Journal of Low Temperature Physics, Vol. 111, Nos. 1/2, 1998

Experimental Performance of a Single Stage Superfluid Stirling Refrigerator Using a Small Plastic Recuperator

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(Received November 18, 1997)

The experimental performance of the first superfluid Stirling refrigerator (SSR) to use a plastic recuperator is reported. This SSR is a single stage machine, has a total internal volume of 83 cm^3, and uses a 3 cm^3 Kapton heat exchanger. Operating from a high temperature of 1.0 K and with a 1.5% ^{3}He–^{4}He mixture, this SSR achieves a low temperature of 344 mK and delivers net cooling powers of 1.86 mW at 750 mK, 358 μW at 500 mK, and 97 μW at 400 mK. Cooling power versus cold piston temperature for various frequencies of operation and for two piston stroke configurations are provided.

1. INTRODUCTION

The superfluid Stirling refrigerator (SSR) uses the Stirling cycle and a working fluid of liquid ^{3}He–^{4}He to provide cooling below 2 K. To first approximation, the ^{3}He component of the working fluid behaves as an ideal Boltzmann gas in an inert background of superfluid ^{4}He. The pistons of the SSR are bypassed with superleaks so that only the ^{3}He component of the working fluid goes through the Stirling cycle. The thermodynamically inert ^{4}He component of the working fluid is free to flow through the superleaks. A more detailed explanation of the cycle is given by Watanabe, Swift, and Brisson.[1]

The SSR was first demonstrated in 1990 by Kotsubo and Swift[2,3] (K & S). Their refrigerator used a regenerator that consisted of thirty 200 micron ID CuNi capillaries immersed in pure liquid ^{3}He. The refrigerator ran with typical speeds of 0.25 rpm (4 minutes per cycle), typical volume displacements of 0.9 cm^3 and typical ^{3}He concentrations of 12%. The

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refrigerator exhausted its waste heat to a pumped ^{4}He pot at 1.2 K. It achieved temperatures of 590 mK and a net cooling power of 5 μW at 700 mK.

Brisson and Swift[4] (B & S) realized the achievable cooling power of the K & S machine was limited by the regenerator and built a recuperative SSR that consisted of two Stirling refrigerators operating 180 degrees out of phase with each other. These two refrigerators regenerated each other by using a counterflow heat exchanger (the recuperator). This recuperator consisted of 238 250 μm ID CuNi capillaries silver soldered in a hexagonally close packed array with alternating rows corresponding to each half of the SSR. The use of convective heat transfer in a recuperator rather than diffusive heat transfer used in the K & S regenerator design allowed higher operating speeds and a corresponding increase in the refrigerator's cooling power. The B & S refrigerator had typical operating speeds of 3 rpm (20 seconds per cycle), typical volume displacements of 0.8 cm^3, and typical ^{3}He concentrations of 6.6%. The refrigerator exhausted its waste heat to a pumped ^{4}He pot at 1.05 K and achieved an ultimate temperature of 296 mK. Cooling powers of 930 μW at 750 mK and 140 μW at 500 mK were demonstrated. Operating the same SSR, Watanabe, Swift and Brisson[5] demonstrated cooling to 168 mK while exhausting heat at 387 mK to a ^{3}He evaporation refrigerator.

Previous work on the SSR was intended only as a demonstration of the Stirling cycle at low temperatures. For the SSR to become a practical refrigerator, higher cooling powers and lower ultimate temperatures must be achieved. These goals, however, require that the efficiency of the SSR's recuperators be increased, especially at lower temperatures.

The main obstacle to low temperature, high efficiency recuperators is the Kapitza boundary resistance. Kapitza boundary resistances dominate the overall heat transfer coefficient in heat exchangers at low temperatures. To mitigate this effect, previous workers[6] used sintered-metal heat exchangers to increase the thermal contact in dilution refrigerator heat exchangers. Unfortunately, these sintered heat exchangers can not be used in a SSR due to their large internal volumes. Large internal volumes in a SSR result in a reduced pressure oscillation and, consequently, reduced cooling. There is no such effect in dilution refrigerators.

