Testing of New Non-Rare-Earth Composite Regenerator Plates

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ABSTRACT

This paper discusses a testing technique and facility that has been developed in order to characterize a novel microchannel regenerator for 4 Kelvin pulse tube cryocoolers. These cryocoolers are used in applications such as military defense radio frequency transmission. The design utilizes circular silicon disks with a perforated outer edge and a center puck consisting of a non-rare-earth composite material that is proprietary in nature. However, the operation of the disks requires that they be exposed to helium at high pressure during operation which complicates the testing process.

Typically, a solid material is used at cryogenic temperatures to provide capacitance in regenerators at low temperatures. However, most materials have very low specific heats at 4 Kelvin. Creare is developing a non-rare-earth composite material that promises to achieve a very high specific heat. The composite material will be thermally coupled with the silicon outer ring of an exchanger disk, creating what could be a significant improvement in regenerator plates used in cryogenic applications.

This paper discusses the development of a test facility that will compare the disks to other types of materials in order to quantify the improved performance. The testing facility is a cryostat composed of a dewar that bathes a stainless steel test chamber in liquid helium. The tests are carried out within the chamber at temperatures below 10 Kelvin and pressures in excess of 1 MPa which are consistent with the conditions experienced inside of a cryocooler and required by the disks. The testing technique is transient in nature. A pulse of energy will be released into the disk causing a thermal wave to propagate through the material. Cernox™ temperature sensors will measure the time required for this process. A longer time response corresponds to a larger effective heat capacity. Therefore, the time response of a new plate compared to a typical rare earth metal regenerator corresponds to a greater heat capacity and therefore, an improvement in regenerator plates.

INTRODUCTION

A new type of regenerator plate, a non-rare-earth material, is being developed that promises a greater specific heat than traditional regenerators. The purpose of this project is to develop a method and experimental facility to measure the increase in thermal capacitance. Traditional methods of measuring specific heat calorimetrically rely on adding controlled amounts of energy

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in a vacuum and measuring the associated temperature change. These methods are not possible using the new plate as it requires a high pressure helium environment that is consistent with the actual operating environment of a pulse tube cryocooler operating at 10 Kelvin and 1 MPa of helium. It can be shown that the response time of a thermal wave through a regenerator is almost directly related to its specific heat: response time increases as specific heat increases. The experiment will take advantage of this relationship. This paper focuses on the design and construction of all components.

MODELING

The first part of modeling analyzed the proposed 30 mm diameter regenerator disks in order to verify that a measurable response time could be achieved in the experiment. Because only five 150 µm thick disks are being provided for the measurement it is a concern that the thickness of a stack of disks might be so small that differences between regenerator materials could be indistinguishable given the response time of the thermometry. It was necessary to provide additional thermal resistance between the disks using nylon spacers; this is equivalent to reducing the effective conductivity in the axial direction. The nylon spacers do not add significant heat capacity. The addition of the nylon increases the thermal response time of heat propagation through the regenerator.

The approximate equation below provides insight into the motion of a thermal wave within a semi-infinite material:

$$t = \frac{\delta^2 \rho_{eff} c_{eff}}{4k_{eff}} \tag{1}$$

where t is the time response of a thermal wave through a stack of disks, δ is the thickness of the stack, ρ_{eff} is the effective density, c_{eff} is the effective specific heat, and k_{eff} is the effective conductivity of the disk structure. If the thickness of the nylon is chosen, all of the variables on the right side of Equation (1) can be estimated and thus the time response t can be calculated. Thickening the nylon extends the time response t to a measurable number and also makes the measured time more sensitive to the effective heat capacity. Equation (1) was taken from *Heat Transfer* by Nellis and Klein. Results obtained for effective properties that lie within the expected range of the new material are shown in Figure 1. Material properties were determined in all calculations assuming a temperature of 10 Kelvin and pressure of 1 MPa; the next step focused on designing a capable facility.

DESIGN

A liquid nitrogen jacketed dewar is being used as a cryostat operating at atmospheric pressure to cool down a pressurized stainless steel chamber that holds the regenerator disks. The design is shown in Figures 2 and 3. A long, thin-walled stainless steel tube leading to the testing chamber is used to minimize the heat leak.

The construction is carried out in such a way as to allow a vacuum if it is ever required in future experiments. Many of the design ideas came from Ekin's *Experimental Techniques for Low-Temperature Measurements*. Instead of epoxy, all joints have either been welded or use compression fittings.

A VCR port for LN2 pump-out after pre-cooling was designed using an extended surface analysis in order to allow a thermal standoff that minimizes frost on the top plate. According to radiation calculations, it was also determined that the boil-off rate of helium changed negligibly after the addition of three radiation shields. Therefore three shields were added to the setup just above the test volume. Multilayer insulation was placed on the warm side radiation shield where it is most effective, as discussed by Barron in *Cryogenic Systems*.

