m diam. in different locations, see Fig. 2), which we expect will permit excellent operation of the system.

This design can verify a limited amount of gravity independence of the operation on the ground.

III. SHALLOW MIXING CHAMBER

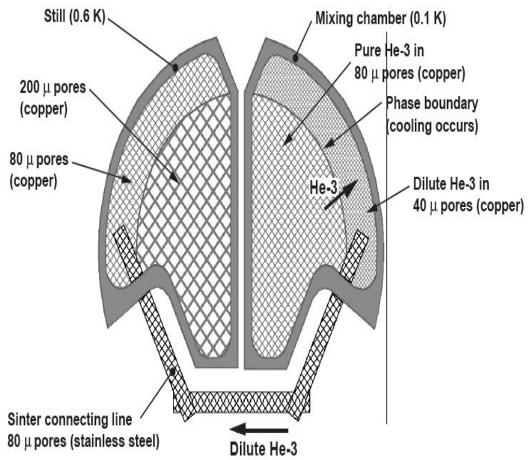

Figure 2. Arrangement of different size sinters for confining liquid helium in still and mixing chamber.

In its normal position with the shallow still next to the shallow mixing chamber, and the pumping line coming out of the top of the still, it will operate even without sinter in the chambers. It would not continue to operate with the system tilted slightly so that one chamber was above the other. With the coarse sinter in the chambers, however, we expect to be able to tilt the system 5-10 degrees in either direction with little change in operation (see fig. 3). If the system is tilted more than this, either one or the other of the sinters where the connecting line attaches becomes empty, stopping the dilute He-3 circulation, or else the He-3 in the mixing chamber escapes into the surrounding small pores, allowing it to leave the mixing chamber.

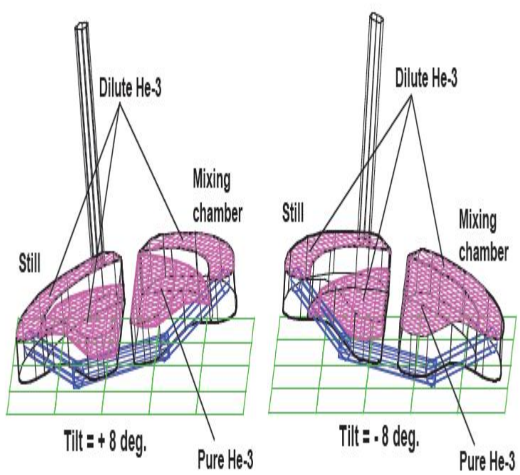

Figure 3. Distribution of liquid He as the shallow dilution refrigerator is tilted (on the ground).

In a more convincing demonstration of gravity independence, the chambers can be inverted so that the still pump line is on the bottom (see fig. 4) and the system should still operate normally. Clearly, no operation in this orientation would be possible without the sinter; the liquid in the still would simply run into the pumping line. Even in this orientation the system can be tilted 5-10degrees in either direction before the capillary forces are overcome by gravitational forces and the liquid runs from one chamber into the other. These limited confirmations of capillary confinement will be a good indication that the system will work well in space.

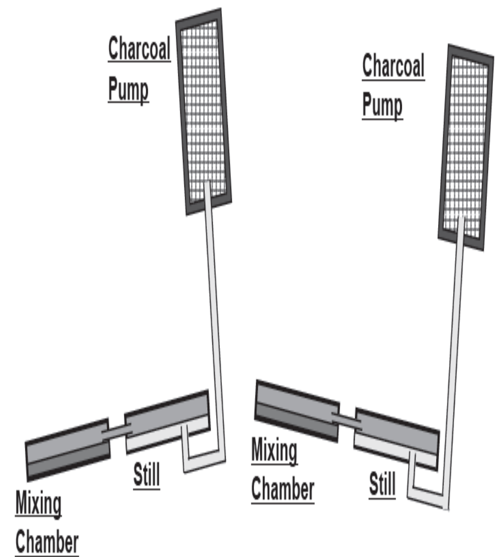

Figure 4. Shallow dilution refrigerator can be tilted even while its chambers are inverted to convincingly demonstrate gravity independence.

IV. CONTINUOUSLY-OPERATING DILUTION REFRIGERATOR

We are developing a continuously-operating dilution refrigerator that will directly cool to 0.040 K in a microgravity environment. Such a refrigerator could also pre-cool an adiabatic demagnetization stage for reaching temperatures of 0.001 K and below. Figure 5 shows the configuration we propose to test on the ground. The still and mixing chamber of this design are similar to those of the single-cycle refrigerator we have built. The dilute He-3 flows out of the mixing chamber into the still as before. But the He-3 gas, instead of being pumped from the still into a charcoal pump, now goes to a new chamber, the condenser, at 0.4 K, where it condenses back to a liquid and pure He-3 returns to the mixing chamber. Thus this He-3 never leaves the low-temperature region. As long as the still is heated to maintain its temperature at 0.6 K and the

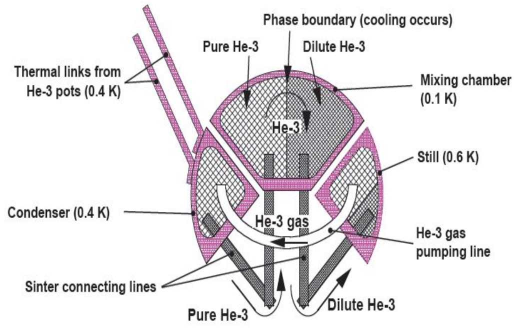

Figure 5. Details of the low-temperature chambers of the continuously-operating dilution refrigerator.