Frossati and co-workers[7-9] developed and demonstrated a novel approach towards mitigating Kapitza resistance effects in low temperature heat exchangers by using plastics. Frossati realized that the Kapitza resistance between helium and plastics is lower than that of helium and metals and that thin plastic membranes between two helium flows have better heat transfer characteristics than a corresponding metal heat exchanger at low temperatures.

Our analysis of recuperator designs for superfluid Stirling refrigerators[10] results in our adoption of a plastic recuperator design. Our models suggest that above 600 mK metal recuperators will slightly out-perform plastic recuperators of similar geometry; however, below 600 mK, properly designed plastic heat exchangers will out-perform metal heat exchangers. Additionally, plastic recuperators are ten times cheaper to build than metal recuperators of the same size ($1,200 total cost for the plastic recuperator used with this SSR versus $10,000 material cost for a similarly sized metal recuperator).

In this paper, we describe the experimental performance of the first SSR to use a plastic recuperator. This high cooling power SSR markedly out-performs all previous SSR's at high temperatures. Operating from high temperatures about 1.0 K and with a typical ^{3}He concentration of 1.5%, cooling powers of 1.86 mW at 750 mK, 358 μW at 500 mK, and 97 μW at 400 mK are measured, and an ultimate low temperature of 344 mK is achieved.

2. DESCRIPTION OF THE SSR

Figure 1 shows a schematic of our SSR. This refrigerator is of the B & S type having two SSR's operating 180 degrees out of phase with each other and using a counterflow recuperator as the regenerator. The SSR consists of a hot (compressor) platform connected to a cold (expander) platform by a Kapton recuperator. We refer to this machine as a single stage SSR because it has only a single expander platform and because this SSR's expander platform will eventually serve as the upper expander of a two expander machine called the two stage SSR.[10]

The hot and cold platforms of this SSR are made of solid blocks of OFHC copper on which pistons are mounted. The pistons are made with edge welded stainless steel bellows[11] which have convolutions that nest into one another to minimize void volume. The effective areas of the pistons, based on the manufacturer's specifications, are 17.74 cm^2 for the hot platform pistons and 13.16 cm^2 for the cold platform pistons. The hot platform pistons are rigidly connected together and driven sinusoidally using a push rod from a room temperature drive. The cold platform pistons are similarly connected and driven. The hot platform temperature is pinned at approximately 1.0 K by a ^{4}He evaporation refrigerator.

Within each piston platform, there are superleaks made from porous Vycor glass which allow the superfluid ^{4}He to freely flow between the halves of the SSR during operation. In the hot platform, the superleaks are three Vycor cylinders 6.03 cm in length with diameters of 1.39 cm, 1.35 cm, and 0.72 cm. In the cold platform, the superleaks are three Vycor cylinders

