Design and Preliminary Testing of BEI's CryoPulse 1000, the Commercial One Watt Pulse Tube Cooler

S.W.K. Yuan, D.T. Kuo, and A.S. Loc

Cryocooler Group, Edcliff Division
BEI Technologies
Sylmar, California 91342

ABSTRACT

This paper describes BEI's efforts in producing a One Watt Pulse Tube Cooler, the CryoPulse 1000, for commercial applications. The cooler was designed by a computer model which has been validated against various Stirling and Pulse Tube coolers in the literature[1-8]. The cooler was designed, fabricated and tested. Preliminary testing showed that the CryoPulse 1000 produces good cooling. However, the heat exchanger at the hot end of the regenerator needs to be modified, to more efficiently reject heat energy generated. Detailed test results will be presented in a later paper.

INTRODUCTION

BEI is a manufacturer of Stirling-cycle cryocoolers based on the concept of clearance seal, pneumatically driven displacer and linear drive motors. Several cooler models are available covering refrigeration requirements ranging from 150 mW to 5.0 Watts of cooling at 78 K. In pursuit of a long-life cooler, BEI has started an in-house program to design and manufacture a cooler based on the concept of pulse tube and flexure bearings. CryoPulse 1000 is the first step toward this goal, by replacing the pneumatically driven displacer of our B1000 Stirling Cooler[9], with a Pulse Tube. The B1000 Stirling Cooler satisfies Army's specification on the SADA II cooler which requires one watt of cooling at 77K with a maximum input power of 40W (ambient temperature of 23 degree Celsius). At an elevated ambient temperature of 71 degree Celsius, the cooler should provide 0.55W of refrigeration capacity with a maximum input power of 60W. The actual performance of BEI's B1000 Stirling cooler far exceeds that of the SADA II requirement. Thus, although pulse tubes are generally less efficient than their Stirling cousins, the BEI CryoPulse 1000 cooler is still expected to produce one watt of cooling at 78K (ambient case temperature).

Proc. Of the 10th International Cryocooler Conference
Page 191-196
Monterey, California, 1998

BEI Technologies, Inc.
13100 Telfair Avenue, Sylmar, CA 91342
Tel: (818) 364-7204; FAX (818) 362-2487
Sidney@yutopian.com

COMPUTER ANALYSIS

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 BEI Pulse Tube Model was used to design the CryoPulse 1000 Cooler.

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.

The PTRM model was modified from the Stirling Refrigerator Performance Model. The expansion space of the SRPM was replaced by the pulse tube with an orifice (or inertance tube) and the surge volume. The volumetric variation and the flow passage (to the displacer motor) at the hot end of the regenerator (of the Stirling model) were also eliminated. The gas transport in the pulse tube is modeled as unidirectional laminar or turbulent flow, depending on the Reynolds number. Heat transfer in the axial direction is modeled as enthalpy flow whereas the radial heat transport is predicted by the forced flow heat transfer coefficient (for both laminar and turbulent regimes). The transport across the orifice is modeled by the discharge flow coefficient.

