A Superfluid Pulse Tube Driven by a Thermodynamically Reversible Magnetic Pump

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ABSTRACT

A concept for a superfluid pulse tube refrigerator that uses a ^{3}He - ^{4}He mixture as the working fluid is described. The proposed pulse tube refrigerator will be driven by a novel, thermodynamically reversible, magnetic pump that is currently being developed at the Goddard Space Flight Center. This pump consists of a volume packed with a paramagnetic material that is surrounded by a superconducting magnetic coil. Estimates of the performance of this pump are used to develop a preliminary design for a proof-of-concept superfluid pulse tube refrigerator that requires no moving parts.

INTRODUCTION

The idea of using a ^{3}He-^{4}He mixture to run low temperature Stirling cycles was invented by Kotsubo and Swift[1] at Los Alamos National Laboratory. The theoretical basis for these cycles was the idea that ^{3}He behaves like an ideal gas in an inert background of ^{4}He when it is in solution in superfluid ^{4}He in low concentrations at temperatures around 1K. Below 1.0 K the ^{4}He in the mixture is almost all in the ground state and is therefore thermodynamically inert. The ^{3}He dispersed at low concentration throughout the mixture does not interact with the ^{4}He and at low concentrations the interaction potentials between the ^{3}He atoms is also negligible. Therefore, the ^{3}He essentially behaves like an ideal gas.

Several superfluid Stirling machines were built and tested at Los Alamos and at the MIT Cryogenics Engineering Laboratory. These refrigerators all used displacers constructed with a bellows to compress, expand and displace the fluid. Because the helium has a high heat capacity compared to typical solid materials at these temperatures the most successful machines had recuperators rather than the regenerators typically seen in standard Stirling machines. This recuperative cycle was implemented by running two Stirling cycles 180 degrees out of phase and allowing the fluid flow in one cycle to act as the regenerative heat capacity for the flow in the other.[2] Further developments to the superfluid Stirling included multistaging[3] and plastic heat exchangers.[4] The plastic heat exchangers were introduced to reduce the Kapitza resistance between the helium working fluid and the solid walls of the recuperative heat exchanger.[5,6]

The superfluid Stirling machines require no gravity for operation. This would appear to make this cycle a good candidate for a low temperature flight cooler. However, the recuperative Stirling design required four bellows piston assemblies per stage. This high number of moving parts made the reliability a significant concern and the superfluid Stirling machines were not considered good candidates for further development for space flight.

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In 1996 the groups at Los Alamos and MIT built and tested a proof-of concept superfluid orifice pulse tube refrigerator.[7] This design eliminated the need for pistons on the cold end of the Stirling cycle by replacing the cold pistons with pulse tubes. Instead of using pistons to extracting work at the cold end of the machine the pulse tube acts as a gas piston and the work is dissipated in flow though an orifice at the warm end of the tube. The efficiency degradation due to the dissipation is small because the entropy generated in the orifice does not need to be lifted by the cycle.

Eliminating all of the moving parts in the Stirling cycle could be achieved by introducing a thermal pump at the warm end of the machine. One possible design would use a heater and a weak thermal link to the precooling stage. This pump would operate by turning the heater on to increase the temperature and consequently the pressure due to the ^{4}He fountain effect. Turning off the heater and allowing the pump to cool via the weak thermal link would complete the pump cycle. However, this process is inefficient because the entropy that is generated during the heating part of the cycle must be rejected to the precooling stage via the weak thermal link for each pump cycle. Another disadvantage of this configuration is that the pump cycle time must be fixed and must match the design of the weak thermal link.

A pump that we are currently developing at NASA Goddard will eliminate this irreversibility and still allow pumping with no moving parts. This pump consists of a bed packed with paramagnetic material with void space for the working fluid. A superconducting magnetic coil surrounds the bed. Changing the current in the coil changes the magnetic field and therefore the temperature of the paramagnetic material due to the magnetocaloric effect. Because the fluid in the pump body is in good thermal contact with the paramagnetic material its temperature tracks that of the paramagnetic material.

As the magnetic field increases the magnetic entropy in the paramagnetic material decreases causing the thermal entropy of the material and the fluid to increase resulting in an increase in temperature. When the field is reduced the magnetic entropy in the paramagnetic material increases causing the temperature of the material and fluid to decrease. This process is reversible because the entropy used to increase the fluid temperature during the high-pressure part of the pump cycle comes from the magnetic entropy of the paramagnetic material and can be returned to the material when the magnetic field is reduced. This eliminates the need for the thermal link to the precooling stage and the need to lift of all of generated entropy that would result from a heater. This new type of pump is thermodynamically reversible in its theoretical limit.

The result of combining the superfluid pulse tube concept and the magnetic thermal pump is an efficient sub-Kelvin refrigerator that will require no moving parts and will therefore be suited for use as a low-temperature flight cooler.

