

# RECENT ADVANCES IN STIRLING CYCLE REFRIGERATION

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## INTRODUCTION

Over the past few years research has been undertaken to investigate the suitability of the free-piston Stirling cycle for domestic refrigeration /1, 2, 3/. This work has been motivated by the potential of environmental attractiveness and low cost of the Stirling unit. In November 1993, a Dutch consortium of environmental groups, utilities and government energy research agencies funded a demonstration project to build a Stirling cooled, solar powered, battery-free super efficient refrigerator /4/. No-sun operation was provided for by a thermal store. Figure 1 shows the demonstration project refrigerator with the door open to reveal the thermal store while Figure 2 shows the small free-piston Stirling specifically developed for the project. The results of this effort were extremely encouraging. One of the more striking attributes to be shown by the study is the ability of the free-piston Stirling to maintain high efficiencies at low lifts. A COP of better than 2.0 (0 to 30°C) over lift from 8 to 50 W was achieved. This confirmed the idea that the free-piston Stirling would be an ideal choice for supplying the small cooling capacities required by super insulated cabinets now under development. The program described here extends the original program to further investigate possibilities of performance improvement in the Stirling unit and the potential of the Stirling / vacuum super insulated (VSI) cabinet combination. Strong emphasis continues to be placed on solar operation with the aim to demonstrate an environmentally friendly photovoltaic refrigerator of about 270 l with an energy consumption of around 50 kWh / yr.

The Stirling cycle is fundamentally different to that used in conventional refrigerators (the Rankine cycle). Helium is employed as the working medium and no phase change occurs. The particular unit described here is a free-piston machine driven by a linear motor /1/. All internal running surfaces are supported by gas bearings so that during steady operation no contact wear takes place. The entire unit is hermetically sealed and dynamically balanced for low noise and vibration. Operational characteristics include the fact that the lift (capacity) is easily modulated since the piston amplitude is directly proportional to the drive voltage. More complete technical and theoretical descriptions are contained in /1, 5/. Suffice it to say that in its ideal form, the Stirling cycle has the highest obtainable efficiency of any cooling device.

The VSI technology used for this study is that developed by L. Schilf (Vacutherm GmbH - Germany). This technology has the advantage of being completely recyclable and having been tested in the form of insulated wall panels and commercial steam pipes. In both applications, the reliability has been excellent. Aside from the low heat loss, VSI cabinets have a better ratio of storage to outside volume compared to conventional refrigerators. The vacuum insulated cabinets have been designed by the Swiss Foundation Ökokühlschrank.

Integration of the Stirling unit is different to the way compressors are integrated into conventional refrigerators. Heat transfer to and from the cooler must be arranged by secondary media. The original demonstrator used conduction to transfer the cabinet load to the cold head, while the warm side heat transfer was augmented by a small 1.4 W fan. The current project will employ different techniques to the demonstrator project. However, these techniques are not covered in this presentation.

Six example installations are presently being pursued, namely:

- a) Two single temperature refrigerators of 270 litres, one solar powered and the other mains powered.
- b) Two two-temperature refrigerators of 220 litres fresh food and 30 litres freezer. Again, one solar and the other mains.

- c) Two solar cool boxes of 40 litres powered by a removable photovoltaic panel in the lid.

DEMOFRIDGE PHOTO

DEMO MINICOOLER PHOTO

Figure 1 The demonstration fridge  
(cabinet supplied by Foron GmbH)

Figure 2 The demonstration Minicooler

### **THE SYSTEM**

The basic system consists of:

- a) a free-piston Stirling cooler capable of high performance over a turn-down ratio of 10:1. Target COP is 3.0 for 0 to 30°C.
- b) a super insulated cabinet with extremely low static heat leaks. Target heat leak is 8 W to both the freezer and fresh food section for the two temperature cabinet.
- c) a heat transport system capable of heat transfer with high effectiveness and low parasitics.
- d) an optional electronic control system capable of being directly connected to a small photovoltaic panel. Consumption has been budgeted at 1 W or less.
- e) an optional thermal store capable of storing thermal potential in order to avoid the use of storage batteries. Store should provide enough potential for 24 hrs of no electrical input.

