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Numerical investigation of alternative regenerators in regenerative cryocoolers operating below 20 K

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Abstract. In regenerative cryocoolers, the regenerator is critical to performance and often contributes the most to system losses. Conventional materials such as stainless steel exhibit insufficient heat capacity below 20 K, increasing overall losses between gas and solid. Rare-earth materials like $HoCu_2$ and Er_3Ni offer high heat capacity in specific temperature ranges, but are costly and exhibit high flow resistance due to their spherical particle geometry. To explore practical alternatives derived from three existing design concepts, this study numerically evaluates three structures: coated #400 stainless steel mesh, stainless steel capillary tubes, and activated carbon fiber (ACF). Both the capillary and ACF configurations aim to enhance heat capacity by retaining helium within internal cavities and porous structures, respectively. Results show that the coated mesh performs between uncoated mesh and $HoCu_2$ spheres. The capillary design demonstrates excellent potential but is currently limited by dimensions of commercially available capillaries. In contrast, the diameter of existing ACF fibers matches well with the thermal penetration depth, ensuring their effectiveness. Its combination with $HoCu_2$ in an axially segmented configuration improves efficiency below 10 K. In summary, the findings highlight the potential of adsorption-based regenerators and offer a reference for future cryogenic regenerator design.

1. Introduction

In regenerative cryocoolers such as Stirling cryocoolers or pulse tube cryocoolers, the regenerator is a critical component that significantly affects overall system efficiency. Candidate regenerators for cryocoolers must satisfy several design criteria[1]. Most importantly the regenerator should provide sufficient volumetric heat capacity compared to the working gas, which is typically helium. Then, the solid matrix should have suitable thermal conductivity and hydraulic diameter, with characteristic dimensions within the thermal penetration depth, to facilitate efficient heat exchange of gas and solid and reduce axial conduction losses. In addition, a trade-off exists between minimizing flow resistance and enhancing gas–solid heat transfer, since the friction factor and Nusselt number are often positively correlated.

However, most commonly used regenerator materials fail to simultaneously meet these requirements, particularly in the sub-20 K temperature range. Most conventional regenerator materials, such as stainless steel mesh suffer from insufficient volumetric heat capacity below 20 K[2]. Current technology primarily employs rare-earth metals such as $HoCu_2$ and Er_3Ni, which

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offer high volumetric heat capacity within distinct temperature ranges. Owing to the inherent properties of these materials, they are commonly fabricated into spherical particles, a morphology that leads to substantial flow resistance losses. Moreover, their high cost and machining challenges restrict their widespread use in cryocooler applications.

To address these issues, several prior studies have proposed three alternative regenerator concepts. The first concept involves coating stainless steel mesh with high-heat-capacity materials, seeking to combine low flow resistance with enhanced heat capacity[3]. The second explores open-cavity structures capable of trapping helium[4], leveraging its high specific heat in oscillatory flow environments. The third considers the use of adsorbent materials to physically adsorb helium and improve effective heat capacity[5].

To identify suitable regenerators for cryocoolers operating below 20 K, this study numerically investigates three practical configurations—coated #400 stainless steel mesh, stainless steel capillary tubes, and activated carbon fiber (ACF)—each representing one of the three concepts described above. The performance and feasibility of these approaches are analysed to provide guidance for future regenerator designs.

2. Modelling and analysis

To quantitatively evaluate the performance of the alternative regenerator configurations, a simplified Stirling-type cryocooler subsystem model was constructed. The model includes a constrained compression piston, a regenerator, cold and warm heat exchangers and a constrained expansion piston as illustrated in Figure 1. The simulations were conducted using Sage software[6].

