LA-UR -90-3380

LA-UR--90-3380

DE91 002311

2

TITLE: Superfluid Stirling Refrigerator: A New Method for Cooling Below 1 Kelvin

AUTHOR(S): V. Kotsubo and G. W. Swift

SUBMITTED TO: Proceedings of 6th International Cryocooler Conference
Plymouth, Mass. October 25-26, 1990

Los Alamos — Los Alamos National Laboratory
Los Alamos, New Mexico 87545

SUPERFLUID STIRLING REFRIGERATOR: A NEW METHOD FOR COOLING BELOW 1 KELVIN

V. Kotsubo, P-10

G. W. Swift. P-10

Contributed paper for: Proceedings of 6th International Cryocooler Conference Plymouth, Mass. October 25-26, 1990

Submitted September 24, 1990

LA-UR-90-

We are exploring a novel refrigeration idea: the use of the ^3He solute in a superfluid ^4He-^3He mixture as a Stirling-cycle refrigerant below 1 degree Kelvin. This is a new concept, invented by us. We recently debugged the first such refrigerator, and have reached 0.6 degrees Kelvin from a starting temperature of 1.2 degrees Kelvin. We've already sent an invention disclosure to LC/IP, and submitted a paper to Phys. Rev. Lett. Presenting the work to this conference should bring it to the attention of many of its potential ultimate users (sponsors?), especially NASA.

Temperatures between about 0.5 Kelvin and 0.005 Kelvin are today reached with the dilution refrigerator, which uses the cooling that occurs when liquid ^3He and ^4He are mixed. The dilution refrigerator is important in such diverse fields as particle physics (for polarized targets and advanced detectors), surface chemistry (for enhancing NMR sensitivity), astronomy (for cooling infrared detectors), materials science, and condensed-matter physics.

We realized that there is another way that liquid helium mixtures might be used to produce refrigeration below 1 Kelvin. At such low temperatures the ^4He is in a superfluid quantum-mechanical ground state and is thermodynamically inert, while the dissolved ^3He atoms have the thermodynamic properties of an extremely dense ideal gas. This suggests using the ^3He solute in a ^3He-^4He mixture as the working fluid in a heat engine or refrigerator such as a Stirling cycle. The pistons are superleaks, "pushing" only on the ^3He while letting the ^4He pass through unimpeded. The pistons are driven by an "overhead cam" at room temperature, via long thin pushrods. We also know how to do all this with no moving parts, ultimately an important practical advantage.

Satellite-borne infrared sensors work best at low temperatures, and thus NASA has been working for years on dilution refrigerators that can operate in zero gravity, trying to develop electrostrictive and surface-tension control of the liquid/liquid and liquid/vapor helium interfaces required in dilution refrigerators. The superfluid Stirling refrigerator will work perfectly in zero gravity, because it has no such interfaces.

Dilution refrigerators are extremely inefficient, consuming about 10 kW of electric power while producing typically several μW of refrigeration. This low efficiency is due to the high power consumption of the diffusion pump and mechanical vacuum pump, which are operated continuously to separate the ^{3}He and ^{4}He (by fractional distillation) to return them to the refrigerator for remixing. The superfluid Stirling refrigerator will be about 1000 times more efficient. Efficiency is unimportant on earth (We users of dilution refrigerators don't pay our own electric bills!), but is exceedingly important for satellite applications.

Most of the cost in the multi-million-dollar dilution-refrigerator industry is for large room-temperature plumbing and pumps; these will not be required in the superfluid Stirling refrigerator, which may be a factor of 5 less expensive as a result. This low cost could make low-temperature research easier everywhere, and feasible for the first time at small colleges and in developing countries.

SUPERFLUID STIRLING REFRIGERATOR: A NEW METHOD FOR COOLING BELOW 1 KELVIN

V. Kotsubo and G. W. Swift
Condensed Matter and Thermal Physics Group,
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

ABSTRACT

We have invented and built a new type of cryocooler, which we call the superfluid Stirling refrigerator (SSR). The first prototype reached 0.6 K from a starting temperature of 1.2 K. The working fluid of the SSR is the ^{3}He solute in a superfluid ^{3}He-^{4}He solution. At low temperatures, the superfluid ^{4}He is in its quantum ground state, and therefore is thermodynamically inert, while the ^{3}He solute has the thermodynamic properties of a dense ideal gas. Thus, in principle, any refrigeration cycle that can use an ideal gas can also use the ^{3}He solute as working fluid. In our SSR prototype, bellows-sealed superleak pistons driven by a room-temperature camshaft work on the ^{3}He solute. Ultimately, we anticipate elimination of moving parts by analogy with pulse-tube refrigeration.

