3D-Printed Helium-Based Regenerator for 4K GM and Pulse Tube Cryocoolers

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ABSTRACT

Rare earth materials such as ErNi or $HoCu_2$ are used as the regenerator material in the low temperature region of 4K Gifford-McMahon (GM) and pulse tube cryocoolers. For some applications, non-magnetic regenerators would be favorable. As the cost of the regenerator material is a substantial part of the production cost, materials with lower cost would be desirable. Additive manufacturing techniques have advanced to a level that cost-effective production of 3D-printed structures is within reach.

The use of helium gas as the regenerator material for the low temperature region in 4K GM and pulse tube cryocoolers has been discussed over decades as helium also exhibits a high specific heat capacity in the temperature region of interest. Ideas to confine the helium gas range from helium-filled spheres[1] to the use of adsorbents[2] to trap the helium gas.

In this paper, we discuss an alternative approach for a helium-based regenerator: a 3D-printed metal structure is used to confine the helium gas as the regenerator. The size of the heat exchange surface as well as the flow resistance and dead volume can be tailored to the specific application.

INTRODUCTION

Pressure Wave Systems GmbH has recently started to investigate the use of helium as one of the regenerator materials for the low temperature region in 4K GM and pulse tube cryocoolers. The main driver for this development is a substantial cost reduction compared to rare earth material as well as the possibility to (partially) omit magnetic material.

There have been many efforts and ideas in the past, amongst them the idea of Heiden et al. to confine the helium in spheres and use these spheres to make up parts of the regenerator.[1] Recently, Chen et. al. have been presenting the idea of helium-adsorbing micro-structured silicon.[2]

A heat capacity comparison is shown in Figure 1.[3] It shows the volumetric heat capacity of various rare earth materials compared to ^3He and ^4He at various pressures. It can be seen that ^4He at 15 bar has an even higher volumetric heat capacity than $HoCu_2$.

Concept

Helium has to be confined within a thin walled structure to use as the regenerator material. Good heat exchange with the working gas flow is crucial as well as heat conduction considerations within

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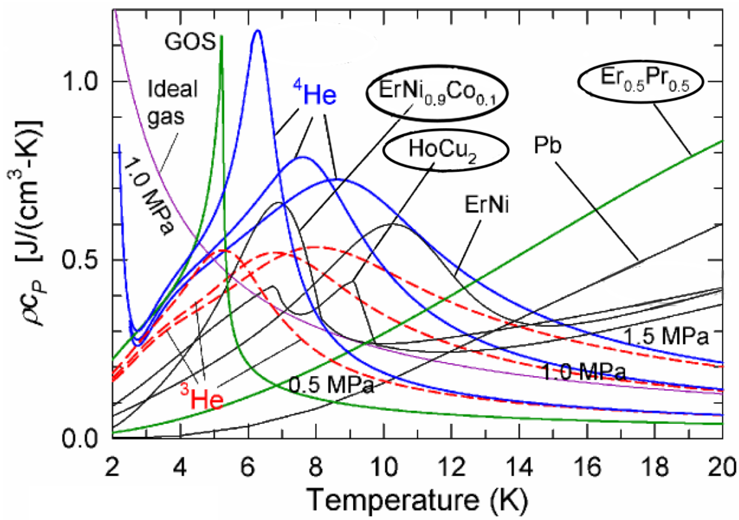

Figure 1. Volumetric heat capacity of various regenerator materials compared with that of ^{3}He and ^{4}He at various pressures[3].

the helium gas. As temperature and pressure conditions change from start-up to normal operation of the cold head it would be favorable if the gas would be in "contact" with the working gas.

To include all considerations above we are proposing the scheme depicted in Figure 2. The regenerator should be composed of thin walled helium containers with a small opening to the working gas space. In this way pressure and temperature of the helium in the regenerator are in equilibrium with working gas. As pressure variations in the helium in the regenerator due to the GM-cycle would introduce substantial PV losses, the opening to the working gas space should be small. It should be sized in a way that the pressure in the helium in the regenerator remains almost constant at the mid pressure of the GM-cycle. This concept can be viewed as a RC-filter for the GM-cycle frequency (Figure 3).

3D-printed structures

To realize this concept, we started to design 3D-printed metal objects to meet the above requirements. Figure 4 shows a sketch and a real 3D-printed metal test structure. The structure consists of a hollow core to confine the helium with small slits for the working gas. Wall thicknesses and slit