### **FREE PISTON STIRLING COOLING UNIT (MINICOOLER)**

Using data obtained from the two demonstrator units and other hardware run at refrigerator conditions, the calculation and design procedure was carefully calibrated. This activity has greatly improved the confidence with which performance may be predicted. A COP in excess of 3.0 appears to be practical for 0 to 30°C for lifts up to 60 W. Figure 3 shows the predicted and measured performance of the original demonstration unit. A COP of around 2.0 was obtained with a square wave driver. On mains the COP was about 2.2. Also shown is the predicted performance for the current project (labeled Opt.). An important feature clearly evident from Figure 3 is the uniformity of the COP over a wide range of input. This is a characteristic of the free-piston Stirling that is not seen in other practical thermodynamic cycles. Additionally, since there is essentially a complete absence of starting torque, no high currents are required. The ability, therefore, exists to provide useful cooling with extremely small amounts of energy which greatly improves the practicality of using photovoltaic panels without battery back-up.

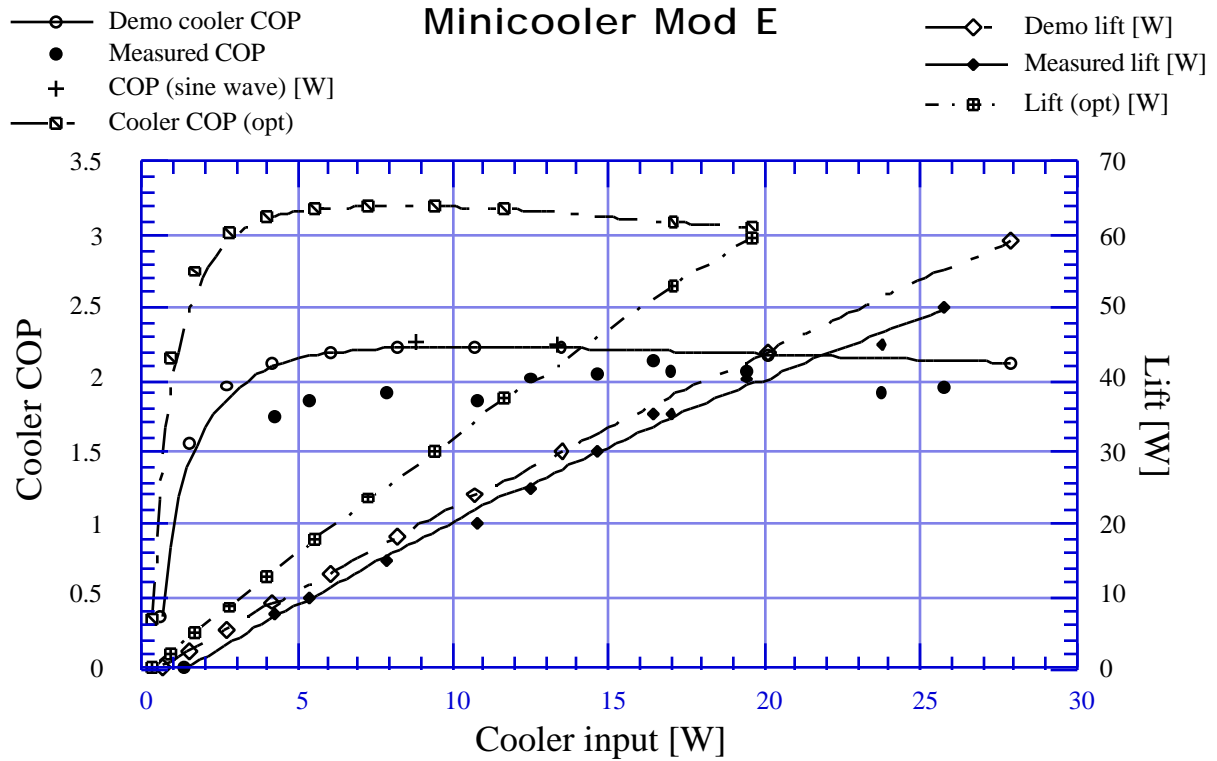


Figure 3 Performance of demonstrator and predicted performance of optimized unit (0 to 30°C)  
 Data marked • is obtained using DC square wave driver  
 Data marked + is obtained using mains (AC sine wave)

Another important feature of the free-piston Stirling is its ability to operate over a wide range of design optimum with relatively small penalty. An example of this is shown in Figure 4. Here the sensitivity of the cycle is shown by plotting the COP against the reject temperature. High ambient temperatures are common in many parts of the world, and can result in reject temperatures in excess of 50°C for the VSI / Stirling configuration. Table 1 shows that the temperature sensitivity of the Stirling compares favorably to the Rankine for operation around the design point. For conventional refrigerators high temperature ambients impose serious penalties. This manifests in the form of increasingly high pressure ratios which result in higher friction loads. Cascading degradation of performance then occurs since as COP declines the load on the heat exchangers increases further causing even higher reject temperatures.