INTRODUCTION

The ^{3}He-^{4}He dilution refrigerator, invented about 30 years ago, is now routinely used[1] to reach temperatures below 1 K. The endothermic heat of mixing of liquid ^{3}He with liquid ^{4}He produces the cooling in the dilution refrigerator; steady refrigeration is achieved by adding a fractional distillation chamber to remove the ^{3}He from the solution, and room-temperature pumps to return the ^{3}He to the refrigerator. Modern dilution refrigerators routinely reach temperatures below 0.01 K, exhausting their waste heat above 1 K.

There are only two other techniques[1] for cooling below 1 K. The evaporation of pure ^{3}He can be used to reach 0.3 K; but, at lower temperatures, the vapor pressure is too low for significant cooling power. Adiabatic demagnetization of a paramagnetic salt, the oldest method for cooling below 1 K, is inconvenient because of the frequent requirement for magnetic shielding between the refrigerator and the apparatus to be cooled.

Here, we describe the first experiments with a new technique for cooling below 1 K: the superfluid Stirling refrigerator (SSR). The SSR uses the ^3He solute in a superfluid ^3He-^4He solution[2] as a thermodynamic working medium, compressing and expanding the solute alone to provide heating and cooling. In such a solution, the ^4He, forming a Bose liquid, undergoes a superfluid transition at 2.2 K, and below 1 K it is, for our purposes, in its quantum ground state. It has no entropy, and flows without dissipation; thermodynamically it is a vacuum. The ^3He solute in such ^4He behaves like an ideal gas, with an equation of state $P_{os} = n_3 k_b T$, and heat capacity per particle $\simeq (3/2)k_b$, where P_{os} is osmotic pressure, n_3 is the ^3He number density, k_b is Boltzman's constant, and T is the temperature. Because of this similarity any refrigeration cycle that uses ideal gases as a working fluid should be adaptable[3] to the regime below 1 K using the ^3He solute working fluid. We chose to use the Stirling cycle[4], shown in detail in Fig. 1.

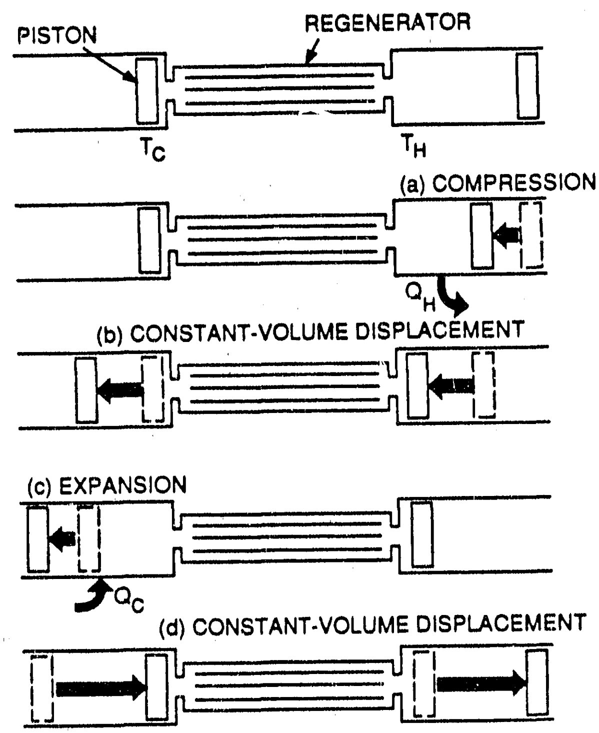

Fig. 1. Four steps of a Stirling-cycle refrigerator. (a) The first step of the cycle is isothermal compression of the fluid in the hot cylinder, rejecting the heat of compression Q_h out of the refrigerator to an external heat sink at T_h. (b) In the second step, both pistons move, displacing the fluid to the left. Because of the good lateral thermal contact in the regenerator, heat is transferred there, between fluid and high-heat-capacity solid, under locally isothermal conditions, reversibly changing the fluid temperature from T_h to T_c as it flows leftward. (c) In step three, isothermal expansion in the cold cylinder absorbs the heat of refrigeration Q_c from the load at T_c. (d) Displacement of the fluid to the right then causes regenerative heat transfer, changing the fluid temperature from T_c back to T_h.

