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LA-UR- 93-1420

Title: **The Superfluid Stirling Refrigerator: a new Method for Cooling Below 0.5 K**

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Submitted to: As contributed full paper to be presented at the 20th International Conference on Low-Temperature Physics, Eugene, OR, 4-11 AUG 93

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THE SUPERFLUID STIRLING REFRIGERATOR, A NEW METHOD FOR COOLING BELOW 0.5 K

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Full paper contributed to the 20th International Conference on Low Temperature Physics, Eugene, OR, 4-11 AUG 93
Submitted 4/9/93
LA-UR-93-

A new subkelvin refrigerator, the superfluid Stirling cycle refrigerator, uses a working fluid of ^{3}He-^{4}He mixture in a Stirling cycle. The thermodynamically active components of the mixture are the ^{3}He, which behaves like a Boltzman gas, and the phonon-roton gas in the ^{4}He. The superfluid component of the liquid is inert. Two refrigerators have been built and temperatures of 340 mK have been achieved.

The superfluid Stirling refrigerator, a new method for cooling below 0.5 K

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A new subkelvin refrigerator, the superfluid Stirling cycle refrigerator, uses a working fluid of ^{3}He-^{4}He mixture in a Stirling cycle. The thermodynamically active components of the mixture are the ^{3}He, which behaves like a Boltzman gas, and the phonon-roton gas in the ^{4}He. The superfluid component of the liquid is inert. Two refrigerators have been built and temperatures of 340 mK have been achieved.

1. INTRODUCTION

The superfluid Stirling refrigerator (SSR) uses a ^{3}He-^{4}He working fluid in a Stirling cycle[1] to cool below 0.5 K. The thermodynamically active components of the mixture are the ^{3}He, which behaves like an ideal gas, and the phonon-roton gas of excitations in the ^{4}He. The superfluid component of the mixture acts as an inert background. action of the refrigerator.

The SSR is equipped with pistons that are bypassed with superleaks. Since the superfluid component of the mixture freely flows through these superleaks, the compressions and expansions are performed only on the normal components of the ^{3}He-^{4}He mixture.

This refrigerator has several advantages over other methods of continuously cooling below 0.5 K. The Stirling refrigerator does not have expensive sealed pumps required by dilution and ^{3}He refrigerators. It does not generate the high magnetic fields of a demagnetization stage. The SSR is efficient; the refrigerator delivers microwatts of cooling power for tens of watts of drive power. The SSR does not require modification to work in a zero gravity environment; this, coupled with its low power consumption, makes the refrigerator ideal for sub-Kelvin applications in space.

2. THE STIRLING CYCLE

Fig. 1 shows a practical Stirling refrigerator. The machine consists of a hot and cold piston connected by a regenerator, an array of narrowchannels through a material with a large heat capacity. Initially the working fluid, a low pressure ideal gas, is in the hot cylinder, and the cold piston is in its fully inserted position. The gas is compressed isothermally in the hot cylinder, rejecting its heat to a thermal reservoir. Both pistons are then moved in tandem so that the gas reversibly (and isochorically) dumps heat to the regenerator as it travels from high to low temperature. The low temperature gas is now allowed to isothermally expand in the cold cylinder, absorbing heat from a low temperature reservoir. The pistons now move to isochorically force the gas back through the regenerator reabsorbing the heat deposited there earlier. The refrigerator is now back in the original state and is ready repeat the cycle.

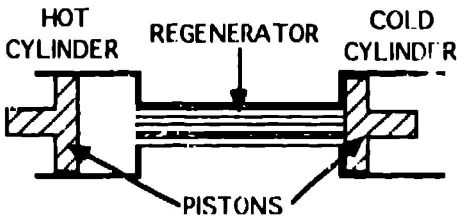

Figure 1. A schematic diagram of a standard Stirling refrigerator.

3. THE FIRST REFRIGERATOR

Fig. 2 shows a schematic diagram of the first SSR[2,3]. The hot piston is held at 1.2K by a pumped ^{4}He pot. The regenerator consists of thirty 200 micron-ID CuNi capillaries immersed in a pure ^{3}He bath, which supplies the heat capacity required in the regenerator. Each piston is made with two nickel bellows which are connected by a superleak made with Vycor glass. The regenerator side of each piston contains the ^{3}He-^{4}He working fluid; whereas, the back side of each piston acts as reservoir for the superfluid ^{4}He that flows through the superleak.