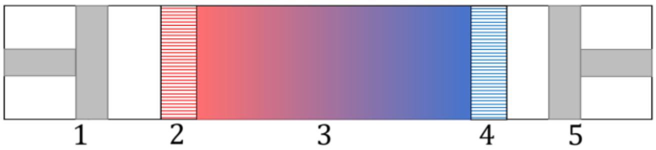


Figure 1. A Stirling-type cryocooler subsystem model

1. Drive piston 2. Hot heat exchanger 3. Regenerator 4. Cold heat exchanger 5. Expansion piston

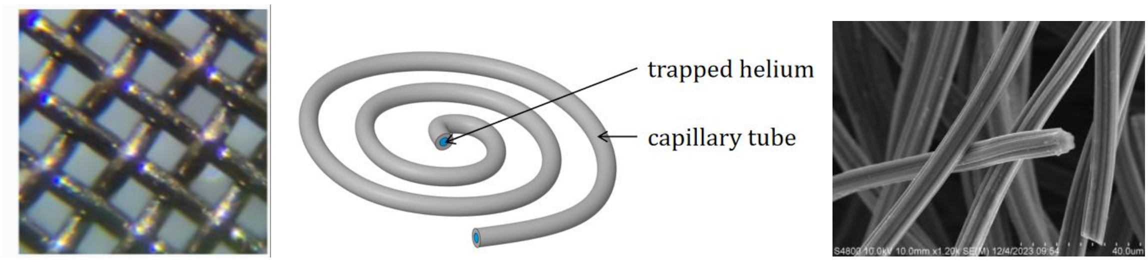
Cryocoolers operating in the 4 K to 20 K range often employ two or three-stage configurations[5]. This study focuses solely on the final-stage regenerator. The warm-end heat exchanger temperature is fixed at 40 K which is selected based on practical systems. The operating frequency is set at 30 Hz, and the acoustic power input is fixed at 8 W. The other operating conditions used in the simulations are summarized in Table 1. In the model with a fixed swept volume, the regenerator dimensions, expander amplitude, and phase are treated as free parameters optimized for each case.

For each alternative regenerator, an equivalent solid material is developed in Sage. The three regenerators studied are all filament-based. The equivalent thermal properties are expressed as $C_{eff} = \sum \phi_i C_i$ and $k_{eff} = \sum \phi_i k_i$, where ϕ_i , C_i and k_i denote the volume fraction, heat capacity, and thermal conductivity of component i, respectively. Although this approach is overly simplified, it still serves as a useful preliminary evaluation of the effective properties. More rigorous and detailed modelling will be addressed in future work.

The outputs of interest include net cooling power, acoustic power loss, and various loss components such as flow friction, surface heat transfer, and axial conduction.

Table 1. The operating conditions used in the simulations

Operating Conditions	Th/Tc	Frequency	Pm	PV Power
All materials	40K / 4-20K	30 Hz	2.0MPa	8 W



(1) (2) (3)

Figure 2. Configurations of the three alternative regenerators

(1) Coated wire mesh with $HoCu_2$ (2) Conceptual illustration of stainless steel capillary (3) SEM image of activated carbon fiber

Acoustic power is defined as

$$W_{pv} = \frac{1}{2}|\widehat{p_1}||\widehat{U_1}|cos\theta \quad (1)$$

Where $\widehat{p_1}$, $\widehat{U_1}$ is the first order quantity of oscillate pressure and volume flow rate, θ is the phase difference of $\widehat{p_1}$ and $\widehat{U_1}$.

The relative Carnot efficiency in terms of consumed acoustic power is defined as:

$$\eta_r = \frac{Q_c}{\Delta W_{pv}} / \frac{T_c}{T_h - T_c} \quad (2)$$

In this study, coated #400 stainless steel wire mesh was used to implement the first regenerator concept. A small batch of samples was fabricated via physical vapor deposition (PVD), coating each 25.4 μm wire with a 5 μm layer of $HoCu_2$ or Er_3Ni. Geometric estimates show the coating accounts for ~50% of the total cross-sectional area. The coated wire diameter remains much smaller than the thermal penetration depth, satisfying the criterion for a homogeneous mixture. The stacked wire mesh model was employed to represent the structure.

One advantage of this approach is that it retains the structure of the original mesh structure, ensuring low flow resistance. In addition, the mechanical stability is expected to be reliable over extended periods, which is particularly important for cryocoolers designed for long-term operation without maintenance. However, the use of rare-earth materials and PVD process significantly increases cost, making it less attractive for cost-sensitive or commercial-scale cryocoolers.

Stainless steel capillaries are investigated as a structural realization of the second regenerator concept. The inner cavity of each capillary acts as a reservoir for helium gas, while the small openings at both ends allow for helium retention under high-frequency oscillating flow conditions.

Initial consideration was given to commercially available capillaries with typical outer diameters of 0.4–0.6 mm and wall thicknesses of approximately 0.1 mm, resulting in helium volume fractions ranging from 25% to 44%. However, even the smallest internal diameter (~0.2 mm) exceeds the thermal penetration depth of helium, violating regenerator design principles[7]. For this reason, a virtual capillary with zero wall thickness is assumed, with an outer diameter of 25.4 µm.

The primary advantage of this design lies in its structural simplicity and considerable reliability. However, due to current fabrication limitations, the capillary dimensions remain too large for effective use as regenerators. Additionally, the associated cost is relatively high.