PRELIMINARY DESIGN

Pump Concept

We are currently developing a proof of concept model of the reversible magnetic pump. A diagram of the pump is shown in Figure 1. The pump consists of two canisters packed with Gadolinium Gallium Garnet (GGG) spheres that are connected by a superleak (a porous piece of Vycor glass). A superconducting magnetic coil surrounds each of the canisters.

Our preliminary calculations show that this pump will be very effective at producing high pressures for modest fluid temperature change because of the thermo-mechanical (fountain) effect in superfluid ^{4}He. The fraction of normal fluid which contributes to the pressure in the superfluid mixture is a strong function of the temperature in the 1.4 K to 1.8 K range.

Using the relation:

$$P_f(T) = \frac{1}{V}\left[BT^4 + AT^{\frac{3}{2}} e^{\frac{-\Delta_1}{T}} + Ce^{\frac{-\Delta_2}{T}} \right], \quad where \tag{1}$$

$$A = 23.2 J/mol,\ B = 6.75\times 10^{-6}\ J/mol\ K^4,\ C = 500\ J/mol,$$

$$\Delta_1 = 8.65\,K,\ \Delta_2 = 15.7\,K,\ V = 27.58\times 10^{-6}\ m^3/mol$$

for the thermo-mechanical (fountain) effect in superfluid ^{4}He we calculate a pressure ratio of greater than 4.0 for temperature swing in the pump bed from 1.4 K to 1.8 K.[8] The ^{4}He fountain pressures at 1.8 K and 1.4K are calculated to be 1.68 bar and 0.41 bar respectively.

One of our concerns was the relative magnitudes of the specific entropy change for the GGG and the fluid contained in the bed during the pump cycle. If the heat capacity per unit volume of fluid is high compared to that of the GGG a simple bed of packed spheres with high void volume would not work. In that case a very carefully structured bed with low void volume would be needed. We calculated the entropy change per unit volume for the GGG going from 0 field and 1.4 K to 1.5 Tesla and 1.8 K. This change is - 0.134 J/(cm^3 K). The entropy change for ^{3}He-^{4}He mixture with a 3% ^{3}He concentration going from 1.4 K to 1.8 K is 0.057 J/(cm^3 K). This calculation shows that a simple packed bed with a void volume of the order of 30% will work well for this pump.

Our preliminary calculations show that a bed that is 4.5 cm in diameter by 7.5 cm long can produce approximately 25 mW of PV power when operating with a 0 Tesla to 1.5 Tesla magnetic field change and a cycle time of approximately 100 seconds. This calculation shows that the size of the pump assembly needed to drive the pulse tube will be reasonable.

The pump cycle operates in the following way. The current in one coil is increased while the current in the other is decreased. This causes the magnetic field in one bed to increase while the magnetic field in the other decreases. As the field increases in the paramagnetic GGG spheres the magnetic entropy decreases causing the thermal entropy in the spheres and the surrounding fluid to increase (the temperature increases). At the same time the field in the other bed is decreasing so the temperature of the spheres and fluid in the other bed decreases. Using two beds configured in this way connected by a superleak allows high pressure fluid to flow out of the port of the high temperature bed and low pressure fluid to flow into the low temperature bed. The superleak allows superfluid ^{4}He to flow between the pump beds so that continuity is satisfied. The flow is reversed by decreasing the current in the coil that was increasing in the first half of the cycle causing fluid to flow into that bed and out of the other.

Superfluid Pulse Tube Concept

A schematic of the proposed superfluid pulse tube refrigerator is shown in Figure 2. The refrigerator consists of a reversible thermal magnetic pump module, two warm heat exchangers, a recuperative heat exchanger, two cold heat exchangers, two pulse tubes and an orifice. This machine is really two superfluid pulse tube refrigerators that run 180 degrees out of phase. The flow from one machine exchanges heat with flow from the other in the recuperator. This technique is used because most solid regenerator materials do not have significant heat capacity compared to the helium working fluid at temperatures below 1 Kelvin. A large mass of solid regenerator material would be required and heat transfer would be inefficient due to thermal penetration depth problems.

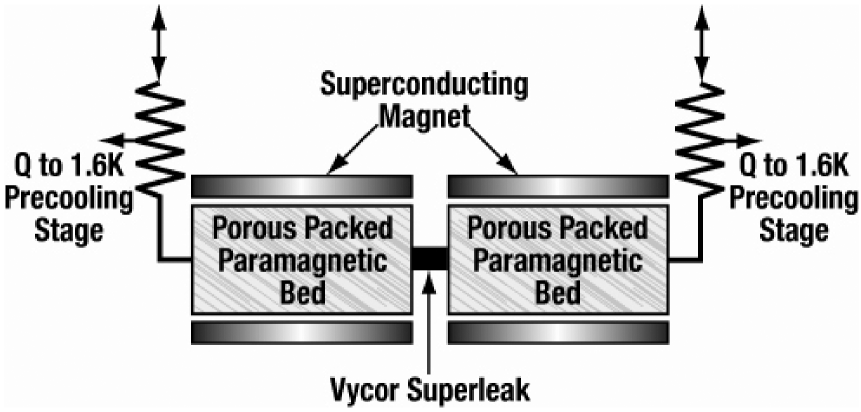

Figure 1. Schematic of the thermodynamically reversible magnetic fountain effect pump.