DESIGN AND CONSTRUCTION

Building the SSR required several unique design features, shown schematically in Fig. 2. The compressor and expander had to work on only the ^3He solute, and not the relatively incompressible bulk liquid, so superleak pistons were used. Each of these consisted of a 4.65-mm long, 0.36-mm-diam rod of microscopically porous Vycor glass (Corning 7930) sealed with Stycast 2850 epoxy into a hole drilled through the length of a copper piston. The piston was then sealed between two bellows (Servometer FC-16 nickel bellows), forming two containment volumes for the solution connected by the glass rod. Vycor glass, which has channel diameters of about 10^{-8} m, viscously locks the ^3He solute, allowing only the superfluid ^4He component to flow through, so a displacement of the piston compresses only the ^3He. The copper pistons were designed to take up as much as possible of the excess volume within the bellows to maximize the compression ratio. The final total fluid volume within each bellows was about 2 cm^3.

The pistons were driven with long rods from a camshaft and dc motor/gearbox assembly at room temperature. Each drive rod consisted of a moving 1.77-mm-od stainless tube inside of a 2.4-mm-od, 1.8-mm-id stationary tube, bent slightly where necessary, much like a bicycle cable. The two cams were 5.08-cm-diam ball bearings mounted 0.32-mm off center to provide 0.64-mm displacements. The cams were mounted on separate but colinear driveshafts connected by a clamp, so the phase between the cams could be adjusted by loosening the clamp and rotating one cam with respect to the other. Because the overall drive system was not completely rigid, 0.64-mm camshaft displacements at the top of the cryostat caused only about 0.4 - 0.5-mm displacements at the pistons, and the resulting piston motions were hysteretic and non-sinusoidal. Final volume displacements were about 0.9 cm^3/stroke, but were different for each piston, and also drifted over time.

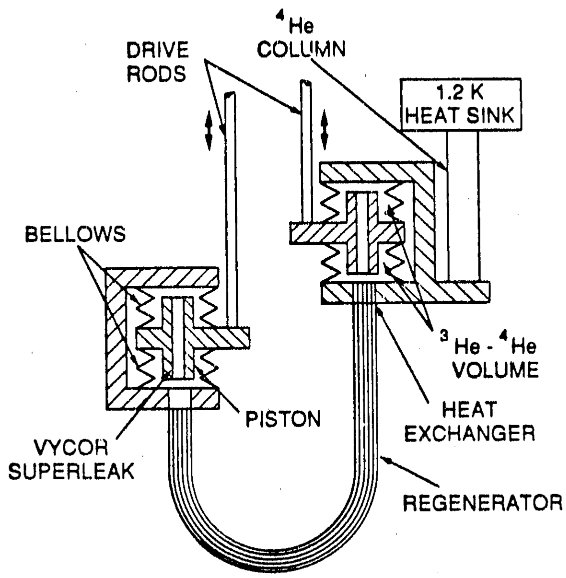

Fig. 2. Schematic of the SSR. Entire assembly is sealed in a vacuum can, which is immersed in a 4-K liquid ^{4}He bath.

One of the bellows volumes at each piston was sealed off with a flange, acting simply as a reservoir for the ^{4}He superfluid that flows through the superleak. The other volume was the actual compression/expansion space for the refrigerator, and was sealed with a ported flange connecting to the regenerator. On the compressor, the port consisted of 19 0.8-mm-diam holes drilled through the 1-cm thick copper flange to act as a heat exchanger to remove the large amount of heat rejected. The working fluid flowed through these holes, then into the regenerator. The copper flange was connected to a 1.91-cm-diam, 18-cm long copper tube filled with pure ^{4}He, which acted both as a thermal reservoir and a thermal link to a standard pumped ^{4}He coldplate[5] which provided a starting temperature of about 1.2 K. There was no heat exchanger on the expander--the heat load was simply the heat capacity of the expander. The expander was thermally isolated from the compressor by three 25-cm long, 0.64-cm-od thinwall stainless-steel support tubes.