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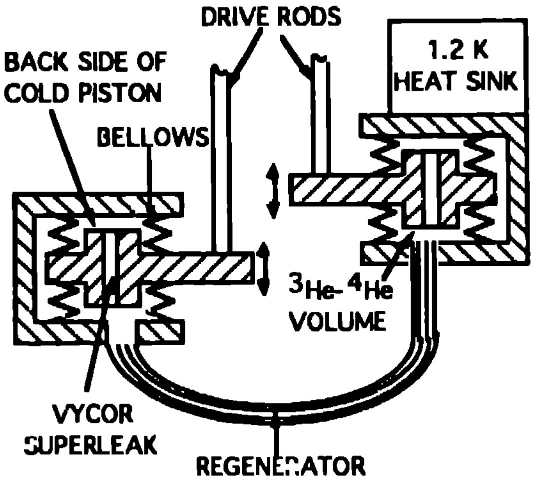

Figure 2. A schematic of the first SSR. The double arrows indicate the motion of the the pistons.

This refrigerator was operated at typical speeds of 0.25 rpm (4 minutes per cycle) with piston volume displacements of 0.9 cm^3 and typical ^{3}He concentrations of 12%.

The ultimate temperature reached by this refrigerator is 590 mK. The net cooling power of this refrigerator at 700 mK is approximately 5 μW.

4. THE SECOND REFRIGERATOR

Fig. 3 is a schematic diagram of the second SSR[4]. This SSR consists of two refrigeratorsthat operate 180° apart from each other. The pistons are double acting, and the regenerator is a heat exchanger between the counterflowing fluids in each half of the SSR. The regenerator consists of a total of 238 250-micron ID 40 micron-wall thickness CuNi capillaries silver soldered in a hexagonally close packed array with alternating rows corresponding to each half of the SSR. The pistons are made from welded bellows with nested convolutions to minimize the clearance volume in the piston. The ^{3}He-^{4}He working fluid resides on both sides of the pistons.

This refrigerator was operated at typical speeds of 4 rpm (20 seconds per cycle) with piston volume displacements of 0.8 cm^3 and typical ^{3}He concentrations of 6.6%. The volume in each half of the refrigerator is 7 cm^3

The ultimate temperature reached by this refrigerator to date is 340 mK. The net cooling power of this refrigerator is approximately 160 μW at 700 mK and approximately 50 μW at 500mK.

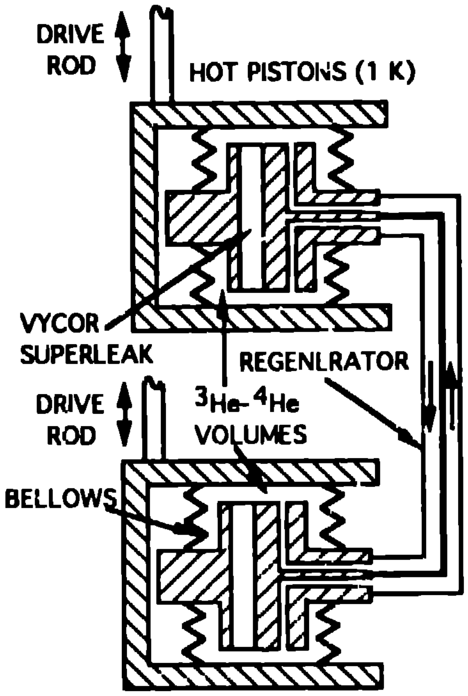

Figure 3. A schematic of the second SSR. The double arrows indicate the motion of the drive rods. The arrows in the regenerator indicate the counterflow in each half of the regenerator.

5. CONCLUSIONS AND FUTURE WORK

There are effects at both high and low temperatures that make the working fluid behavior deviate from that of an ideal gas. At high temperatures the excitations in the ^{4}He contribute, and at low temperatures the ^{3}He becomes a Fermi gas. We hope to characterize and understand both phenomena in the SSR.

We have demonstrated the viability of the superfluid Stirling refrigerator. The SSR has cooled continuously to temperatures of 340 mK and shows much promise of achieving lower temperatures.

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