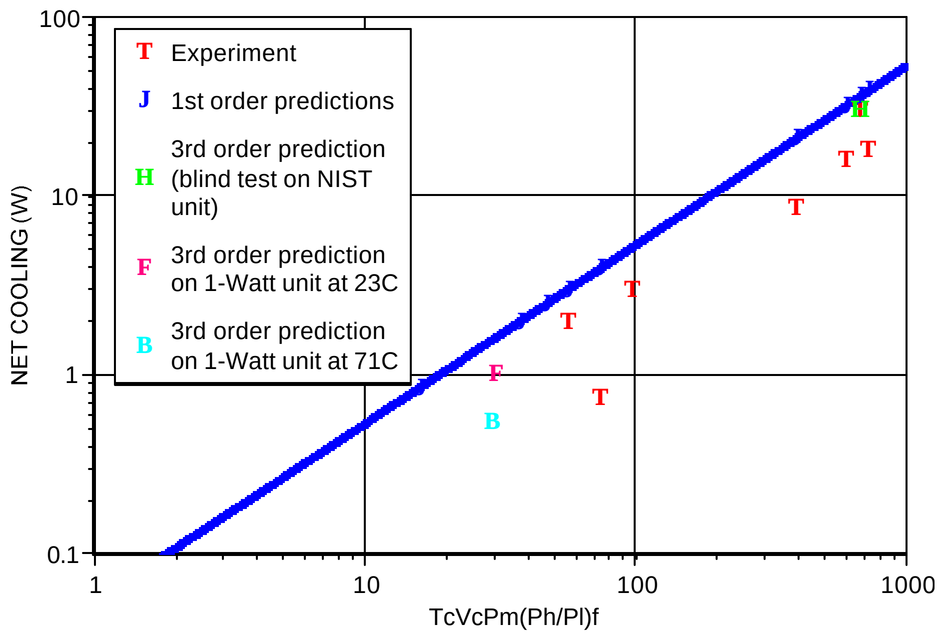

Figure 1- Comparison of model prediction with experimental data.

BEI Technologies, Inc.
13100 Telfair Avenue, Sylmar, CA 91342
Tel: (818) 364-7204; FAX (818) 362-2487
Sidney@yutopian.com

Figure 1 compares the experimental and predicted performances of pulse tube coolers in the literature. It includes a commercial 30 Watt unit built by NIST (Reference 3), which the PTRM model was validated against without prior knowledge of the performance. All the experimental data fall below the first order analysis (i.e., net cooling is proportional to the cold tip temperature (Tc), the swept volume (Vc), the mean pressure (Pm), compression ratio (Ph/Pl), and frequency (f)). This indicates the optimism of the first order analysis, not being able to incorporate all losses (for example, losses associated with dead volume, streaming effect, and boundary layer effect). Also included in the plot are the predicted performances based on the third-order BEI Pulse Tube Model. They include the blind test of the NIST unit and the current predicted performance of the One Watt CryoPulse cooler discussed in this paper.

