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ORIGINAL

New Regenerator Materials for Use in Pulse Tube Coolers

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ABSTRACT

A two-stage pulse tube cooler driven by a linear compressor is being developed to provide cooling at 20 K. The first stage of the cooler will have the conventional stainless steel screen regenerator matrix. The matrix for the second stage regenerator (<60 K) will be made from a new class of Er based alloys which was recently developed at Ames Laboratory, in Ames, Iowa. These alloys exhibit heat capacities that exceed that of all other materials, including lead, over a wide range in temperature ($15\text{ K} < T < 85\text{ K}$). The performance of one such alloy was shown to be better than lead when tested in a single-stage pulse tube cooler driven by a G-M compressor and operating at 2 Hz. An effort is underway to establish their suitability at frequencies above 40 Hz. An approach to testing these alloys at low temperatures while using a low-power linear compressor is presented.

INTRODUCTION

Future NASA missions will involve transportation and/or storage of liquid hydrogen tanks for use as propellant. If no precautions are taken substantial amounts of liquid may be lost by evaporation due to inevitable parasitic heat loads, well before cryogen utilization. Cryocoolers may intercept parasitics, thereby, achieving zero boil off of the cryogen. This is necessary if the mission design requires a small tank volume or if the mission duration is sufficiently long.¹ Several such missions are discussed in Ref. 1, including a mission that realizes on-Mars propellant production (CH_4 and O_2 made from seed H_2 and atmospheric CO_2) sufficient to power a return vehicle back to earth. A representative cooling requirement for the seed-hydrogen tank to be transported to Mars is 2 W at 20 K plus 10 W at 60 K for cooling the heat shield.

For this and other similar applications requiring a cryocooler with high reliability and low vibration a pulse tube cooler (PTC) driven by a linear compressor is an attractive choice. The absence of cold moving parts in a PTC reduces wear and vibration and increases reliability. Consequently, the PTC is becoming the cryogenic cooler of choice on-board spacecraft.

Single-stage PTCs, driven by linear compressors and with a stainless steel stacked-screen regenerator matrix have achieved no-load temperatures below 40 K.² To provide cooling at lower temperatures, the PTC requires additional stages. In a multi-stage PTC there can be a large temperature difference between the heat rejection point and the cold tip. For high performance the regenerator materials need to have high heat capacity over the full temperature span. In general, this requirement cannot be satisfied using a single material. For lower temperature stages, materials other than SS are used.

Multi-stage PTCs have achieved temperatures below 4 K using low frequency G-M compressors.³ However, long-term reliability, compactness and mass favors the high frequency linear compressor over the G-M compressor.

To date no multi-stage PTC for use in space has yet been developed to provide cooling at temperatures below 40 K while rejecting heat at 300 K. A two-stage PTC is being designed to provide 10 W of cooling at 60 K and 2 W at 20 K. The matrix for the 1st stage regenerator will be 400 mesh SS screen. The matrix for the 2nd stage regenerator (<60 K) will be made from a new class of Er alloys which has recently been developed at Ames Laboratory, in Ames, Iowa.⁴ The heat capacity of these alloys exceeds that of all other materials, including lead, over a wide range in temperature (15 K < T < 85 K). The heat capacities of these and other regenerator materials are shown in Fig. 1. Another pertinent advantage of these alloys over lead is that they do not oxidize readily. Also, unlike lead, they are strong enough not to lose their sphericity over time when used as a spherical powder in a regenerator.

In-house experimentation on a GM-driven single-stage PTC validated Er ($\text{Er}_{96.8}\text{O}_{2.7}\text{N}_{0.3}\text{C}_{0.2}$) as a suitable low temperature regenerator material. In that study the regenerator consisted of two sections. The first section had a stacked SS screen matrix; while, the second section was packed

Figure 1. Volumetric heat capacity of various materials.

Figure 2. Rolled-foil regenerator matrix.

with either 200 μm Er or lead powder. With Er in the second section, the cooler achieved a lower no-load temperature.

Next to regenerator materials selection, the configuration given to these materials affects the performance of the PTC. One of the more significant regenerator parameters to be maximized is the ratio of gas-solid heat transfer to pressure drop across the regenerator. This ratio is highest for the parallel-plate regenerator configuration.⁵ Implementing this concept with the Er alloys will be explored. With proper heat treatment, a 25 μm thick foil of Er has been formed. The foil can be rolled around a low thermal conductivity mandrel, i.e., G10 (see Fig. 2). The spacing between foil layers will be maintained by inscribing lateral ridges in the foil. Uniform ridges were formed by Concurrent Technology on a sample Er foil. The length of each rolled-foil stack will be a fraction of the overall regenerator length requiring several of these stacks in the regenerator. A small gap will be maintained between adjacent stacks, thereby, enabling redistribution of the flow and minimizing mal-distribution of the flow between neighboring flow passages.

