THERMAL MANAGEMENT OF COMPUTER SYSTEMS USING ACTIVE COOLING OF PULSE TUBE REFRIGERATIORS

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ABSTRACT

With the advances in computational speed, thermal management becomes a major concern in computer systems. Heat dissipation as high as 100 to 150 watts has to be rejected from the CPU chip. Conventional cooling methods have their shortcomings. Combining convective fans and heat sinks have limited cooling capacity, and heat pipes contain undesirable working fluids that may leak and contaminate the computer components. The feasibility of using the active cooling of a pulse tube refrigerator for thermal management is studied in this paper. Pulse tube coolers are very similar to Stirling coolers, which have been used extensively in the tactical world, e.g. cooling of sensors in infrared cameras. Pulse tube coolers are more reliable than Stirling coolers with less moving parts but are generally less efficient. Recently, the research in Pulse Tube coolers has shown that Pulse Tube refrigerators are just as efficient as Stirling coolers in the range of cooling capacities discussed above. The thermodynamic efficiency, design and packaging of a Pulse Tube cooler for thermal management of a computer system will be discussed in detail.

INTRODUCTION

The primary objective of thermal management of computer system is to remove heat from the junctions of ICs to ensure that they operate properly and to avoid triggering temperature-activated failure mechanisms. This is generally accomplished by conducting the heat away from the chips and into a gas or liquid coolant. However, the power dissipation per chip has increased dramatically in recent years. This change has provided thermal engineers with the challenges of managing the increasing thermal budget in order to maintain the die at a safe operating temperature because conventional cooling solutions reach their limits. With the increase in thermal power generation, new cooling solutions continue to be investigated.

The speed, reliability and, noise characteristics of most semiconductor devices improve with cooling to low temperatures. In addition, certain unique capabilities become available at low temperatures through the use of superconducting electronics. This paper will explore the possibilities of using pulse tube coolers (PTC's) as the thermal solution of the high-end computers.

CRYOCOOLERS

Cryocoolers have been widely used to cool infrared sensors for space and military applications. Among all the cryocoolers, pulse tube coolers (PTC's) are the most reliable, due to the lack of moving parts. In the past, PTC's are found to be less efficient than the conventional Stirling coolers. Recent advances in the research and development of PTC's closes the gap between the performance of Stirling and the PTC, especially for larger systems with cooling capacities exceeding 1 watt.

THEORY

The theory behind Pulse Tube Coolers is very similar to that of the Stirling Refrigerators, with the volume displacement function of the expander piston replaced by the orifice / surge volume configuration of the PTC. Figure 1 shows the analog between the Stirling cooler and the PTC (Figure 1a depicts the schematic diagrams of a Stirling cooler and a PTC; Figure 1b plots the thermodynamic cycles of the coolers). As the compressor compresses from 1) to 2), the pressure in the system increases. Heat of compression ($Q_H=T_H dS$) is rejected from the compressor. During this phase of compression, very little gas is transferred into the surge volume via the orifice as the initial pressure difference across the orifice is small. As the compressor compresses further from 2) to 3), more working gas passes through the orifice into the surge volume. The end result is very close to an isochoric process in a Stirling cycle (with the expansion of the expander piston). The net effect is that the working gas is displaced across regenerator with heat transfer between the gas and the regenerator matrix material. As the compressor piston reaches its maximum stroke and becomes stationary 3) to 4), expansion occurs because gas continues to flow into the surge volume which is at a lower pressure and the pressure within the pulse tube system drops. During this phase, heat ($Q_C=T_C dS$) is being absorbed by the PTC. Finally, a combination of gas exiting the surge volume and the expansion of the compression space result in another near-isochoric process, 4) to 1) that completes the cycle.

DESIGN

Figure 2 shows a schematic diagram of BEI's pulse tube cooler (see Reference 1 and 2). For the sake of easy packaging, a concentric design has been adopted, with the regenerator wrapping around the pulse tube. A parcel of gas travels from the compressor and enters the expander, which then goes through the regenerator, passes the coldtip, enters the pulse tube, and finally arrives at the surge volume via the orifice. The main advantage of this design is that the cold tip of the pulse tube is exposed and can come into direct contact with the computer chip to be cooled. The only moving parts in the cooler are the compressor pistons. However, due to the presence of a clearance gap between the piston and the liner there is no rubbing parts, and hence nothing to wear. Flexure bearings are used in place of conventional springs, which provides stiffness in the radial direction, holding the tolerance of the clearance seal. Flexure bearings are routinely used in the manufacture of artificial hearts and are extremely reliable. The non-contacting gap seals, infinite fatigue life suspension springs (flexure bearings), and the lack of moving parts ensures long life of the current design.

