Micro-Stirling Active Cooling Module (MS/ACM) for DoD Electronics Systems

Douglas S. Beck
Beck Engineering, Inc.
1490 Lumsden Road, Port Orchard, Washington, U.S.A., 98367-9179

Abstract: *The Department of Defense has many systems that can benefit from the features of a cm-scale micro-refrigerator. We are developing for DARPA a cm-scale Micro-Stirling Active Cooling Module (MS/ACM) micro-refrigerator to benefit the DoD systems. Under a DARPA contract, we are designing, building, and demonstrating a breadboard MS/ACM.*

Keywords: Stirling; cooler; active cooling module; micro-Stirling; electronics; heat sink.

Introduction

The Department of Defense has many systems that can benefit from the features of a cm-scale micro-refrigerator. We are developing for DARPA a cm-scale Micro-Stirling Active Cooling Module (MS/ACM) micro-refrigerator to benefit the DoD systems. Our MS/ACM uses miniaturized versions of components we have already developed for space-based cryocoolers for the MDA, AFRL, and NASA. Stirling coolers are highly efficient and compact. For example, the high efficiency and compactness (and lightweight) of Stirling coolers have made Stirling coolers the dominant type of cooler for cooling space-based electronics. In theory, the Stirling refrigeration cycle can achieve the Carnot COP (the maximum possible COP) of 11.5 for a cooling-load temperature of 15 C and a heat-sink temperature of 40 C. Practical considerations limit actual COPs to smaller values, but a COP better than 3 seems achievable. Under a DARPA contract, we are designing, building, and demonstrating a breadboard MS/ACM.

In the following, we first show how our Micro-Stirling Active Cooling Module (MS/ACM) will potentially benefit electronics cooling. Then we describe how an ideal Stirling cooler works. Then we describe technical challenges to implementing a practical Stirling cooler and our approach to overcoming the technical challenges. Finally we describe the wide range of applications for Stirling-cycle coolers, cryocoolers, and generators.

How Our MS/ACM will Benefit Electronics Cooling: Figure 1 shows micro-electronics that are cooled by some advanced passive components that are being developed by DARPA contractors. High-performance electronics produce large flows of heat (with units of W). Also, for high electronics performance, the temperature difference (K) between junctions and the ambient environment must be small to maintain junction temperatures below certain limits. Therefore, the overall thermal resistance (K/W) of the cooling system must be minimized to remove a large heat flow (W) with a small temperature drop (K) across the cooling system. The thermal resistances of the passive components sum to the overall thermal resistance, so the thermal resistance of each passive component must be minimized to achieve a small overall thermal resistance. Even with advanced components being developed by DARPA contractors, the overall thermal resistances of cooling systems are too large to accommodate many advanced electronics that could benefit the DoD.