The regenerator was an array of 30 0.20-mm-id, 0.37-mm-od, 38-cm long CuNi capillaries, stuffed into a series arrangement of a 0.47-cm-diam, 2.86-cm long CuNi tube, a 6.35-mm-od, 25-cm long stainless-steel tube, a 6.35-cm long section of 0.64-cm-od, 0.32-cm-id bellows, and a 0.32-cm-diam, 2.5-cm long CuNi tube, all sealed together with soft solder. The bellows formed a U-shaped bend to allow the regenerator to match the positioning of the ports of the expander and the compressor; the smaller diameter tubes at either end fit into the ports. The capillaries were sealed to the outer tube assembly's ends with soft solder, so that the ^{3}He-^{4}He solution could flow through the capillaries, and the outer tube assembly was filled with pure ^{3}He, thereby immersing the capillaries in a high-heat-capacity reservoir (which would be provided by solid parts in a conventional Stirling refrigerator). The total heat capacity of the regenerator was calculated to be 1.1 J/K at 0.6 K and 1.2 J/K at 1 K.

Two separate fill lines were used to fill the refrigerator. One fill line filled the refrigerator itself, and the other filled the reservoir volumes on the back of each piston. By having two separate fill lines, the concentrations on either side of the superleaks could be adjusted separately by filling each side first with the required amount of ^{3}He, and then adding ^{4}He. The fill lines were closed using low-temperature valves pneumatically operated with pressurized ^{4}He. Without the valves, liquid moved up and down the fill lines between the warm and cold parts of the refrigerator during operation, thus causing a substantial heat leak.

Resistance thermometers were mounted on the outsides of the flanges which connected the expander and compressor to the regenerator, and a resistance wire heater was mounted on the outside of the flange of the cold expander. Following the method described by Kierstead[6], the ^{3}He concentrations were determined from the dielectric constant of the solution, which was measured using compact 5-pF capacitors mounted in the end flanges in direct contact with the liquid within the expander and compressor.

EXPERIMENTAL RESULTS

The refrigerator was filled with a 12% ^{3}He solution. Although at this high concentration, the thermodynamic properties of the ^{3}He solute deviate slightly from ideal-gas behavior[2], this concentration was chosen to improve the cooling power at high temperature by increasing the oscillating osmotic pressure. Several cooldowns were performed with various drive speeds and various phases between the compressor and expander.

For one set of measurements, the speed was set to 0.25 rpm, and the phase between the maximum of the compressor cam and the minimum of the expander cam was varied between 70° and 130°. The lowest average temperature of about 0.65 K was reached during these runs with the phase set at about 100°. A set of measurements was then made with the phase set at 100°, with speeds of 0.07, 0.25, 0.31, and 0.45 rpm. For these runs, the lowest temperature reached was also 0.65 K, also at a speed of 0.25 rpm. Fig. 3 displays the average expander temperature as a function of time for this run. For these cooldowns, the compressor temperature was not regulated, and varied from 1.16 K at the slowest speeds to 1.23 K at the highest speed, so the largest temperature difference, about 0.55 K, was reached with the speed of 0.31 rpm. Other temperature differences were 0.54 K, 0.53 K, and 0.45 K at speeds of 0.25, 0.45, and 0.07 rpm respectively. In a later cooldown, where the backside of each piston was filled with only a 2% solution, and the concentration in the refrigerator was about 10%, a low temperature of 0.59 K was reached. Peak-to-peak concentration amplitudes were about 0.45 of the average concentration, and peak-to-peak temperature amplitudes in the expander at the lowest temperatures were about 50 mK.

The net cooling power of the refrigerator was determined from cooling-rate data such as Fig. 3 by using the measured heat capacity of the expander, adding the calculated heat capacity of 1/2 the regenerator, and then multiplying by the rate of change of temperature. To obtain what we call the gross cooling power, two corrections are added to the net cooling power: a correction of 33 μW/rpm due to heating from the bellows motion, determined by running the expander with no liquid in the refrigerator; and a second correction for thermal conduction down the regenerator, support structure, and fill lines of 11.5 μW/K, determined by measuring the warmup rate with the refrigerator not running. Gross cooling power as a function of T_c is shown in Fig. 4.