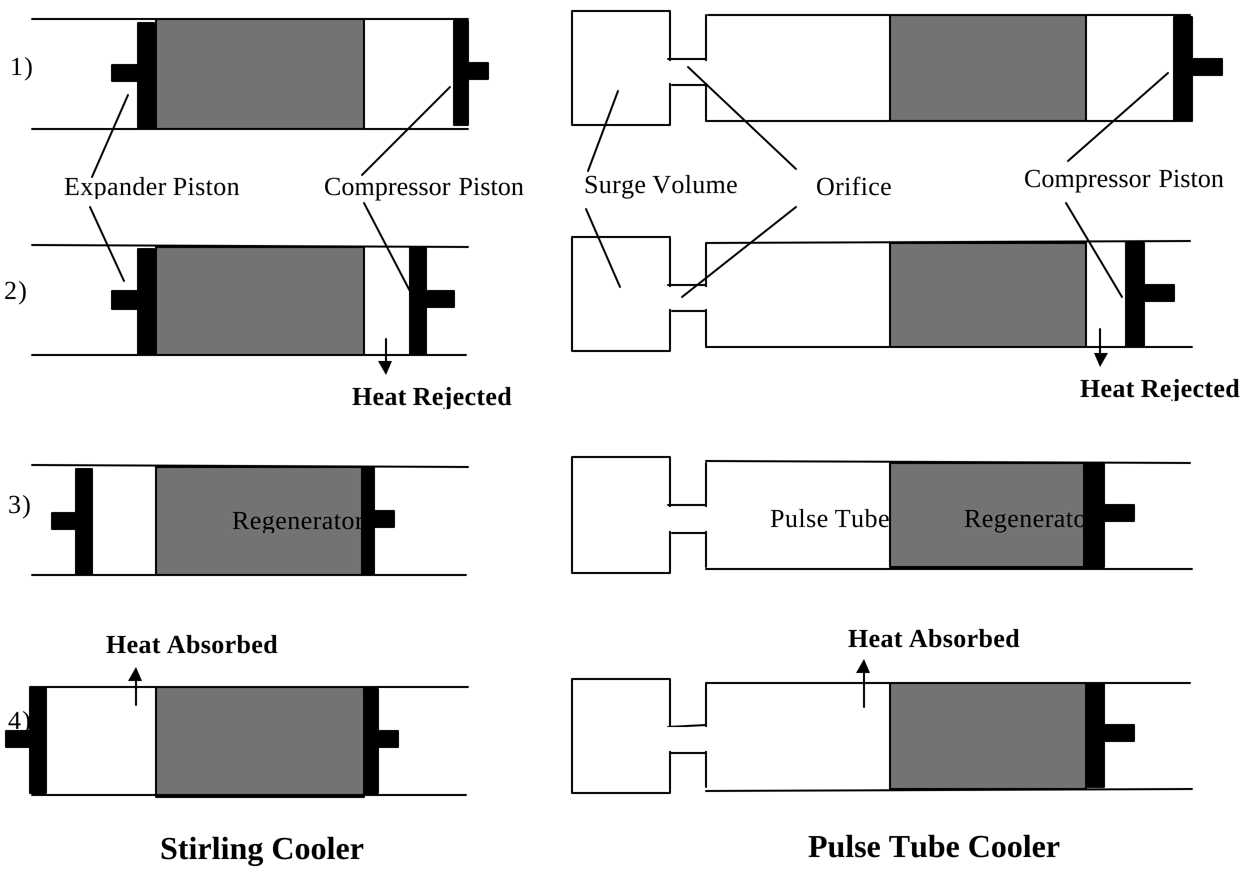
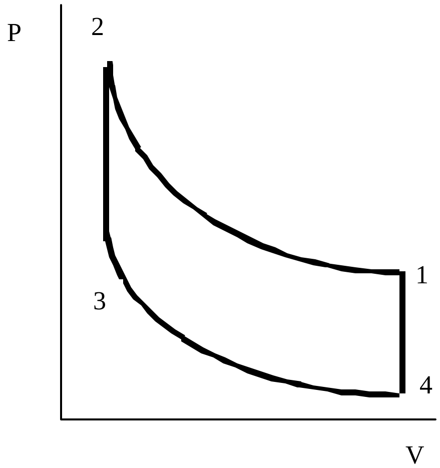