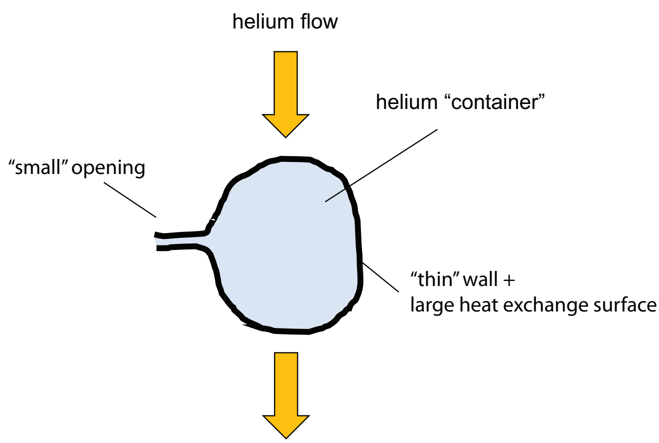

Figure 2. Concept for Helium regenerator

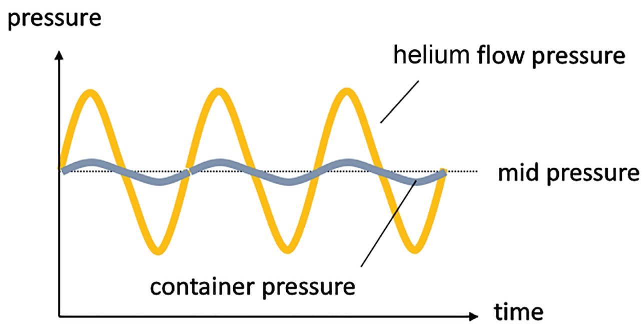

Figure 3. Sizing of the opening: pressure oscillations of regenerator gas (container pressure) compared the working gas (Helium flow pressure)

dimensions are in the few hundred-micron region. The depicted test structure has a diameter of 30 mm and a thickness of 1.4 mm.

Looking at volume, viscosity, pressure and temperature of the helium working gas in the low temperature regenerator region one finds that the characteristic time constant for the size of the opening to reduce the pressure oscillations to less than 10% needs to be at least in the minute range at room temperature. Figure 5 shows the characteristic time constant measurement for a test structure with an "accidental" opening in the right size. It turns out that for cubic centimeter volumes the opening needs to be in the few micron range.

To make up a full regenerator these structures can be stacked to the desired regenerator length and volume. Spacers may be introduced in between the structures to prevent thermal conduction alongside the regenerator.

STATUS AND CONCLUSIONS

We have successfully manufactured 3D-printed test structures with suitable dimensions and characteristics for a helium regenerator for a 4 Kelvin GM or pulse tube cryocooler. We are currently investigating the controlled fabrication of openings in the few micron range with ultra-short laser pulse manufacturing techniques. We hope to prepare a regenerator stack in the near future that can be verified in real cryocooler cold head operation.

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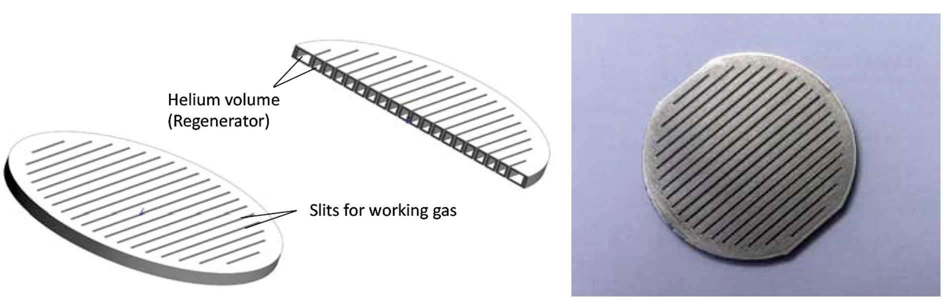

Figure 4. The regenerator test structure consists of a hollow core for the helium gas as well as slits for the working gas for heat exchange

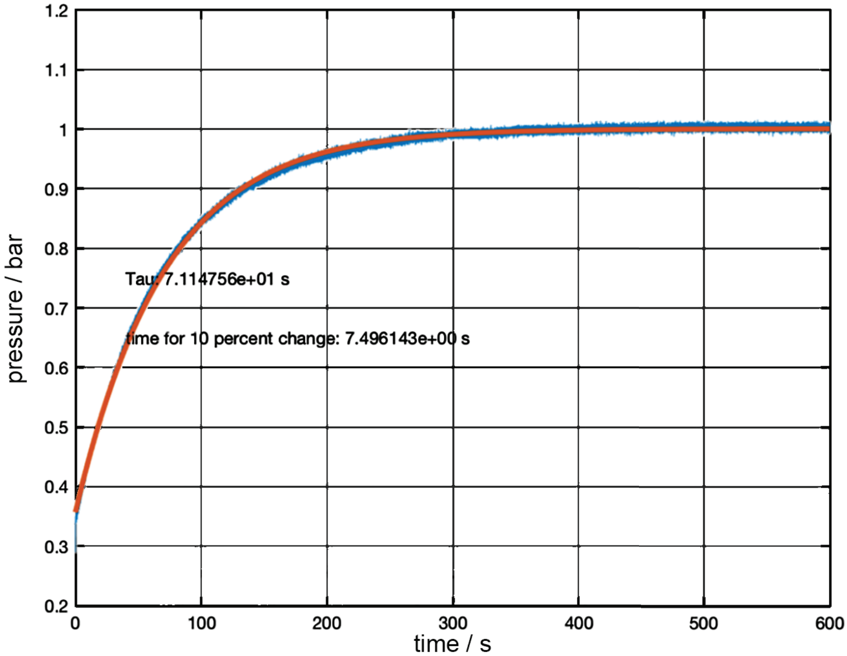

Figure 5. Measurement of characteristic time constant of a test structure. The time constant was measured to 71s.

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