Figure 5 shows the average concentration in the expander and compressor as a function of expander temperature for the speeds mentioned above. For ideal-gas behavior, the relation between the temperatures and concentrations would be $X_c T_c = X_h T_h$, where X_c and X_h are the concentrations in the expander and compressor, and T_h is the average compressor temperature. In Fig. 5, $X_c T_c \cong 1.6 X_h T_h$. The deviation from ideal-gas behavior is partly due to the ^{3}He solute showing slight effects of the Fermi degeneracy, and mostly due to heat

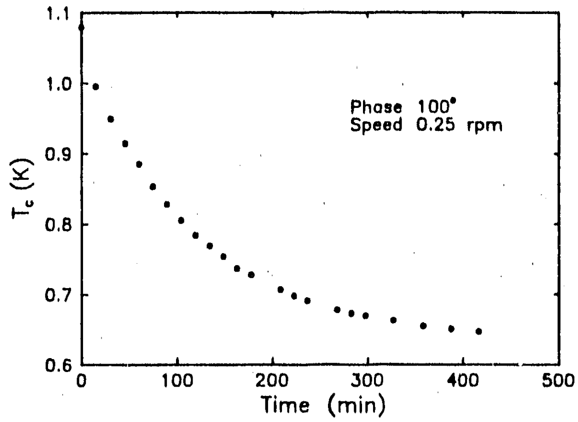

Fig. 3. Expander temperature as a function of time for a typical cooldown.

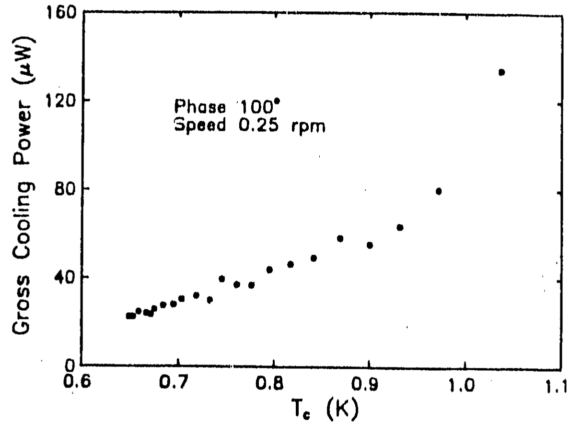

Fig. 4. Typical gross cooling power as a function of temperature.

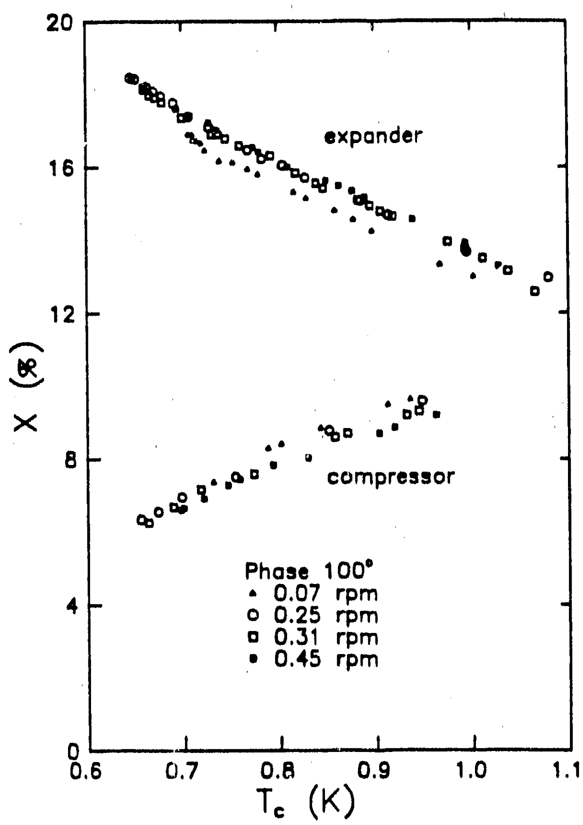

Fig. 5. Average ^3He concentration in the expander and compressor as a function of expander temperature, taken at four different speeds. As expected, the curves intersect at 12% when $T_c = T_h$.

flushing. In the heat-flush effect, the presence of a temperature gradient causes the ^4He normal-fluid excitations to flow down the temperature gradient, and the superfluid component to flow up the temperature gradient, with superfluid-normal fluid conversion taking place at the heat source and sink. The ^4He normal fluid drags ^3He atoms along with it, causing an excess buildup of ^3He atoms at the cold end. The factor of 1.6 agrees with rough extrapolations from data by Gestrich, Walsworth, and Meyer[7].