Figure 1a. Analog between the Stirling Refrigerator and the Pulse Tube



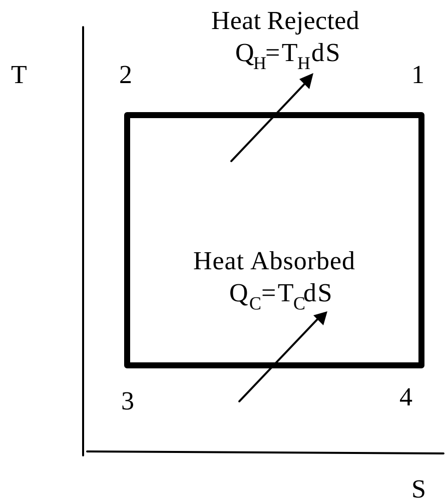


Figure 1b. P-V and T-S diagram Stirling and the Pulse Tube cycles

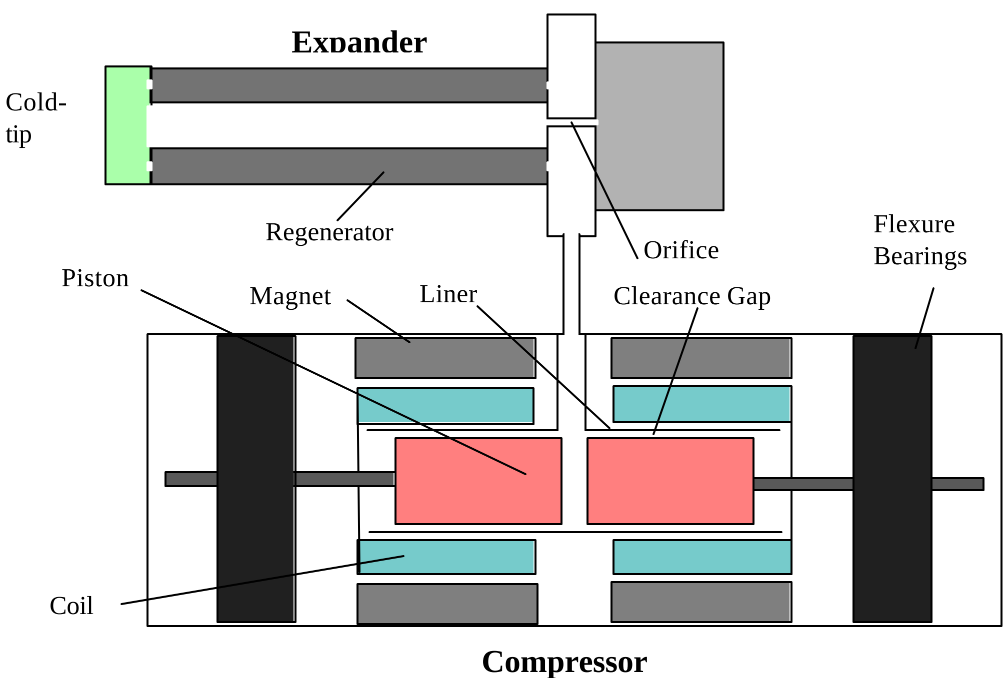


Figure 2. A schematic diagram of the Pulse Tube Cooler

COMPUTER MODEL

At BEI, a pulse tube computer model has been developed which is very similar to the Pulse Tube Performance Model (PTRM) that was validated against two different pulse tube coolers (References 3 and 4), including a blind test. This model was modified from the Stirling Refrigerator Performance Model (SRPM) which is a third order model that has been validated extensively against various Stirling coolers in the literature. They include the Lucas-Lockheed 60K unit[7], the NASA/Philips Magnetic Bearing unit[6], the Oxford refrigerators[5], and the Astronomic Infrared Sounders (AIRS) units A, B, and C. A detailed description of the model can be found in Reference 8.