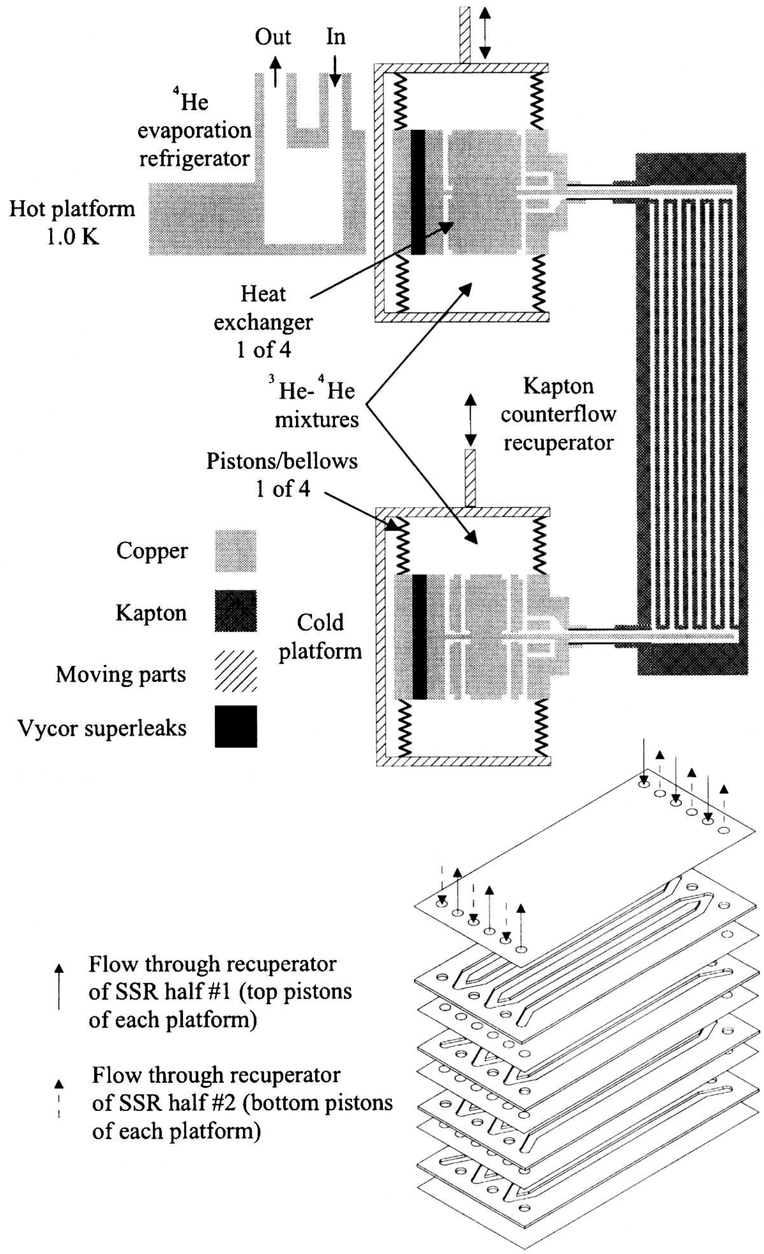


Fig. 1. Diagram of SSR. The top portion of the figure shows a cross sectional view of the SSR. The bottom portion shows how alternate layers of Kapton film are arranged within the recuperator to form a counterflow heat exchanger.

10.63 cm in length with diameters of 0.74 cm. The large number of Vycor cylinders in the platforms provide a total superleak cross sectional area of 4.63 cm^2 and allow the SSR to run at higher speeds and higher temperatures and with larger volume displacements than previous SSR's without exceeding ^4He critical velocities.[12] The total volume of the Vycor glass in the SSR is 33.8 cm^3. Since 28% of the Vycor glass is void space,[13] the glass contributes 9.5 cm^3 to the total ^3He–^4He mixture volume of the SSR. However, the ^3He that diffuses into this volume does not participate in the operation of the SSR because its diffusion times are substantially longer than the SSR cycle period. This ^3He is effectively trapped and does not undergo either compression or expansion during the SSR cycle.

Within each piston platform, there are also isothermal heat exchangers. These heat exchangers are necessary for the SSR to deliver high cooling powers because most of the expansion (compression) of ^3He within the pistons of a large SSR occurs adiabatically and heat must be added (removed) from the working fluid before it enters the recuperator. To accomplish this, large surface areas are needed to overcome the Kapitza boundary resistance between the copper and the ^3He–^4He mixture. However, this surface area must come with minimal void volume in order to maintain the magnitude of the pressure oscillation within the SSR.

Our SSR's isothermal heat exchangers are made from nested OFHC copper cylinders press fit into the piston platforms. A 76 μm gap exists between the inner wall of an outer cylinder and the outer wall of an inner cylinder. At the top and bottom of each cylinder, there is a flow distributor 0.64 mm deep and 0.32 cm wide around the cylinder circumference. Each half of the hot piston platform contains one cylinder, 2.14 cm in length with a diameter of 3.80 cm, which provides a total heat transfer area of 65.9 cm^2. Each half of the cold piston platform contains two cylinders that provide a total heat transfer area of 210 cm^2. The first cylinder is 3.97 cm in length with a 4.11 cm diameter while the second cylinder is 4.88 cm in length with a 3.52 cm diameter. These heat exchangers are a significant improvement over the heat exchangers used in the B&S SSR. The B&S machine had a 1.14 cm^2 hot platform heat exchanger and a 2.11 cm^2 cold platform heat exchanger with area over volume ratios of 50 cm^{-1} and 78 cm^{-1} respectively. The area over volume ratio of this SSR's heat exchangers is 106 cm^{-1} (which improves to 260 cm^{-1} if the flow distributors are neglected).