INITIAL INTERPRETATION OF RESULTS

Because of high local heat capacity and good thermal contact with the working fluid, a perfect regenerator allows no local temperature oscillations of the working fluid within the regenerator. For insight into the consequences of this characteristic, we write the energy flux density for hydrodynamic flow of an ordinary fluid:

$$H = \rho v(v^2/2 + w) \quad ,$$

where ρ is the fluid density, v is the fluid velocity, and w is the specific enthalpy. In an oscillating flow, ρ and w can be expanded as $\rho = \rho_0 + \rho_1$, $w = w_0 + w_1$, and $v = v_1$, where ρ_0 and w_0 are the average values and ρ_1, w_1, and v_1 are the first-order oscillating quantities. Substituting, taking the time average, and keeping only the lowest order terms:

$$H = \rho_0 \overline{v_1 w_1} \quad ,$$

where the overbar denotes time average. Using $dw = Tds + (1/\rho)dP$ and $ds = (c_p/T)dT - (\beta/\rho)dP$,

$$H = \rho_0 c_p \overline{T_1 v_1} + (1 - T_0\beta)\overline{P_1 v_1} \quad ,$$

where T_0 is the local average temperature, P is the pressure, c_p is the isobaric specific heat, and β is the isobaric expansion coefficient. For an ideal gas, $T_0\beta = 1$, so the second term vanishes. *Thus, in a perfect regenerator, where there are no temperature oscillations, the energy flow is zero.* The phasing of the pistons, however, is such that the work flow, given by the time average $\overline{P_1 \dot{V}_1}$, where $\dot{V}_1$ is the volume flow rate, is nonzero, flowing from the compressor to the expander. Since the energy flow through the regenerator is zero, the heat absorbed by the expander, $\dot{Q}_c$, must be equal to the work done on the expander, $\overline{P_1 \dot{V}_e}$, where $\dot{V}_e$ is the volume displacement rate of the expander.

Thus, we expect the cooling power of the SSR to be approximately $2\pi f P_{0s} V_1 \cos\varphi$, where P_{0s} is the osmotic pressure amplitude, V_1 is the volume displacement, f is the frequency, and φ is the phase angle between P_1 and V_1. We infer P_{os} from measurements of n_3 using $P_{os} = n_3 k_b T$. V_1 was measured at room temperature. The phase was determined from the time between the maxima of the cam position and the concentration. In this way, we estimate the cooling power for the cooldown in Fig. 5 at the lowest temperatures to be 50 μW, close to the observed cooling power. This estimate is not expected to be better than a factor of two, since the piston motions were extremely non-sinusoidal, and the volume displacements were not accurately known.

To make further progress, we display in Fig. 6 $Q_c(1+T_h/T_c)$ vs T_h-T_c, where Q_c is heat per cycle removed by the expander, obtained by dividing the measured cooling power of Fig. 4 by the operating frequency. In the classical-gas Stirling cycle, with given volume displacements in the expander and compressor, a 90° phase shift between the two, and negligible regenerator volume, the cooling per cycle[8] is frequency independent and has a temperature dependence given by $(1+T_h/T_c)^{-1}$, so that $Q_c(1+T_h/T_c)$ is temperature independent. In contrast, in Fig. 6 $Q_c(1+T_h/T_c)$ has a slight frequency dependence and a large temperature dependence. The frequency dependence is likely due