Cycle	COP / COP [%]	
	Cold side	Warm side
Rankine /6/	4%	3%
Stirling	3%	2%

Table 1: Temperature sensitivity around design point

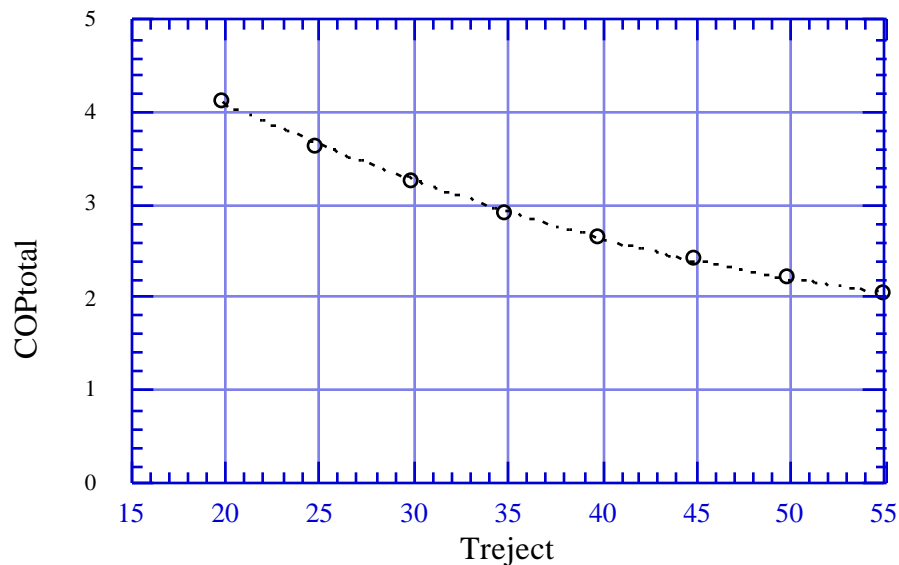


Figure 4 Sensitivity to reject temperature (calculated)

A test rig has been constructed and well instrumented in order to investigate and optimize the thermodynamics and mechanical details of the Minicooler (Figure 5). Many mechanism and cycle losses may be directly or indirectly measured. Mechanism losses include losses associated with gas bearings, hysteresis, windage, centering and motor inefficiency. Cycle losses are the internal irreversibilities associated with the actual cycle. Figure 6 shows an example of mechanism and cycle losses as measured on the test rig. The mechanism loss is expected to be some 50% less in the final unit.

An important purpose of the test rig is to empirically parameterise the design in those aspects that are intractable by other means. The optimization approach, therefore, involves a close coupling of analytical and empirical procedures. By this method, the confidence in achieving design goals is greatly magnified.

At the time of writing, only limited operational data has been taken. This is shown in Table 2. As can be seen, the measured COP is between 2.7 and 2.8 for these tests (a fraction of Carnot of about 30%). It is expected that when parasitics unique to the test rig are removed, the objective COP will be achieved at about 35% Carnot. In any event, the current test rig performance is excellent for a small lift device. Also shown is one point for -25°C to 28°C. The COP here is 1.59 which at 34.3% is a higher fraction of Carnot than the 0 to 30°C points. The COP<sub>adjust</sub> column is the estimated COP at the design condition based on the achieved fraction of Carnot.

Once optimum parameters are verified with the test rig, the Minicoolers will be fabricated for installation into the VSI cabinets. The estimated final overall dimensions of the new Minicooler which is shown in Figure 7 will not change much by this process.