Condenser is cooled to maintain its temperature at 0.4 K; He-3 will be continuously pumped from the still into the condenser and forced back into the mixing chamber. This continuous circulation of He-3 will produce continuous cooling in the mixing chamber where He-3 crosses the phase boundary from pure He-3 into the He-4. The notable feature of this design is the method by which the condenser is continuously cooled (while maintaining the advantages of compactness, reliability and the complete absence of moving parts). The condenser is cooled by a pair of independent, single-cycle He-3 refrigerators (see Fig. 6),

Figure 6. Components of a continuously-operating dilution refrigerator for microgravity use.

Each with its own charcoal pump and each thermally linked to the condenser by a gas-gap heat switch. While one He-3 pot is cold and coupled to the condenser, the other He-3 pot is isolated from the condenser while it is being refilled at high temperature. Then, before the first He-3 pot runs empty, the second He-3 pot would be cooled down and coupled to the condenser by its heat switch. The first He-3 pot could then be decoupled and refilled and there would have been no interruption of cooling to the condenser.

V. CONCLUSIONS

We have built a 'shallow' single-cycle dilution refrigerator to demonstrate the principle of capillary confinement in a refrigerator that can reach 0.1 K or below in microgravity. We have designed a continuously-cooling version of a dilution refrigerator that builds on the design of the single-cycle refrigerator while maintaining its advantage of no moving parts. The continuously cooling version will be very useful by itself for microgravity experiments that require cooling to as low as 0.04 K; it will also be invaluable for experiments that require temperatures as low as 0.001 K because it can be used to pre-cool adiabatic demagnetization systems that can reach those temperatures.

REFERENCES

[1] Yu B.F., Gao Q., Zhang B., Meng X.Z., Chen Z. (2003) Review on research of room temperature magnetic refrigeration, International Journal of Refrigeration 26, p. 622-636.

[2] Tishin A.M., Spichkin Y.I. (2003) The Magnetocaloric Effect and its Applications, Institute of Physics Publishing, London

[3] Gschneidner K.A. Jr., Pecharsky V.K., Tsokol A.O. (2005) Recent development in magnetocaloric materials, Reports on Progress in Physics 68, p. 1479-1539.

[4] Gschneidner K.A. Jr., Pecharsky V.K. (1999) Magnetocaloric effect and magnetic refrigeration, Journal of Magnetism and Magnetic materials 200, p. 44-56.

[5] Halbach K. (1980) Design of permanent multipole magnets with oriented rare earth cobalt material, Nuclear Instruments and Methods 169, p. 1-10.

[6] Gschneidner K.A. Jr., Pecharsky V.K. (2008) Thirty years of near room temperature magnetic cooling: Where we are today and future prospect, International Journal of Refrigeration 31, p. 945-961.

[7] Zimm C.B., Sternberg A., Jastrab C., Pecharsky V.K., Gschneidner K.A. Jr., Osborne M., Anderson I. (1998) Description and performance of a near room temperature magnetic refrigerator, Adv. Cryog. Eng. 43, p. 1759-1766.

[8] Zimm C.B., Boeder A., Chell J., Sternberg A., Fujita A., Fujieda S., Fukamichi K. (2006) Design and performance of a permanent-magnet rotary refrigerator,International Journal of Refrigeration 29, p. 1302-1306.

[9] Zimm C.B., Auringer J., Boeder A., Chell J., Russek S., Sternberg A. (2007) Design and initial performance of a magnetic refrigerator with a rotating permanent magnet, Proc. 2nd International Conference on Magnetic Refrigeration at Room Temperature. Portorož, Slovenia, p. 341- 347.

[10] Meeker D (2006) Finite Element Method Magnetics, version 4.0., User`s manual.
[11] Tušek J. (2007) Developing of a regenerator for the magnetic refrigerator, Diploma Thesis, University of Ljubljana, Faculty of Mechanical Engineering.
[12] Popović D.R., Dimitrijević S., Blagojević M., Kejik P., Schurig E., Popovic R.S. (2007) Three-axis teslameter with integrated hall probe, IEEE Transactions on Instrumentation and Measurement 56, p. 1396 – 1402.
[13] Šarlah A. (2008) Thermo-hydraulic properties of heat regenerators for magnetic refrigerator, PhD Thesis, University of Ljubljana, Faculty of Mechanical Engineering.