The recuperator used in this SSR is a new design made of plastic. A complete description of the construction and design of this type of heat exchanger will be given by Patel and Brisson.[14] The total volume of the recuperator is 10.7 cm^3, of which only 3.0 cm^3 (1.5 cm^3 per SSR half) is devoted to recuperative heat transfer. The recuperative portion of the heat exchanger consists of alternating layers of 127 μm Kapton[15] film and

25 μm Kapton film glued together using Stycast 1266.[16] Each 127 μm layer has five passages 2.38 mm in width and 20 cm in length. As shown in Fig. 1, ten 127 μm layers, separated by nine 25 μm layers, form 50 flow passages (25 per SSR half) which are arranged in a counterflow heat exchanger pattern.

The total volume of the SSR including the ^{3}He–^{4}He mixture trapped in the Vycor superleaks is 83.0 cm^3. Excluding the volume trapped in the Vycor, the SSR's volume is 73.6 cm^3 (36.8 cm^3 per SSR half).

The two fill lines into each of the SSR halves are sealed at low temperature by valves mounted on the hot platform. These valves are actuated manually from room temperature and are needed to prevent the ^{3}He–^{4}He mixture from moving up and down the fill capillaries during the operation of the SSR. Such a movement would put a significant heat load on the ^{4}He evaporation refrigerator and would also decrease cooling by reducing the magnitude of the pressure oscillation within the SSR.

Calibrated ruthenium oxide thermometers[17] mounted on the outside of the piston platforms are used to monitor the temperature. The precision of our temperature measurements is ± 0.67 mK at 1.0 K and ± 1.02 mK at 350 mK. Cooling powers are measured by monitoring the voltage across and current through a heater made of wound manganin wire mounted on the cold piston platform. The precision of our cooling power measurements is $\pm 2\,\mu$W.

3. PROCEDURE AND RESULTS

The SSR was prepared for operation by first cooling the refrigerator to 1.0 K, then centering the pistons on each platform to ensure equal volumes of working fluid in each SSR half, and finally filling the refrigerator with a 1.5% ^{3}He–^{4}He mixture. The fill lines to the SSR were then closed and the SSR was operated at various speeds using a hot piston stroke of 1.00 cm (17.7 cm^3 volume displacement) and a cold piston stroke of 0.98 cm (12.9 cm^3 volume displacement) to find a minimum temperature of 364 mK at a speed of one cycle every 44 seconds. We then measured cooling power as a function of operating speed and temperature. This was done by measuring the average cold and hot piston temperatures during the cycle at each operating speed while supplying a constant heat load to the cold piston platform. The cold piston stroke was then changed to 0.69 cm (9.1 cm^3 volume displacement) and the above procedure was repeated. An ultimate temperature of 344 mK was achieved at a speed of one cycle every 44 seconds using this piston stroke configuration.

The average piston temperature was determined by averaging the maximum and minimum temperature of the platform during a cycle. The peak to peak temperature difference during a cycle did not exceed 13 mK for the cold piston temperature and 20 mK for the hot piston temperature for any of the operating conditions. Typical values were 6 mK and 12 mK respectively.

Figures 2a and 3a provide a map of the performance of the SSR for the two stroke configurations. These figures show that there is an optimal operating speed for a given cooling power to minimize the cold piston temperature. Figures 2b and 3b give the corresponding hot piston temperature for data shown in Fig. 2a and Fig. 3a. The figures show that the hot piston temperature is kept almost constant for a given operating speed and stroke configuration by the ^{4}He evaporation refrigerator. In Fig. 2b, the hot piston temperatures for runs using the 44 second cycle period are lower than those for the 80 second cycle period because the liquid helium bath supplying the ^{4}He evaporation refrigerator dropped below the level of its filling capillary which reduced the heat load to the evaporation refrigerator.