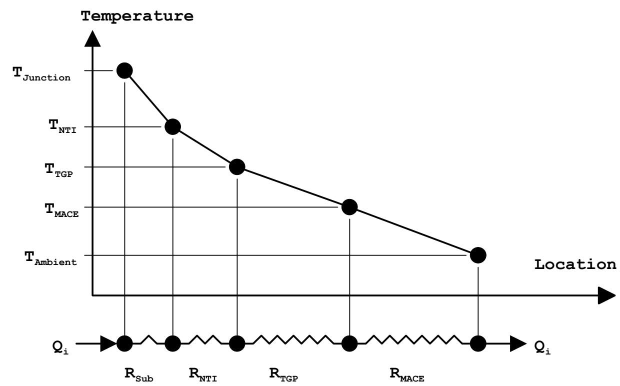

Figure 1. Electronics Cooled by Only Passive Components

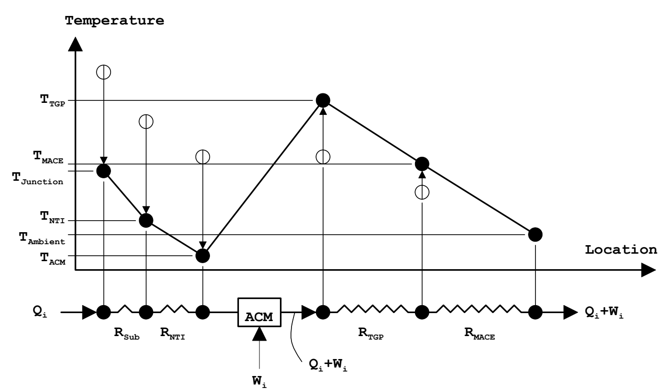

Figure 2. Electronics Cooled with Our MS/ACM

Figure 2 shows how our Micro-Stirling Active Cooling Module (MS/ACM) has the potential to benefit electronics cooling. Our MS/ACM provides a negative thermal resistance that subtracts from the overall thermal resistance of the cooling system. Therefore, our MS/ACM enables lower junction temperatures and/or higher heat flows to accommodate advanced electronics.

Our MS/ACM uses an electrical power input (W) to absorb heat (W) at a cool temperature (15 C, for example). According to the First Law of Thermodynamics, our MS/ACM rejects the sum of the electrical power input and

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
MAR 2012

2. REPORT TYPE
N/A

3. DATES COVERED
-

4. TITLE AND SUBTITLE
Micro-Stirling Active Cooling Module (MS/ACM) for DoD Electronics Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Beck Engineering, Inc. 1490 Lumsden Road, Port Orchard, Washington, U.S.A., 98367-9179

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADB379283. GOMACTech - 12: Government Microcircuit Applications and Critical Technology Conference (37th) Spanning the Spectrum: Innovations in Micro-Technologies for System Supremacy. Held in Las Vegas, Nevada on 20-22 March 2012., The original document contains color images.

14. ABSTRACT
The Department of Defense has many systems that can benefit from the features of a cm-scale microrefrigerator. We are developing for DARPA a cm-scale Micro-Stirling Active Cooling Module (MS/ACM) microrefrigerator to benefit the DoD systems. Under a DARPA contract, we are designing, building, and demonstrating a breadboard MS/ACM.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**3**	

the absorbed heat to the downstream components of the cooling system. The figure of merit for our MS/ACM (and all other refrigeration systems) is the Coefficient Of Performance (COP), which is defined as the absorbed heat divided by the power input. The amount of heat rejected by our MS/ACM must be minimized, so downstream components of the cooling system do not become too hot. Therefore, our MS/ACM must have a compact size (2 cm × 2 cm × 0.5 cm) so it can fit within tight size constraints for electronics cooling systems, and our MS/ACM must have a high COP.

How an Ideal Stirling Cooler Works: Figure 3 shows how shows how an ideal Stirling cooler works. The ideal Stirling cooler consists of a cylinder in which a regenerator and a piston move up and down and perform thermodynamic processes on a gas that is contained in the cylinder. The regenerator is porous along the axis of the cylinder. The top of the regenerator is cool and the bottom of the regenerator is warm. When the regenerator moves downward through a warm gas, the gas flows upward through the regenerator core, the regenerator absorbs heat from the gas, and cool gas exits out the top of the regenerator. When the regenerator moves upward through a cool gas, the gas flows downward through the regenerator core, the regenerator releases heat to the gas, and warm gas exits out the bottom of the regenerator.

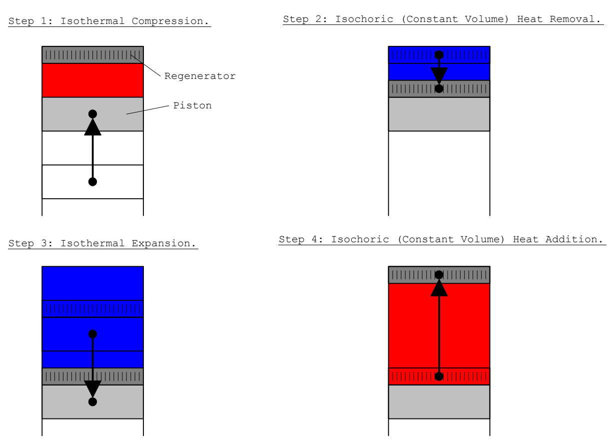

Figure 3. Steps in an Ideal Stirling Refrigeration Cycle

The ideal Stirling cooler uses a thermodynamic cycle that consists of four steps:

Step 1: Isothermal Compression. The piston starts at the bottom of its stroke and moves upward to compress the gas in the cylinder. During the compression process, the gas is continuously cooled and maintained at a constant temperature (isothermal) as the cycle rejects heat.

Step 2: Isochoric (Constant Volume) Heat Removal. The regenerator starts at the top of its stroke and moves downward through the gas to cool the gas. While the gas is cooled, there is no change to the total volume of the gas in the cylinder.

Step 3: Isothermal Expansion. The piston and the regenerator move downward to expand the gas in the cylinder. During the expansion process, the gas is continuously heated and maintained at a constant temperature (isothermal) as the cycle absorbs heat.

Step 4: Isochoric (Constant Volume) Heat Addition. The regenerator moves upward through the gas to heat the gas, and the regenerator returns to the top of its stroke. While the gas is heated, there is no change to the total volume of the gas in the cylinder.

After Step 4, the piston and the regenerator are at their original positions at the beginning of Step 1, so the above cycle can be repeated.

A Stirling cooler can operate as a Stirling generator if the heat-input temperature is hotter than the heat-sink temperature. A Stirling generator absorbs heat at the heat-input temperature, generates electrical power, and rejects the remaining heat at the heat-sink temperature.

Thermodynamic modeling of the ideal Stirling refrigeration cycle indicates the ideal Stirling refrigeration cycle achieves the Carnot COP, which is the theoretical maximum possible achievable COP. However, practical technical challenges limit the COP that is practically achievable from a Stirling cooler.

Challenges to Implementing a Practical Stirling Cooler: The main technical challenges to implementing practical Stirling-cycle coolers and generators depend on the temperatures at which heat is input and rejected from the cycle. For large temperature differences that are typical for cryogenic cooling and power generation using a high-temperature heat source, the main challenges are associated with design of a regenerator that can absorb and release large amounts of heat with only small flow pressure drops across the core. On the other hand, for small temperature differences across Stirling-cycle coolers or generators (for example, the small temperature differences experienced by our MS/ACM), the main challenges are associated with minimizing temperature drops during the compression and expansion processes and achieving near-isothermal processes at the heat-rejection temperature (during the compression process) and the heat-input temperature (during the expansion process).

In the following, we consider a simple example that illustrates the main technical challenges to implementing a practical Stirling cooler with a small difference between the heat-input temperature and the heat-rejection temperature. First consider an ideal Stirling cooler with a 15 C (288.15 K) heat-input temperature and a 40 C (313.15 K) heat-rejection temperature. The COP of the ideal Stirling cooler is equal to the Carnot COP:

$$\text{COPc} = \frac{\text{Ti}}{\text{Tk - Ti}} = \frac{288.15}{313.15 - 288.15} = 11.5 \qquad (1)$$

where,

$COPc$ = Carnot COP, -;

Ti = Heat-input temperature, K; and

Tk = Heat-rejection temperature, K.

Let us assume that the only losses in the actual Stirling cooler are due to an R = 0.1 K/W thermal resistance to heat flow from the heat source to the gas and from the gas to the heat sink. The thermal resistance from the gas to the heat sink causes the isothermal compression process to occur at an elevated temperature of 51.68 C (324.83 K). The thermal resistance from the heat source to the gas causes the isothermal expansion process to occur at a reduced temperature of 5.00 C (278.15 K). Therefore, the actual Stirling cooler can achieve only the following COP:

$$COPc = \frac{Ti'}{Tk' - Ti'} = \frac{278.15}{324.83 - 278.15} = 6.0 \qquad (2)$$

where,

COP = Actual COP, -;

Ti' = Temperature of isothermal expansion, K; and

Tk' = Temperature of isothermal compression, K.