# PHOTO TEST RIG

Figure 5 The test rig

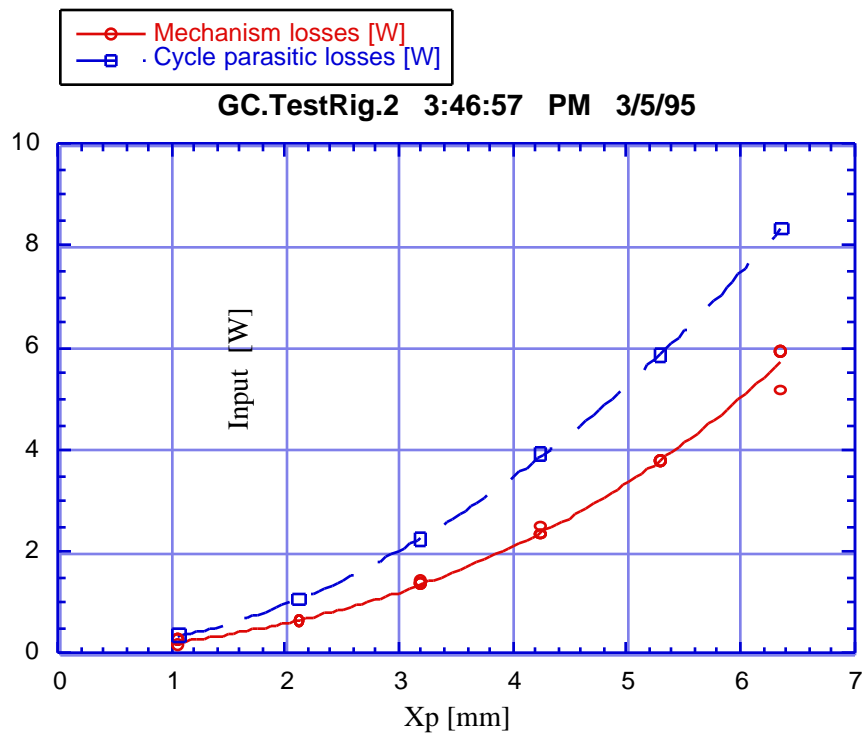


Figure 6 Mechanism and cycle parasitic losses measured on test rig

Cold side [°C]	Warm side [°C]	Input [W]	Lift [W]	COP	Carnot %	COP <sub>adjust</sub>
0.2	32.5	13.50	33.93	2.51	29.7	2.70
-1.7	31.6	21.79	54.60	2.51	30.8	2.80
-0.7	29.3	7.12	19.30	2.71	29.9	2.72
-1.0	28.2	3.11	7.06	2.27	24.4	2.22
-0.6	33.2	14.14	35.90	2.54	31.5	2.87
-1.1	29.6	17.22	45.4	2.64	29.8	2.71
-0.8	29.6	9.70	26.49	2.73	30.5	2.78

-1.5	29.1	4.25	9.96	2.34	26.4	2.40
-25.3	28.2	12.70	20.16	1.59	34.3	1.62*

Table 1: Data from test rig

\*Design condition here: -23°C to 30°C

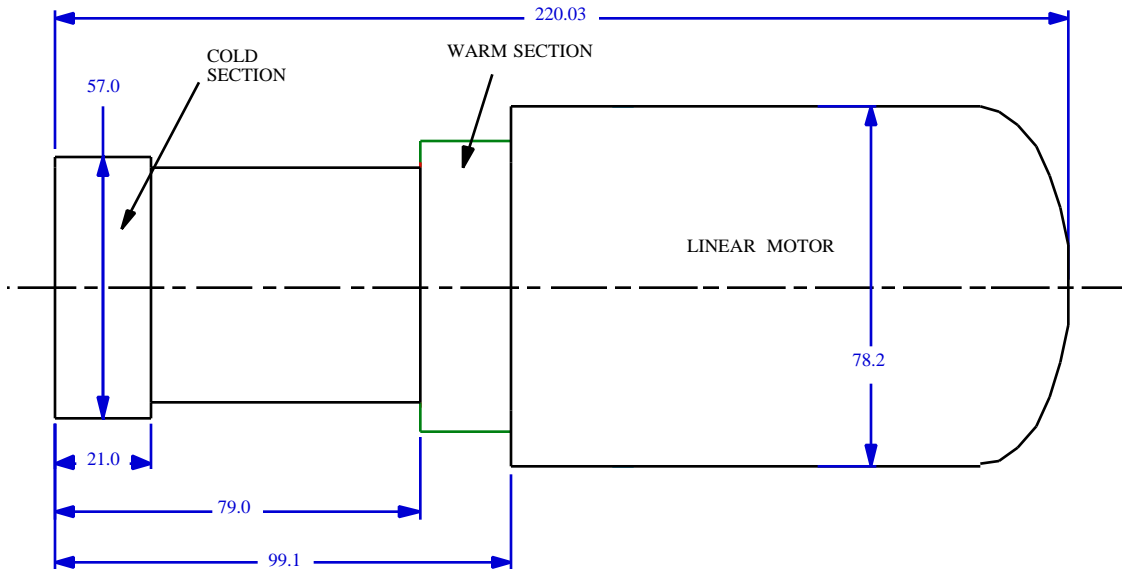


Figure 7 Overall size of new Minicooler (total mass: 2.3 kg)

## THE TEST CABINETS

The cabinets are of the following sizes:

- 1) One temperature cabinet: 270 l
- 2) Two temperature cabinet: 220 l for fresh food and 30 l for the freezer. The freezer is a separate vacuum insulated box that inserts into the basic fridge cabinet.
- 3) Solar cool boxes: 40 l.