The equations and assumptions used in the PTRM model were discussed elsewhere[8]. The model breaks up the pulse tube cooler into a number of nodes. The number of nodes in each section depends on the value of the state variables. For examples, more nodes are required in the regenerator because of the large temperature difference and large pressure drop in the axial direction. Conservation of energy, momentum and mass are solved until the solutions converge. Equation of states and empirical equations for pressure drop and heat transfer are also used. No fudge factors are used in the program.

RESULTS AND DISCUSSION

The above model was used in predicting the performance of using PTC to cool the high power chip. With a heat load of ~90 watts, the required PTC is much bigger in capacity and size than the two previous Pulse Tubes designed by BEI. The model predicts that, at 105C, it will take approximately 150 watts of input power to reject 90 watts of heat from the high power chip, and at 50C, the input power is close to 200 watts (Figure 3). The size of the expander is approximately 0.5 inch in diameter and 3 inches long with the coldtip coming into direct contact with the chip. The expander is connected to the compressor by a flexible transfer line. The compressor is about 3 inches in diameter and 8 inches long, and it should preferably reside on the outside of the computer chassis for the ease of heat rejection. Figure 4 shows a BEI Pulse Tube cooler in action. (Note: the cold tip temperature of the cooler in the picture was substantially lower than the freezing point of water. No condensation of water is expected for the operation of the Pulse Tube cooler at room temperature or above.)

BENEFITS

Based on preliminary study and evaluation, a large number of benefits of using pulse tube coolers for the electronic applications were found.

1. Pulse tube refrigerator technology is well established, and can be directly transfer to computer application.
2. Pulse tube coolers has been used in space and military applications many years and met the severe design requirements, which demonstrated it could be a reliable product for electronic/computer industries.
3. Heat removal does not have to be at local spot, which will increase the design flexibility in both mechanical and thermal aspects.
4. To lower chip operating temperature can just by changing input power to crycooler, adding coolers in parallel, or sizing to specific application. Operating at low temperature will also expand the benefits to the following areas:
   - At lower temperatures thermal noise is reduced proportional to the absolute temperature, leakage current from thermally induced carriers is dramatically reduced in semiconductor devices.
   - The speeds of chips are all greatly improved at low temperatures; the reliability and heat dissipation of these chips are generally improved at these low temperatures as well.
   - Latch-up is eliminated at low temperatures, allowing denser packing of components on the chip.
   - The metal conductivity increases at low temperatures, thereby reducing interconnect delays.
   - The thermal conductivity of silicon increases by a large factor, improving heat removal.

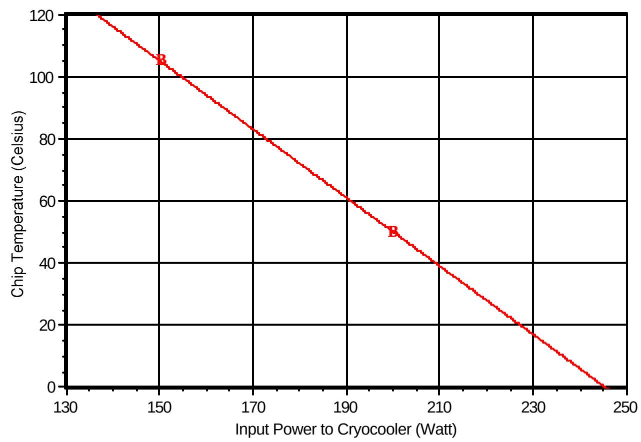


Figure 3. Predicted performance of the PTC used for cooling the chip with 100 Watt

Figure 4. A BEI Pulse Tube Cooler

CONCLUSIONS

Shrinking package size and higher power dissipations have increased ICs heat flux dramatically over the past few years. The preliminary results demonstrated the pulse tube cooler could be an effective thermal solution for high-end computers, and is feasible applying to computer system at typical operating environment. Both cooler size and weight are manageable. Military and Space industries also prove the reliability and serviceability are not issues in their application. CPU/semiconductor/computer system performance can be improved just by increasing the pulse tube cooler input power. Test is planned to validate this cooling concept for commercial electronic applications.

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