An alternative to the parallel-plate regenerator configuration is the more traditional packed-sphere configuration. It is appropriate that this configuration be also pursued in case the parallel-plate configuration does not live up to its theoretical prediction. Since the proposed cooler is to be operated at high frequencies, the particle sizes required tend to be smaller ($<100\ \mu\text{m}$) than those used in the low frequency G-M type. It has been demonstrated that spherical powders of the Er alloys can be manufactured even in small sizes.

Other than improving the PTC by optimizing the regenerators, performance will be enhanced by inserting in each stage an inductance tube between the pulse tube and the respective reservoir. Since it does not permit DC flow the inductance tube is preferred over adding a bypass. The cooler configuration will be optimized using the PTC modeling program Sage.

MATERIAL TESTING

An effort is underway to establish the suitability of the new Er alloys at frequencies above 40 Hz using a linear compressor. To test these regenerator materials a single stage pulse tube cooler using an inductance tube has been fabricated. The cooler is driven by a 350 W linear compressor that can operate from 36 to 72 Hz. In order to achieve a no-load temperature of below 20 K in a single-stage PTC, driven by this low-power compressor, liquid nitrogen is incorporated in the design to

Figure 3. Schematic of the regenerator test apparatus.

enhance the cooling power. To this end, the regenerator is made up of three sections. The matrix material for the first two sections is 400 mesh SS screen. A heat exchanger, externally cooled by liquid nitrogen, is inserted between these two sections. The heat exchanger is packed with 80 mesh copper screens.

The third section which is attached directly to the second section is packed with spherical powder of the material under test. Below this section reside the cold heat exchanger and the pulse tube. The warm end of the pulse tube, the inertance tube and the reservoir are all maintained at liquid nitrogen temperatures. Thus, the pulse tube warm heat exchanger is also cooled externally with LN2.

Liquid nitrogen is supplied to the heat exchangers from a LN2 can which shares the same vacuum enclosure with the pulse tube cold head. The inertance tube is coiled around the LN2 can. The reservoir is made of copper and is integrated with the bottom of the LN2 can. A schematic and a photograph of the test setup are shown in Figs. 3 and 4, respectively. The applicability of the new regenerator materials will be evaluated by measuring the performance of the test cooler. During testing the pressure will be measured at the outlet of the compressor, at the hot end of the pulse tubes and in the reservoirs using piezo-electric pressure transducers. From the compressor pressure and its displacement the P-V work of the compressor is calculated. The temperature at the inlets and the outlets of the aftercooler and the heat exchangers will be measured by thermocouples to assure their effectiveness. The temperature of the cold heat exchanger will be measured using a silicon diode thermometer. A heater will be placed on the cold heat exchanger to enable testing the cooling capacity of the cooler. The experimental parameters derived from the pressure and temperature data will be compared to the results of the model predictions in order to assess the applicability of the regenerator material.

Figure 4. Photograph of the regenerator test apparatus.

MODELING

The test PTC cold head described above was designed by employing the pulse tube cooler modeling program Sage. This program allows optimization of the various cooler components. It also accounts for the non-ideal behavior of the working fluid (helium), which is important for a realistic design particularly at low temperatures. The modeling effort optimized the dimensions of the pulse tube, the three regenerator sections and the inertance tube (see Tables 1 and 2).

SUMMARY

A new class of Er based alloys has been recently developed at Ames Laboratory, in Ames, Iowa that can be used in the regenerators of multi-stage pulse tube coolers. These alloys exhibit heat capacities that exceed that of all other materials, including lead, over a wide range in temperature ($15\text{ K} < T < 85\text{ K}$). A test apparatus has been constructed to validate the performance of these alloys at frequencies above 40 Hz. It consists of a pulse tube cooler with a regenerator that has three sections. Compensating for the low-power of the compressor the cooler design utilizes liquid nitrogen to achieve a no-load temperature below 20 K. The modeling program Sage has been employed to provide the optimum parameters for the test cooler. Initial check out of the test apparatus is currently underway.

Table 1. Parameters used in the optimization of the test cooler

Frequency	48 Hz
Ambient pressure	20 bar
Hot end temperature	300 K
LN2 HX temperature	80 K
Cold HX temperature	20 K

Table 2. Optimized parameters of the test cooler

Component	Dimension	Size
Regenerator	Length	1.38 cm
1 st section	Diameter	2.92 cm
	Matrix specifics	400 Mesh SS screen Wire diameter = 0.0025 cm
Regenerator	Length	2.67 cm
2 nd section	Diameter	2.50 cm
	Matrix specifics	400 Mesh SS screen Wire diameter = 0.0025 cm
Regenerator	Length	1.96 cm
3 rd section	Diameter	2.50 cm
	Matrix specifics	Spherical Er powder particle size = 125 μ m
Pulse tube	Length	4.15 cm
	Diameter	1.54 cm
Inertance tube	Length	1.51 cm
	Inside Diameter	0.32 cm
Reservoir	Volume	100 cc

Dimensions of the heat exchangers are fixed.

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