Each cabinet consists of an outer and inner stainless steel box with the interstitial space filled with diatomaceous earth under a hard vacuum. The edges of the two boxes are joined with a thin membrane structure in order to keep conduction losses to a minimum and maintain the integrity of the vacuum. The wall thickness is around 2.6 cm for the fridges and slide-in VSI freezer box and about 1 cm for the solar cool boxes. There is only one small hole in the box for the exit of the rejected heat and the power lines. Since the heat rejection of the Minicooler is highly localized, it is possible to install the Minicooler within the cabinet and route the rejected heat to the outside of the cabinet. This results in much lower transmitted noise levels, significantly larger useful fridge volume and lower cabinet fabrication costs. Figure 8 shows schematically the overall size and intended location of the Minicooler in the two temperature fridge cabinet. Heat leakage for the two temperature cabinet is expected to be 8 W for each of the two spaces (the freezer and fresh food sections) for a total of 16 W. For the single temperature cabinet, the heat leak is expected to be about 14 W. The solar cool boxes, with wall thicknesses of 1 cm, will have a heat leak of probably around 6 W. Heat leak numbers are specified at 25°C ambient.

## PREDICTED SYSTEM PERFORMANCE

In order to achieve a yearly energy consumption of 50 kWh for the single temperature 270 l fridge, the average consumption should be about 5.7 W. Using a 25°C ambient test point the transmission loss for this fridge is expected to be about 14 W. A COP of 3.0 would require 4.7 W average input to the cooler leaving about 1 W for the electronic controls and heat transfer system. For the mains unit it may be possible to reduce control parasitics to even less than 1 W.

The integration of the Minicooler into the two-temperature fridge is especially interesting. The system will be configured in such a way so that the Minicooler only cools one space at a time. By so doing, it is possible to maximize the overall COP. Therefore, for the fresh food compartment the COP would be around 3.0 and for the freezer around 1.8. This translates into a net average energy consumption, inclusive of electronic controls, of around 8 W or about 70 kWh per year.