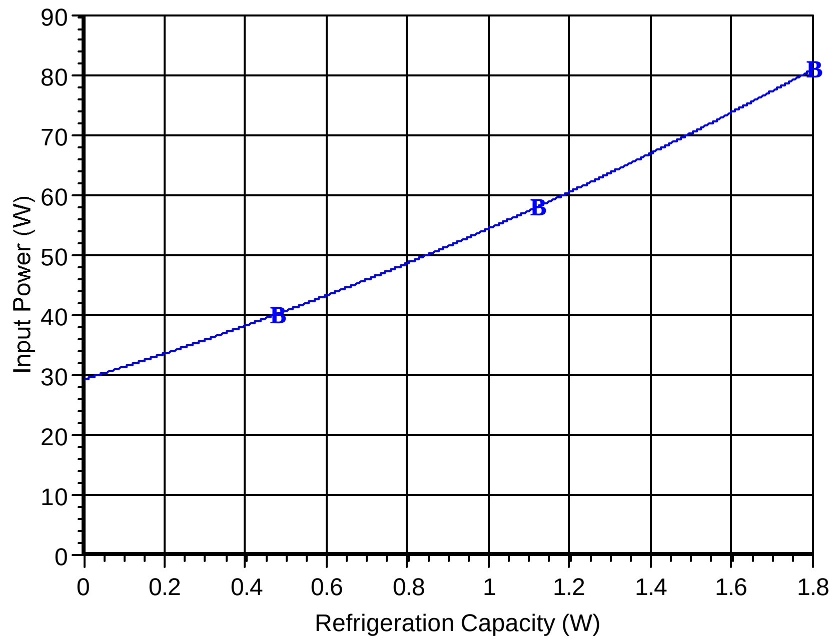

Figure 2. Input power vs. Refrigeration Capacity at 80K

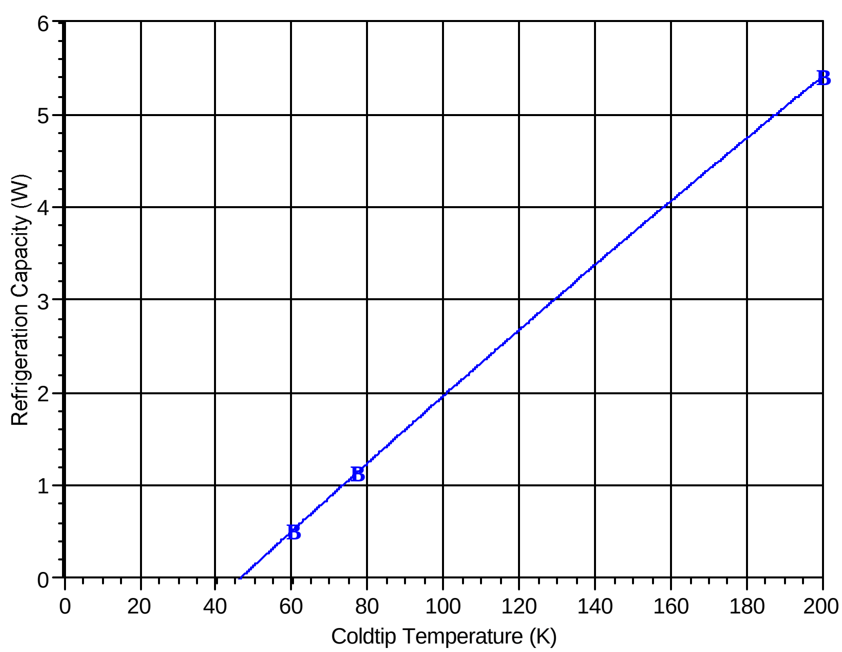

Figure 3. Refrigeration capacity versus coldtip temperature.

BEI Technologies, Inc.
13100 Telfair Avenue, Sylmar, CA 91342
Tel: (818) 364-7204; FAX (818) 362-2487
Sidney@yutopian.com

Refrigeration capacity versus input power (at 80K) is presented in Figure 2. For an input power of 55 watts, CryoPulse provides 1 watt of refrigeration. Refrigeration capacity as a function of coldtip temperature is shown in Figure 3 for a constant input power of 60W. CryoPulse 1000 produces over 5W of cooling at 200K and can cool down to 30K with no load.

The effect of orifice size on the cooling capacity is shown in Figure 4 for two operating frequencies. Based on past experience, the computer model tends to over-predict the orifice size and a smaller diameter was used in the experiment.

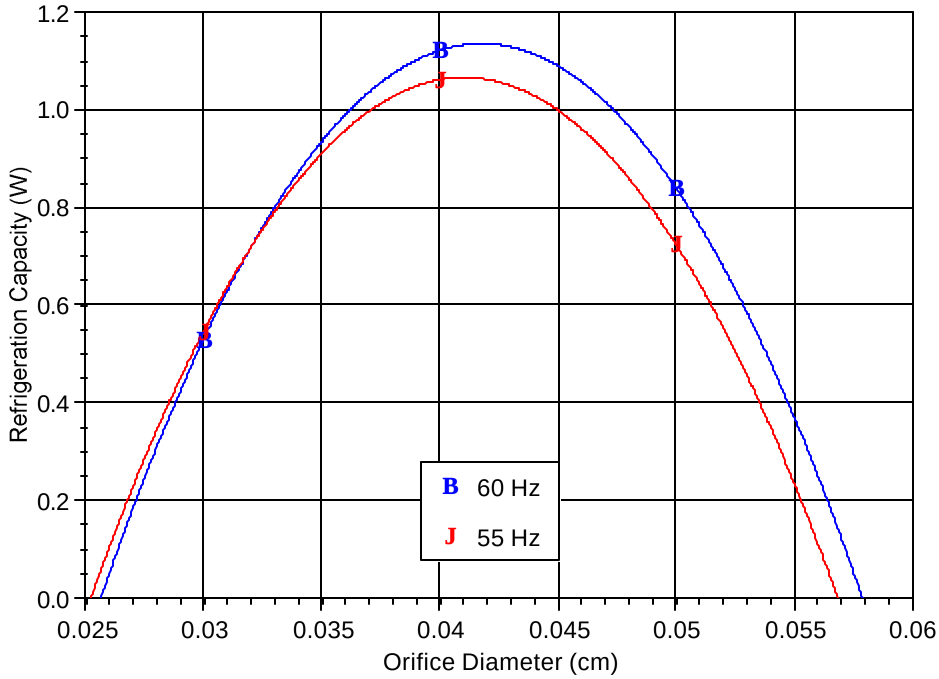

Figure 4. Effect of orifice size on refrigeration capacity.