As a realization of the third concept, this study considers a type of activated carbon fiber (ACF) with a fiber diameter of approximately 10 µm and a BET specific surface area of around 1000 m^2/g. The adsorption characteristics were derived from temperature-dependent experimental measurements[8]. The specific heat and thermal conductivity of activated carbon were taken from data of similar carbon materials[9]. Assuming the ACF as a perfect cylindrical filament with adsorbed helium, i.e., a homogeneous forming a uniform outer shell, the volume of the adsorbed helium is given by:

$$V_{He} = \frac{n_{ads}\rho_{carbon}M_{He}\pi r^2 L}{\rho_{He}} \tag{3}$$

Where V_{He} is volume of adsorbed helium (m^3), n_{ads} is adsorption capacity (mol/g), ρ_{carbon} is density of the carbon framework (kg/m^3), M_{He} is molar mass of helium (≈ 4.0026 g/mol), r is radius (m), L is length (m) and ρ_{He} is density of helium (kg/m^3).

The advantage of ACF lies in its commercial availability and ease of mass production. However, uncertainties remain regarding debris generated due to friction or thermal cycling, particularly under oscillating flow conditions. Furthermore, adsorption heat may induce temperature fluctuations and impact the overall performance of the regenerator[5].

Each approach introduces different mechanisms to enhance effective volumetric heat capacity as shown in Figure 3. In the following section, these configurations are evaluated and compared through numerical simulation to assess their performance under consistent operating conditions.

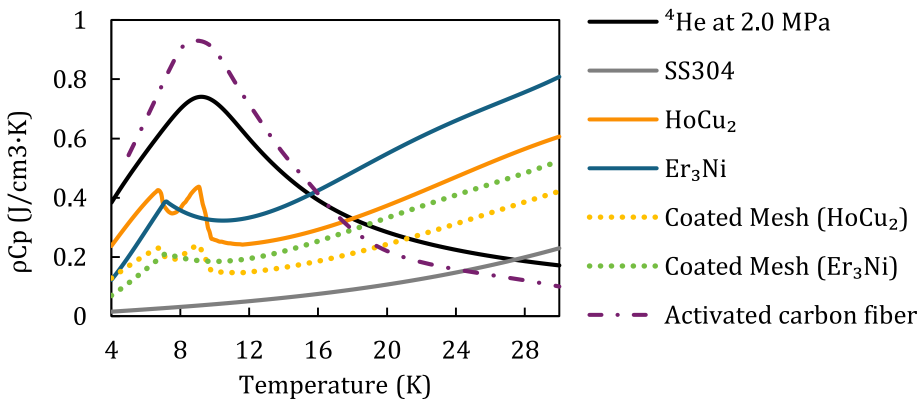


Figure 3. Volumetric heat capacity as a function of temperature for various materials

3. Results and discussion

3.1 Coated wire mesh

The performance of the coated wire mesh regenerator was evaluated by comparison with #400 stainless steel mesh and 80 μm spherical $HoCu_2$ particles. Figure 4 shows the variation in relative Carnot efficiency and losses at 20K for the coated wire mesh.