For monitoring helium levels, an American Magnetics 110A meter and 18-inch sensor have been implemented. Data acquisition uses a simple connection block and National Instruments

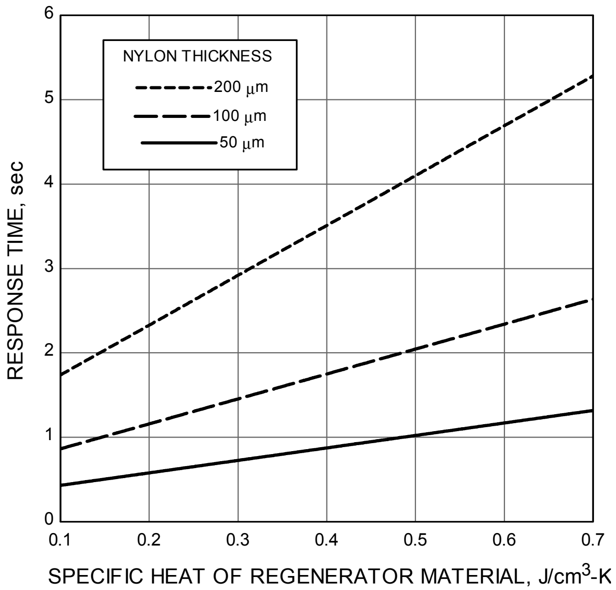

Figure 1. The response time of a thermal wave through a stack of plates as a function of the effective specific heat capacity for various values of the nylon thickness. The time response always increases with an increase in specific heat. The time response also intuitively increases at larger nylon thicknesses.

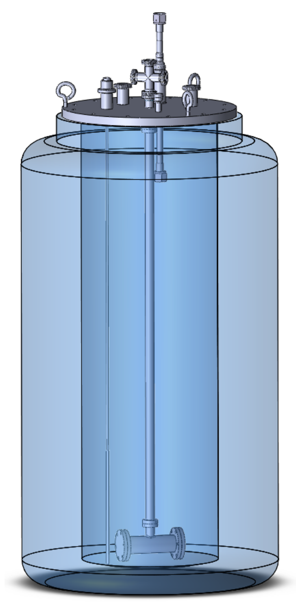

Figure 2. Shown are the main components of the test setup. A stainless steel top plate with various KF and VCR feedthroughs form a seal on the Dewar for both LN2 pump-out and future vacuum purposes. A slender thin-walled stainless tube runs from a top tee to the bottom test chamber; the tube is pressurized while the main space is at atmospheric pressure. The actual Dewar is approximately four feet tall and the inner bore is 12 inches in diameter. Note that for clarity, multilayer insulation and radiation heat shields have been omitted from this drawing.

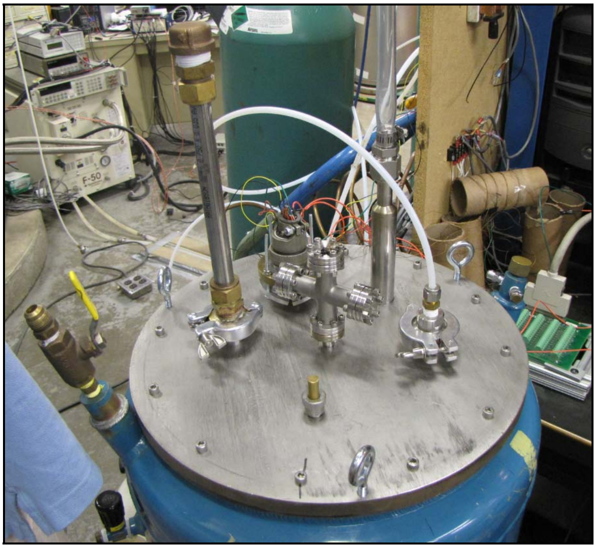

Figure 3. This is a photo of the top plate connected to the Dewar. The top plate is setup for calibration in this figure; a thin walled stainless tube on the left side of the photo is attached to a copper block holding sensors that sits near the base of the dewar. The white tube is a Swagelok helium gas inlet used for LN2 evacuation.

LabVIEW. Four Cernox^{TM} sensors are being used because of their small mass, i.e. fast time response, good accuracy, and broad range of functionality.

Although not constructed yet, inside the test chamber there will be two different regenerators with a resistance heater sandwiched between them. Temperature sensors will be mounted on the outer ends of the disks with one sensor in the center. The difference in the time that it takes an outer sensor's temperature to begin to increase relative to the inner sensor for each stack is the characteristic response time.

SUMMARY

This test station will be used to indirectly measure the specific heat of regenerator materials. Although it is being designed for one application, other similar measurements will be possible using this setup. The flexible design of the top plate allows many operating configurations. Currently it is set up as a calibration rig for temperature sensors. The construction of the facility is near completion; its full functionality is projected in October 2012.

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