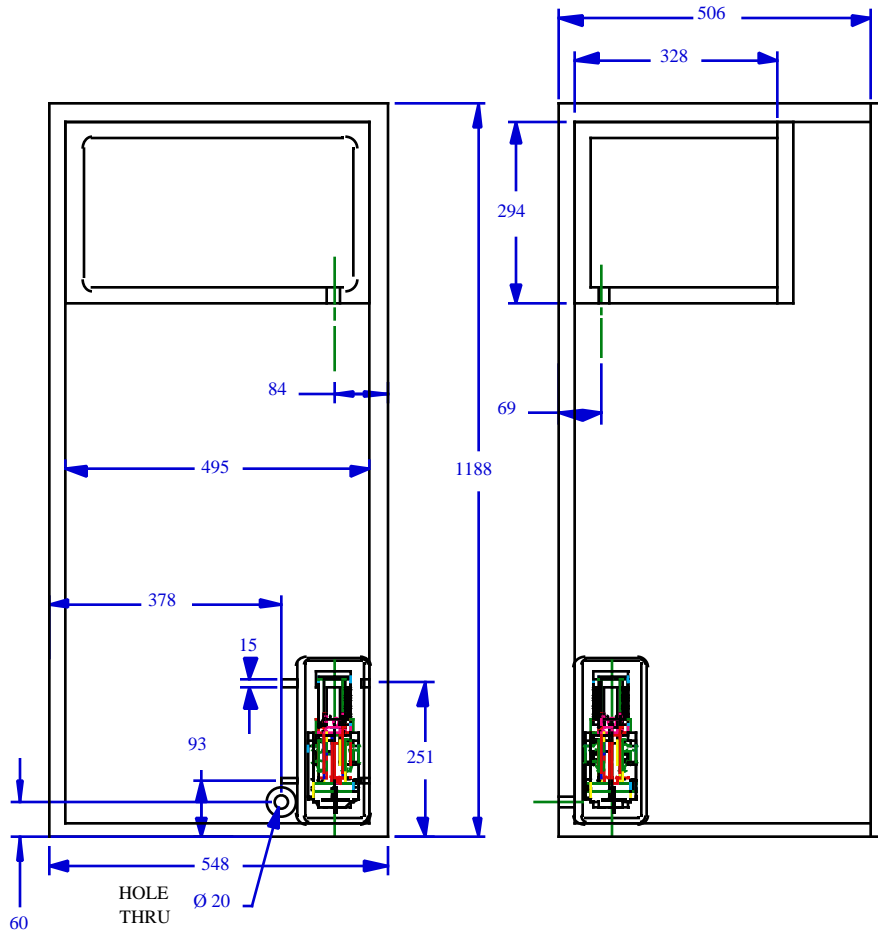


Figure 8 Two-temperature fridge showing intended location of Minicooler

Since the solar cool boxes have a static heat load of about 6 W, the total heat removal will have to be at least 12 W in order to adequately charge the thermal store. Average input to the Minicooler will then be about 4 W. However, it will be the installed peak capacity together with the instantaneous solar power that will determine actual lift. With a 12 W<sub>peak</sub> panel on a sunny day it is estimated that between 9 AM and 1:15 PM, the solar power varies between 6 and 12 W in Northern latitudes. This would result in lifts ranging between 18 and 36 W which is enough to charge the 24 hr thermal store. In conditions where less than 6 W is available, the Minicooler will continue to lift substantial heat, even down to 2 W input where the COP would be about 2.0.

The details of the thermal stores are not included here. A functional description of the thermal store as used in the demonstrator fridge is contained in /4/.

## CONCLUSIONS

The use of the free-piston Stirling cooler together with VSI cabinets offers an outstanding opportunity to provide an environmentally friendly refrigerator of remarkably low energy consumption. Excellent performance can be expected in moderate, tropical and hot climates. Both the original demonstration project and the data obtained so far from the test rig strongly endorses

the predicted performance of the cooler. The ability of the free-piston Stirling cooler to make useful cooling with extremely low inputs while maintaining high COPs is an important characteristic for direct photovoltaic operation without the need for storage batteries.

## SUMMARY

Environmental concerns have created a need for domestic refrigeration equipment that do not use Chlorofluorocarbon (CFC), Hydrochlorofluorocarbon (HCFC) and Hydrofluorocarbon (HFC) compounds and operate at much higher efficiencies than current equipment. Specifically addressed in this paper is the potential of Stirling cycle cooled VSI fridges. The performance characteristics are particularly suitable for direct photovoltaic operation without the need for storage batteries. Optimization has been carried out on small Stirling coolers for lifts less than 70 W. Analysis and test results indicate that COP's of 3.0 are possible for one temperature refrigerators under standard conditions. The steady improvement in COP over the last few years for this type of device is discussed. Current COP's are better than any known alternative cycle for similar low lift conditions. Energy consumption figures have been determined showing that for the particular case of a one-temperature, 270 l VSI refrigerator, less than 50 kWh / yr is completely reasonable.

## REFERENCES

- /1/ D. M. Berchowitz and R. Unger. "Experimental Performance of a Free-Piston Stirling Cycle Cooler for Non-CFC Domestic Refrigeration Applications", XVIII International Congress of Refrigeration, Montréal, Canada, August 1991, pp 848-852.
- /2/ W. F. Bessler. *Electrical Motor-Driven Non-Phase Change Gas-Cycle Refrigeration; Phase I: GCR System Study and Design*, Final report, Contract 85X-SJ837C, U. S. Dept of Energy (also General Electric Corp., June 1993).
- /3/ G.Chen. *Free-Piston Gas Cycle Refrigeration for Medical Units: Technical Feasibility Investigation through Demonstration and Testing of a Laboratory Prototype*, SBIR Phase I, Sunpower Inc., March 1994.
- /4/ B.D.Mennink and D.M.Berchowitz. "Development of an Improved Stirling Cooler for Vacuum Super Insulated Fridges with Thermal Store and Photovoltaic Power Source for Industrialized and Developing Countries", International Institute of Refrigeration Conference - New Applications of Natural Working Fluids in Refrigeration and Air Conditioning, Hannover, Germany, May 1994.
- /5/ D. M. Berchowitz. "Free-Piston Stirling Coolers", International Refrigeration Conference - Energy Efficiency and New Refrigerants, Purdue University, July 1992.
- /6/ Gulbrandsen *et al.* *Development of Energy Efficient Electrical Household Appliances, Part One: Refrigerators*, Technical University of Denmark, Final Report for DG-XVII of the Commission of the European Communities, 1986.