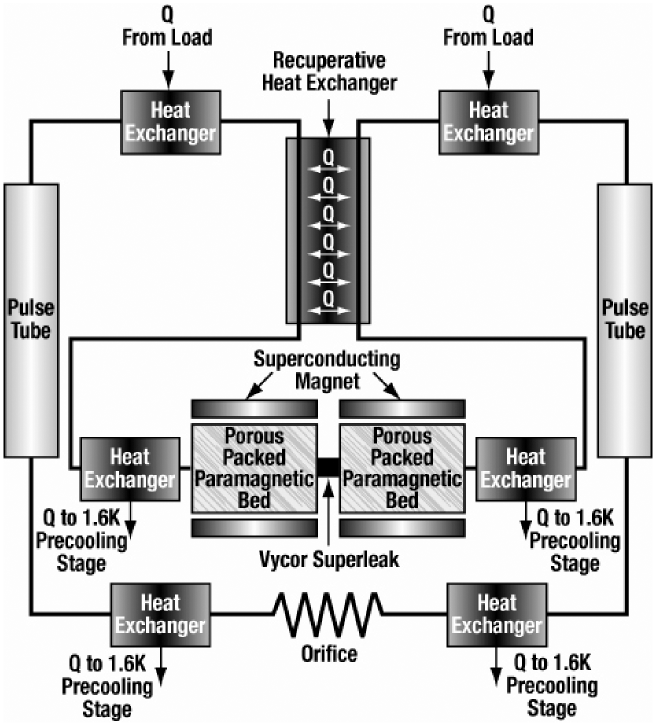

Figure 2. Schematic of the Superfluid Pulse Tube Refrigerator. This refrigerator will provide efficient and reliable cooling below 0.5 Kelvin without moving parts.

All components of this machine except the reversible thermal pump have been demonstrated at least as proof-of concept physical models in previous superfluid Stirling cycle machines. The earlier superfluid Stirling machines used bellows pistons on the warm end to drive the Stirling cycle. The reversible pump is the key technology that must be developed in order to realize a superfluid Stirling cycle with no moving parts. This pump is currently being developed at Goddard Space Flight Center.

One possible physical configuration for the superfluid pulse tube refrigerator is shown in Figure 3. The design of the superconducting coils is based on existing coil designs used in adiabatic demagnetization refrigerators (ADRs) built at Goddard Space Flight Center. These coils are capable of producing average fields of 1.5 Tesla in the bore of the magnet with a current less than 2 A.[9] The paramagnetic bed design, which uses GGG as the paramagnetic material, is based on that of a proof of concept pump that is currently in development at Goddard. The recuperative heat exchanger design is based on the plastic heat exchangers used in the superfluid Stirling refrigerators developed at the MIT Cryogenics Engineering Laboratory.[4] The pulse tube dimensions are based on those from the superfluid pulse tube work done at Los Alamos.[7]

CONCLUSIONS

We have proposed a new concept for sub-Kelvin cooling that will be thermodynamically efficient and requires no moving parts. The key technology that makes this new refrigerator possible is a novel thermodynamically reversible fountain effect pump that is currently in development at Goddard Space Flight Center. Because of the potential for high efficiency and the high reliability this refrigerator could be useful for sub-Kelvin cooling in future space flight missions.

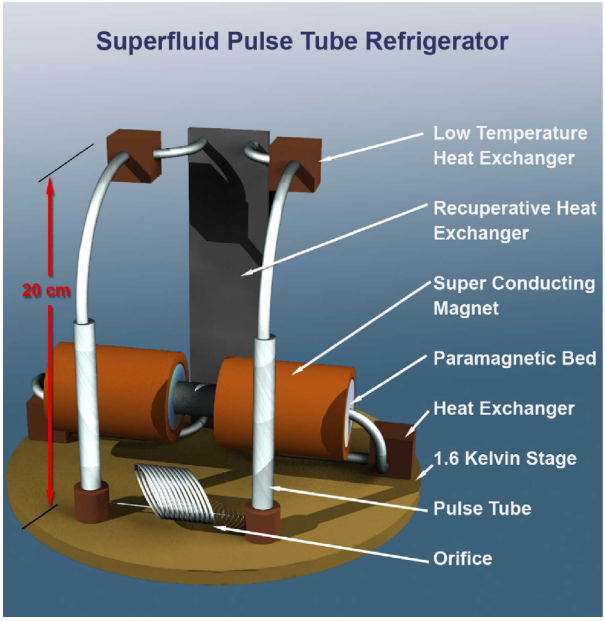

Figure 3. Schematic of the Superfluid Pulse Tube Refrigerator. This refrigerator will provide efficient and reliable cooling below 0.5 Kelvin without moving parts

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