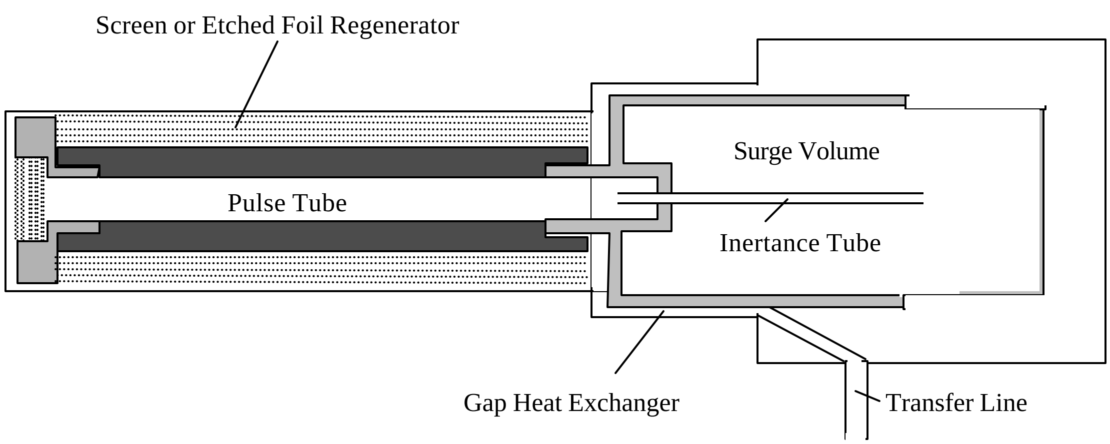

Figure 5. A schematic drawing of the pulse tube.

Proc. Of the 10th International Cryocooler Conference
Page 191-196
Monterey, California, 1998

BEI Technologies, Inc.
13100 Telfair Avenue, Sylmar, CA 91342
Tel: (818) 364-7204; FAX (818) 362-2487
Sidney@yutopian.com

The performance of this cooler can be further enhanced by using an etched-foil regenerator together with by-pass(es) between the regenerator and the pulse tube and/or a double-inlet design.

THE DESIGN

A standard One-Watt compressor for the Stirling Refrigerator is used to drive the pulse tube. The pulse tube was designed to be a retrofit of the displacer of BEI's one watt Stirling cooler (B1000). In order to fit inside the SADA II coldfinger dewar, a concentric design was employed with the regenerator wrapping around the central pulse tube as shown in Figure 5. Helium gas is transported via the transfer line, which passes through a gap regenerator and a conventional regenerator before entering the pulse tube. At the hot end of the pulse tube, an inertance tube is used to tune the phasing for maximum refrigeration. The old gas-spring volume of the Stirling expander is used for the surge volume.

RESULTS AND DISCUSSION

CryoPulse 1000 was fabricated and preliminary tests were performed. The pulse tube was found to have a lot of advantages over the pneumatically driven displacer, with less parts, less tight tolerances, and less contamination issues. Figure 1 shows a picture of CryoPulse in operation with a frost-ball building up at the coldtip of the cooler. Based on our experience, the size of the frost-ball tells us the pulse tube is producing good cooling. However, the gap regenerator (see Figure 5) gets extremely hot during testing and has to be cooled by convection with a fan. In order to accurately monitor the performance of CryoPulse 1000, a temperature sensor and heater have to be mounted at the coldtip and the entire coldfinger inserted into a vacuum jacket. Further tests will be performed and results will be reported elsewhere.