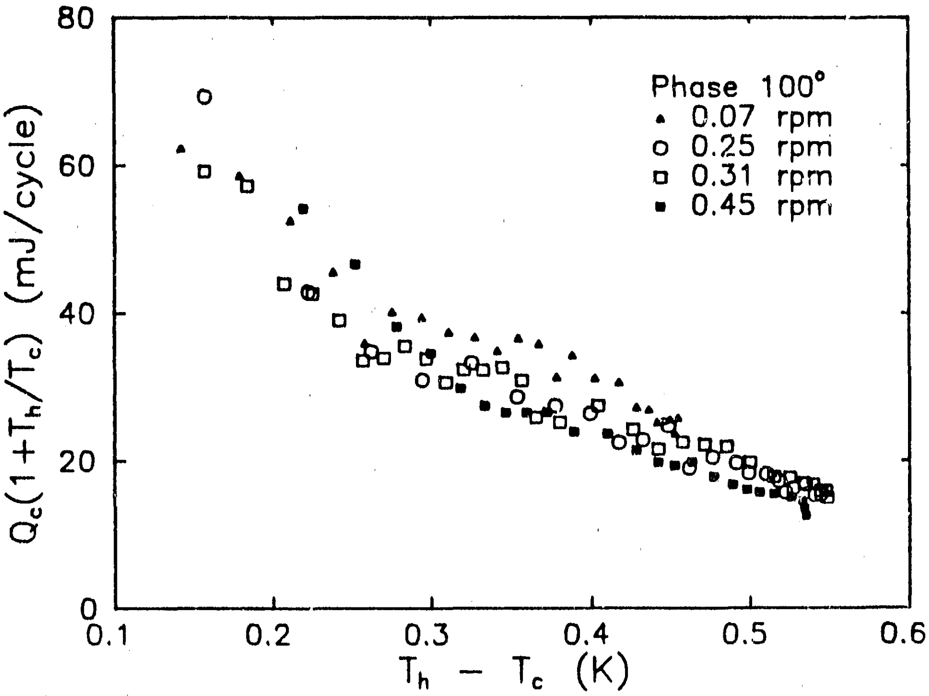

Fig. 6. $Q_c(1+T_h/T_c)$ vs the temperature difference between the compressor and expander. For a reversible, ideal-gas Stirling cycle refrigerator, this quantity is independent of temperature. The temperature dependence in this figure reflects the non-ideality of our prototype. We use T_h-T_c, rather than T_c, as abscissa because the compressor temperature was not well regulated, varying from 1.16 K at the slowest speed to 1.23 K at the highest speed.

either to viscous losses or imperfect thermal contact in the regenerator[9], as both processes are velocity dependent. But the large deviation from constancy with temperature in Fig. 6, corresponding to about 25 mJ/cycle of lost cooling power at the lowest temperatures, must be due to processes that are independent of velocity. We list several candidates here.

The most likely source of inefficiency is the dependence of the heat capacity of the ^{3}He solute on number density[10]. As the ^{3}He concentration increases, the heat capacity per ^{3}He atom deviates from the ideal gas value of $(3/2)k_bT$. This causes a parasitic flow of heat down the regenerator since the heat capacity, and therefore the amount of heat transported, are different on the high concentration and low concentration strokes of a cycle. The heat flow due to this effect[11] is $\pi/2\ \partial c/\partial X\ V_1\,\Delta X \Delta T$, where ΔX is the concentration amplitude and ΔT is the temperature difference between the hot and cold ends of the regenerator. At our lowest temperatures, we estimate this heat load to be about 20 mJ/cycle.

Another irreversible mechanism is that, in the ideal Stirling cycle, the compressions and expansions are isothermal. In our refrigerator, since the thermal penetration depths are on the order of the dimensions of the fluid volumes within the pistons, the compressions are partially adiabatic, and so there is irreversible heat transfer across finite temperature differences[12], such as when the fluid enters the regenerator. The excess entropy generated in this process is $\Delta S \simeq \rho c V \delta T^2/T$, where ρ is the fluid density, c is the heat capacity per mass, V is the volume of fluid displaced into the regenerator, δT is the temperature amplitude in the piston, and T is the temperature of the piston. The work is $T\Delta S$, and is about 1 mJ per cycle at the lowest temperatures, not large enough to account for the losses, and without the strong temperature dependence observed in Fig. 6.

Finally, there are effects in the SSR that are unique to it, not occurring in ideal gas Stirling refrigerators. These include superfluid turbulence[13], where the turbulent state consists of a tangle of quantized vorticity; the heat-flush effect discussed above; and the ^{4}He normal-fluid excitations, which are numerous near 2 K.

Clearly, there is much about the SSR that we do not yet understand.

LIMITATIONS AND IMPROVEMENTS

The ultimate performance of the SSR will be limited by the thermodynamics of the ^{3}He solute as it approaches complete Fermi degeneracy[2] at low temperatures, at concentrations at or below the low-temperature solubility of 6.4%. For example, in a 5% solution, the Fermi temperature is 0.34 K; so that, at about 50 mK, the cooling power of a fixed-volume-displacement SSR is only half what it would be for a classical gas of the same number density, and rapidly drops to zero at lower temperatures.