Figures 2 and 3 show that the stroke configuration with the 0.69 cm cold piston stroke reaches lower ultimate temperatures than the configuration with the 0.98 cm cold piston stroke. Also, at low temperatures and fast operating speeds, the short cold piston stroke configuration delivers higher cooling powers than the long cold piston stroke configuration. There are two possible explanations for these results. The first explanation is that shorter cold piston strokes may reduce recuperator losses more than they decrease the raw cooling power. Shorter cold piston strokes reduce the raw cooling power of the SSR by increasing the void volume and decreasing the magnitude of the pressure oscillation within the SSR. However, shorter cold piston strokes also result in lower mass flow rates through the recuperator and consequently reduced recuperator losses. The second possible explanation for these results is the heating due to bellows flexure. Brisson and Swift[12] observed that bellows heating is linear with operating speed but a very rapidly increasing function of stroke. In their SSR, bellows heating was negligible (on the order of 100 μJ per cycle). Our bellows are not only much larger but operate at higher strokes and frequencies. Although we have not yet been able to experimentally determine the magnitude of the bellows heating in our SSR, we estimate it may be as high as 1 mJ per cycle.

The contribution of phonon-roton gas excitations in the ^{3}He–^{4}He mixture to the cooling of the SSR for cold piston temperatures above 700 mK can be seen in Fig. 4. In the absence of a phonon-roton gas, the cooling power of a SSR should be linear with temperature[12] as shown by the dashed lines. As the cold piston temperature increases, more phonon-roton gas excitations are created which augment the cooling power. Due to their much higher ^{3}He concentrations, this effect was seen in previous SSR's only for cold piston temperatures above 1.4 K.[18]

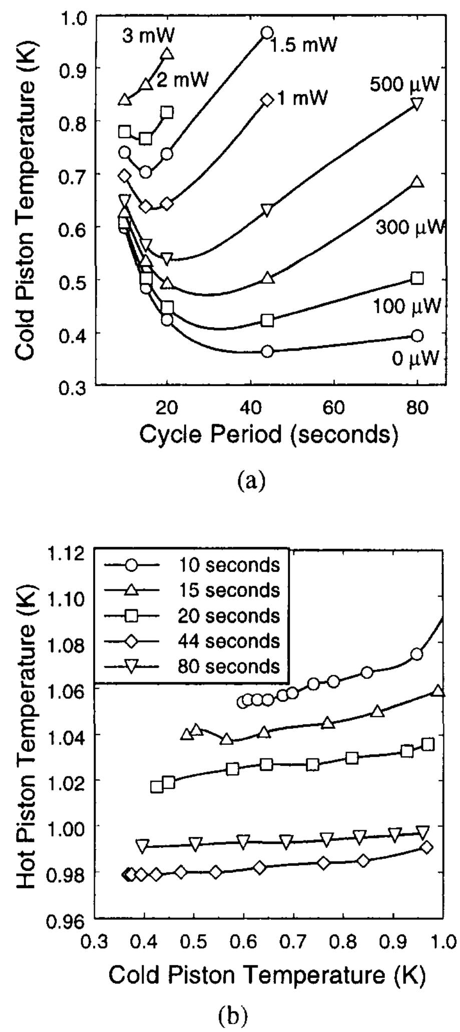
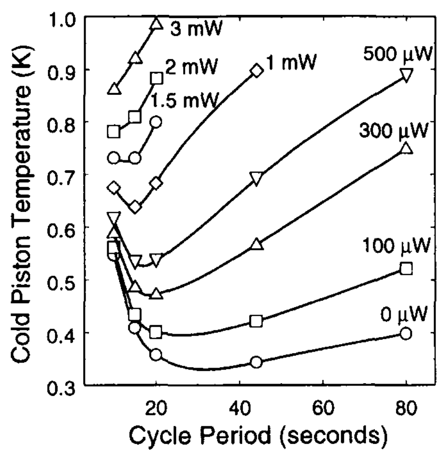
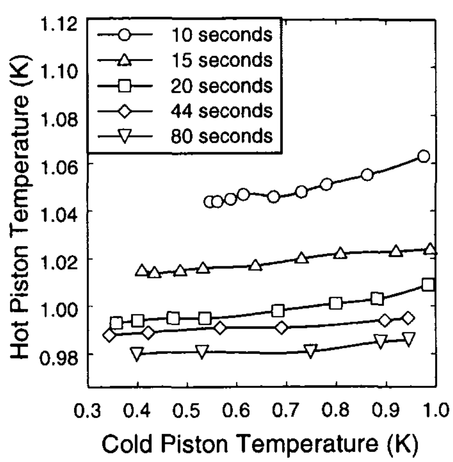