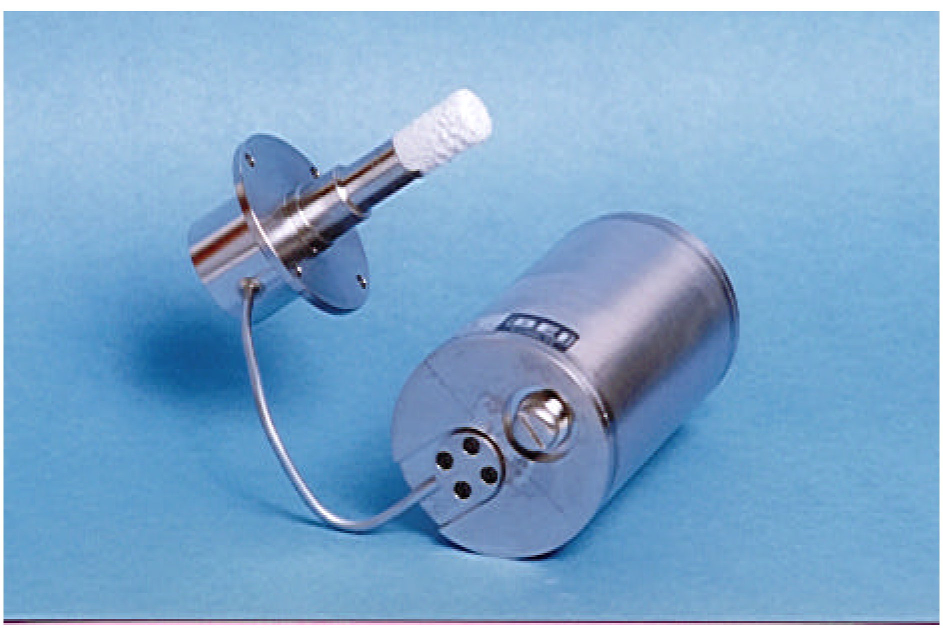

Figure 6. The BEI CryoPulse 1000 Cooler

Proc. Of the 10th International Cryocooler Conference
Page 191-196
Monterey, California, 1998

BEI Technologies, Inc.
13100 Telfair Avenue, Sylmar, CA 91342
Tel: (818) 364-7204; FAX (818) 362-2487
Sidney@yutopian.com

CONCLUSIONS

BEI has been successful in the design and fabrication of our prototype commercial pulse tube cooler, the CryoPulse 1000. Detailed testing will be performed and results will be reported in a later paper. The gap regenerator of the pulse tube was found to get extremely hot during operation. A redesign of this heat exchanger is called for to enhance the performance of CryoPulse 1000. It is also proposed to make the coldfinger out of titanium to reduce the heat conduction from the gap regenerator down the coldfinger.

REFERENCES

1. D. Kuo, T. Loc, and S.W.K. Yuan, Experimental and Predicted Performance of the BEI Mini-linear Cooler, in Proc. the 9th International Cryocooler Conference, (1997) p. 119.

2. D.T. Kuo, A.S. Loc, and S.W.K. Yuan, Enhanced Performance of the BEI 0.5 Watt Mini-Linear Stirling Cooler, to be published in the proc. Of Advances in Cryogenic Engineering, 1997.

3. S.W.K. Yuan and R. Radebaugh, A Blind Test on the Pulse Tube Refrigerator Model, in "Advances in Cryogenic Engineering", Vol. 41, (1996) p.1383.

4 S.W.K. Yuan, Validation of the Pulse Tube Refrigerator Model Against a Lockheed Built Pulse Tube Cooler, in "Cryogenics", Vol. 36, No.10, (1996) p.871.

5 S.W.K. Yuan, I.E. Spradley, and W.G. Foster, Validation of the Stirling Refrigerator Performance Model Against the Oxford Refrigerator, in: "Advances in Cryogenic Engineering", Vol. 39, (1994) p.1359.

6. S.W.K. Yuan and I.E. Spradley, Validation of the Stirling Refrigerator Performance Model Against the Philips/NASA Magnetic Bearing Refrigerator, in: "Proc. 7th Int. Cryocooler Conf.", Vol. 1, Phillips Lab, USA (1993) p.280.

7. S.W.K. Yuan, I.E. Spradley, P.M. Yang, and T.C. Nast, Computer Simulation Model for Lucas Stirling Refrigerators, in: "Cryogenics", Vol. 32, (1992) p.143.

8. S.W.K. Yuan and I.E. Spradley, A Third Order Computer Model for Stirling Refrigerators, in: "Advances in Cryogenic Engineering", Vol. 37 (1992) p.1055.

9 S.W.K.Yuan, D.T.Kuo, A.S.Loc, and T.D. Lody, Experimental Performance of the BEI One Watt Linear (OWL) Stirling Cooler, to be published in the proc. Of the Advances in Cryogenic Engineering, 1997.

BEI Technologies, Inc.
13100 Telfair Avenue, Sylmar, CA 91342
Tel: (818) 364-7204; FAX (818) 362-2487
Sidney@yutopian.com