Many improvements to the SSR seem possible by analogy with ideal-gas Stirling refrigerators. A single stage may ultimately span an order of magnitude in temperature, and two-stage SSRs could reach very low temperatures. A dual-parallel SSR could eliminate the need for the pure ^{3}He heat reservoir: Two SSRs running at the same average temperatures but 180° out of phase in time could regenerate each other. An orifice-pulse-tube[14] configuration would be an exceeding important practical advance, as it would eliminate the moving parts at T_c. Elimination of the remaining moving parts could then be accomplished by use of a thermocompressor.

APPLICATIONS AND ADVANTAGES

Since satellite-borne infrared and X-ray sensors work best at low temperatures, some effort is now spent on adapting dilution refrigeration[15] and demagnetization refrigeration to the space environment. However, both of these conventional methods for cooling below 1 K have drawbacks in the space environment. Both are inefficient; the first doesn't naturally work in zero gravity; the second requires large magnetic fields. As the SSR works quite independently of gravity and magnetism, and has immediate potential for an efficiency of the order of Carnot's efficiency, further development may demonstrate its utility for sub-1-K cooling in space.

Most of the cost in the earth-bound dilution-refrigerator industry is for large room-temperature plumbing and pumps; these will not be required in the SSR, which may be much less expensive as a result. This low cost could make low-temperature research easier everywhere, and feasible for the first time at small colleges and in developing countries. The high efficiency offered by the SSR would also be a modest advantage in this arena; the \$100-\$200 per week electric bill for operation of a typical dilution refrigerator is a significant cost to some researchers.

ACKNOWLEDGMENT

This work is supported by the Division of Materials Sciences in DOE's Office of Basic Energy Sciences.

REFERENCES

1. O.V. Lounasmaa, *Experimental Principles and Methods Below 1 K*, Academic Press, New York (1974).

2. J. Wilks, *The Properties of Liquid and Solid Helium*, Clarendon Press, Oxford (1967).

3. H. London, discussion, Proc. Int. Conf. Low Temp. Phys., Oxford, 1951, p. 157.

4. G. Walker, *Cryocoolers*, Plenum, New York (1983).

5. L.E. DeLong, O.G. Symko, and J.C. Wheatley, "Continuously operating ^{4}He evaporation refrigerator", Rev. Sci. Instrum., vol. 42 (1971) p. 147-150.

6. H.A. Kierstead, "Dielectric constant, molar volume, and phase diagram of saturated liquid ^{3}He-^{4}He mixtures", J. Low. Temp. Phys., vol. 24 (1976) p. 497-512.

7. D. Gestrich, R. Walsworth, and H. Meyer, "Transport properties in ^{3}He-^{4}He mixtures near the superfluid transition", J. Low Temp. Phys., vol. 54 (1984) p. 37-61.

8. I. Urieli and D.M. Berchowitz, *Stirling Cycle Engine Analysis*, Adam Hilger Ltd., Bristol (1984), Fig. 2.18.

9. P.C. Allen, G.H. Fisher, W.R. Knight, D.N. Paulson, and J.C. Wheatley, "Heat regeneration in Malone-type liquid engines using a parallel-plate thermodynamic pile geometry", J. Appl. Phys., vol. 52 (1981) p. 3876-3883.

10. D.O. Edwards, D.F. Brewer, P. Seligman, M. Skertic, and M. Yaqub, "Solubility of ^{3}He in ^{4}He at 0 K", Phys. Rev. Lett., vol. 15 (1965) p. 773-775.

11. P.C. Allen, W.R. Knight, D.N.Paulson, and J.C.Wheatley, "Some heat engine cycles in which liquids can work", Proc. Natl. Acad. Sci. USA, vol. 77 (1980) p. 31-35.

12. Ref. 8, ch. 4.

13. J.T. Tough, "Superfluid turbulence", *Progress in Low Temperature Physics*, D.F. Brewer, ed., North Holland, Amsterdam (1982), vol. 8, p. 133-219.

14. R. Radebaugh, "A review of pulse tube refrigeration", *Advances in Cryogenic Engineering*, Plenum, New York (1990), vol. 35, p. 1191-1205.

15. U.E. Israilsson, D. Petrac, H.W. Jackson, and D.M.Strayer, "Use of an electric field gradient instead of gravity to obtain a suitable ^{3}He-rich/^{4}He-rich interface in the mixing chamber of a dilution refrigerator"; and P.R. Roach, "Thermal efficiency of a zero-g dilution refrigerator", Proc. Int. Cryocooler Conf. 5, Monterey CA, 1988, p. 187-204.

END

DATE FILMED

11 / 27 / 90