Fig. 2. Data for stroke configuration of 1.00 cm hot piston stroke and 0.98 cm cold piston stroke: (a) cold piston temperature versus cycle period for constant cooling powers and (b) hot piston temperature versus cold piston temperature for various cycle periods.



(a)



(b)

Fig. 3. Data for stroke configuration of 1.00 cm hot piston stroke and 0.69 cm cold piston stroke: (a) cold piston temperature versus cycle period for constant cooling powers and (b) hot piston temperature versus cold piston temperature for various cycle periods.

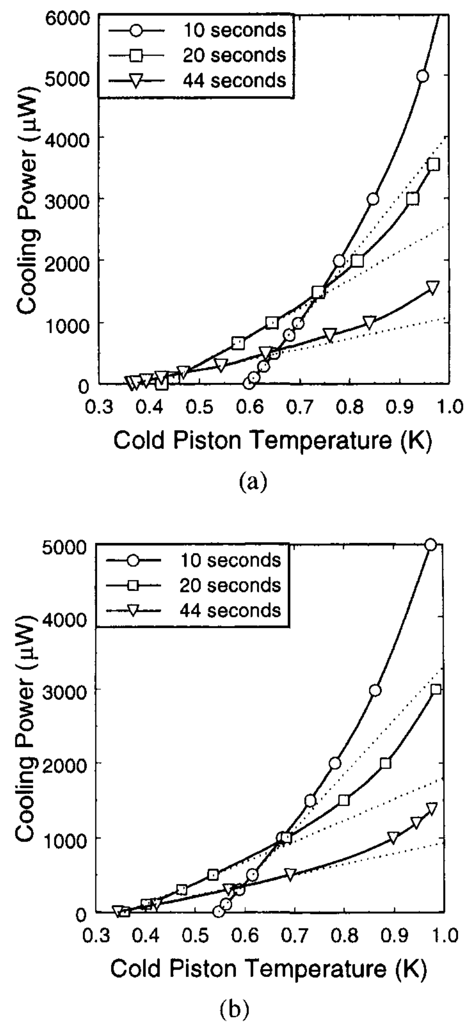


Fig. 4. Cooling power versus cold piston temperature for various cycle periods to show the increase in cooling power at temperatures above 700 mK due to the phonon-roton gas: (a) 1.00 cm hot piston stroke and 0.98 cm cold piston stroke and (b) 1.00 cm hot piston stroke and 0.69 cold piston stroke. The dashed lines show the expected cooling in the absence of phonon-roton gas contributions.

This SSR performs much better than previous SSR's. Due to the smaller percentage of volume devoted to recuperative heat transfer (4.1% compared to 13.3%), this SSR does not reach the ultimate low temperature of 296 mK that the B & S SSR achieved. However, this refrigerator does deliver approximately double the cooling power of the B & S SSR at higher temperatures and provides 1.7, 2.1, and 3.3 times the cooling power per mole ^{3}He at 400 mK, 500 mK, and 750 mK respectively. This increase in performance is largely due to the effectiveness of the plastic recuperator and the increased area of the isothermal heat exchangers within the platforms. More impressively, when the B & S SSR is scaled to the operating speeds and ^{3}He concentration of this SSR, this SSR delivers 7, 10, and 14 times the cooling power at 400 mK, 500 mK, and 750 mK respectively.

This SSR can easily be modified to deliver both lower temperatures and higher cooling powers. Lower temperatures can be achieved by increasing the percentage of the SSR devoted to recuperative heat transfer and by using multiple expansion platforms, and higher cooling powers can be obtained by increasing the ^{3}He concentration of the mixture. A 6% ^{3}He–^{4}He mixture would increase the overall cooling power of our SSR by a factor of 4.