How Our MS/ACM Overcomes Challenges: Figure 4 shows how our MS/ACM overcomes the main technical challenge to achieving a high COP: minimizing the thermal resistances between the heat source and the gas and the heat sink and the gas. Our MS/ACM uses miniature teeth to minimize thermal resistances. As the gas is compressed and expanded, the gas flows between concentric teeth that are machined into: the input plate of the Stirling cooler and the head of the regenerator assembly (at the heat-input end); and the sink plate and the piston head (at the heat-rejection end). As the gas flows between the teeth, the gas is brought into intimate thermal contact with the input plate and the sink plate, which leads to small thermal resistances.

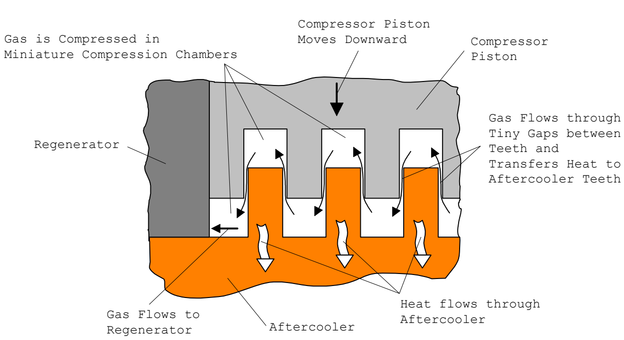

Figure 4. Our MS/ACM Uses Miniature Teeth to Minimize Thermal Resistances

Table 1. Performance Projections for Our MS/ACM

Metrics:	Values:
Heat-Input Temperature.	15 C
Heat-Sink Temperature.	40 C
Cooling Load (Qc).	100 Wth
Electrical Power Input (We).	29 We
Coefficient Of Performance (COP=Qc/We).	3.4
Carnot COP (COPc).	11.5
Efficiency (COP/COPc).	30%

Table 1 lists our projections for the performance of our MS/ACM. We project our MS/ACM will achieve a COP of 3.4, which represents 30% of the Carnot COP.

Applications: Figure 5 indicates the wide range of applications can benefit from our Stirling-cycle cooler, cryocooler, and generator technologies. On the y-axis, heat-input temperatures range from 10 K or colder (for cryocoolers) up to 1,000 K or hotter (for generators). On the x-axis, heat inputs range from 100 mW or less (for cryocoolers) up to 1 MW or more (for generators). For power levels greater than roughly 1 MW, turbo-machines begin to have comparable efficiencies but higher power densities than reciprocating machines.

This material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA) under Contract No. N66001-10-C-4054. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the DARPA.

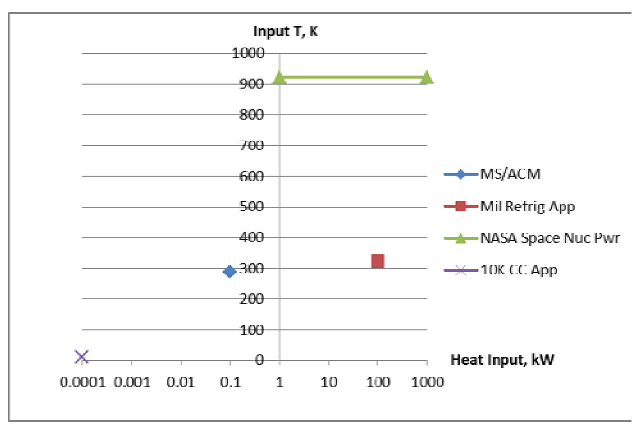

Figure 5. Our Stirling-Cycle Cooler, Cryocooler, and Generator Technologies Can Benefit a Wide Range of Applications