4. CONCLUSIONS

We have demonstrated the first operation of a SSR using a plastic recuperator. Operating from a high temperature of 1.0 K and with a 1.5% ^{3}He–^{4}He mixture, this SSR achieves a low temperature of 344 mK and delivers net cooling powers of 1.86 mW at 750 mK, 358 μW at 500 mK, and 97 μW at 400 mK. The results are promising because with an undersized recuperator, this SSR provides double the cooling power of previous SSR's and delivers 1.7, 2.1, and 3.3 times the cooling power per mole ^{3}He at 400 mK, 500 mK, and 750 mK respectively. When scaled to the same operating speeds and ^{3}He concentrations of previous SSR's, this SSR delivers 7, 10, and 14 times the cooling power of previous refrigerators at 400 mK, 500 mK, and 750 mK. Lower ultimate temperatures and higher cooling powers can be achieved by using larger plastic recuperators, higher concentration ^{3}He–^{4}He mixtures, and multistage machines.

ACKNOWLEDGMENTS

This research is supported by National Science Foundation grant CTS-9416689.

REFERENCES

1. A. Watanabe, G. W. Swift, and J. G. Brisson, Uniform temperature cooling power of the superfluid Stirling refrigerator, *J. Low Temp. Phys.* **103**, 273 (1996).
2. V. Kotsubo and G. W. Swift, Superfluid Stirling refrigerator: a new method of cooling below 1 Kelvin, in *Proceedings of the 6th International Cryocoolers Conference*, **2**, David Taylor Research Center, Bethesda (1991), pp. 59–70.
3. V. Kotsubo and G. W. Swift, Superfluid Stirling cycle refrigeration below 1 Kelvin, *J. Low Temp. Phys.* **83**, 217 (1991).
4. J. G. Brisson and G. W. Swift, A recuperative superfluid Stirling refrigerator, *Adv. Cryo. Eng.* **39B**, 1393 (1994).
5. A. Watanabe, G. W. Swift, and J. G. Brisson, Measurements with a recuperative superfluid Stirling refrigerator, *Adv. Cryo. Eng.* **41**, 1527 (1996).
6. R. C. Richardson and E. N. Smith, in *Experimental Techniques in Condensed Matter Physics at Low Temperatures*, Addison-Wesley, New York (1988), pp. 158–164.
7. G. Frossati and D. Thoulouze, A millikelvin dilution refrigerator with plastic exchangers, in *Proceedings of the 5th International Cryogenic Engineering Conference*, Kyoto, Japan (1974), pp. 229–231.
8. E. ter Haar, R. Wagner, C. van Woerkens, S. Steel, G. Frossati, L. Skrbek, and M. Meisel, Plastic dilution refrigerators, *J. Low Temp. Phys.* **99**, 151 (1995).
9. R. Wagner and G. Frossati, A small plastic dilution refrigerator, *Physica B* **165** & **166**, 43 (1990).
10. A. B. Patel and J. G. Brisson, Theoretical performance of single staff and two stage superfluid Stirling refrigerators using Kapton recuperators, *Adv. Cryo. Eng.* (to be published).
11. Type 60050-1 and 60055-1 from Metal Bellows Division, Senior Flexonics Inc., Sharon, MA.
12. J. G. Brisson and G. W. Swift, Superfluid Stirling refrigerator with a counterflow regenerator, in *Proceedings of the 7th International Cryocoolers Conference*, Phillips Laboratory, Alburquerque (1992), pp. 460–465.
13. Document PI-VPG-91, Corning Glass Works, Corning, NY.
14. A. B. Patel and J. G. Brisson, "Design and construction of a plastic heat exchanger for sub-Kelvin use," (to be published).
15. Dupont High Performance Films, Circleville, OH.
16. Grace Specialty Polymers, Emerson & Cumming Inc., Lexington, MA.
17. Oxford Instruments Ltd., Oxford, England.
18. J. G. Brisson and G. W. Swift, Superfluid Stirling refrigerator: a sub-Kelvin cooler for space, in *Proceedings of the 1994 NASA/JPL Low Temperature Microgravity Physics Workshop*, D. Strayer and U. Israelsson (eds.), NASA Document D-11775 (1994), pp. 340–346.