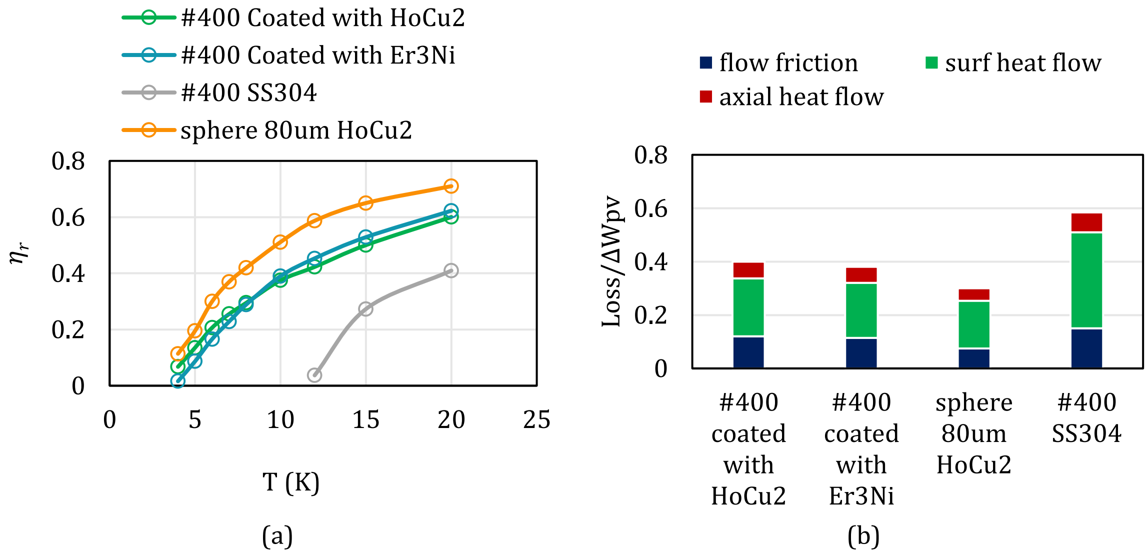


Figure 4. Simulation results of coated wire mesh

(a) Relative Carnot efficiency; (b) Loss breakdown at 20 K("Loss/ΔW_{pv}" denotes the ratio of each loss component to the consumed acoustic power)

The coated mesh exhibits intermediate performance between #400 stainless steel mesh and $HoCu_2$ spheres. In terms of loss components, it notably reduces the heat transfer loss between gas and solid compared to the uncoated mesh, but it remains higher than that of the $HoCu_2$ spheres. Besides, flow loss constitutes a relatively small portion of the total loss. Therefore, despite the lower flow resistance of the coated mesh compared to the spheres, the overall performance still falls short of that achieved by $HoCu_2$ spheres.

3.2 Open capillary tube

To address the insufficient heat capacity above 25 K, two axial segmental packing configurations were investigated. In the first configuration, #400 stainless steel mesh was used in the warm section and capillaries in the cold section. In the second configuration, 80 μm $HoCu_2$ spheres were used in the warm section, again with capillaries in the cold section. The performance is shown in Figure 5 together with that purely using $HoCu_2$ sphere or stainless steel mesh for comparison.

Simulation results indicate that, when combined with stainless steel mesh, the virtual capillary structure significantly outperforms the #400 stainless steel mesh alone. However, due to the limited hea capacity of both helium and stainless steel in the 15–30 K range, its overall performance remains inferior to that of $HoCu_2$ spheres. The optimized filling fraction of capillaries increases as the cold-end temperature decreases, with a transition around 30 K.

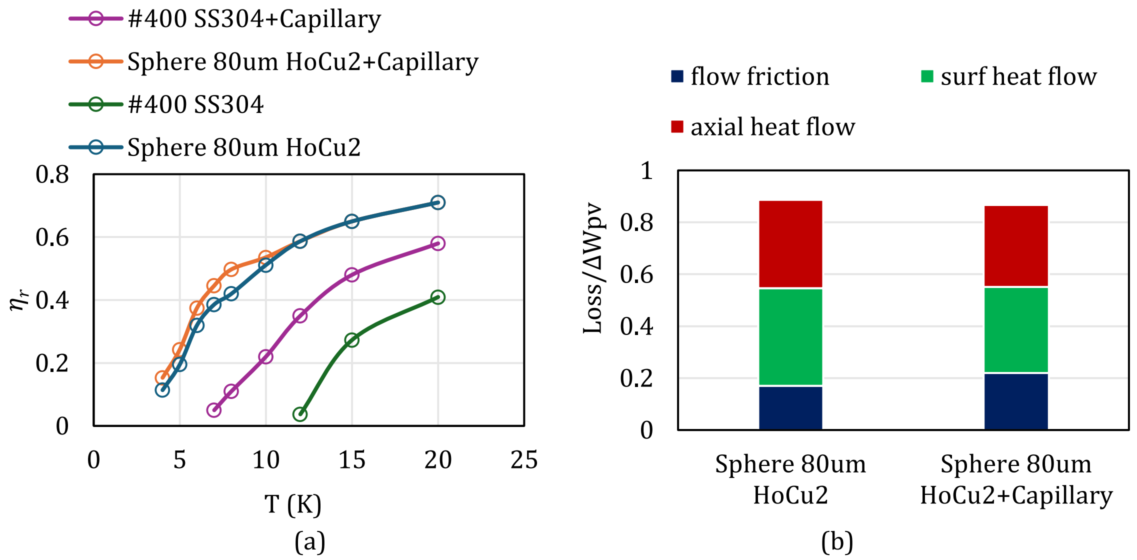


Figure 5. Simulation results for combined $HoCu_2$ sphere and open capillary tube regenerators

(a) Relative Carnot efficiency; (b) Loss breakdown at 4K ("Loss/ΔW_{pv}" denotes the ratio of each loss component to the consumed acoustic power)

When combined with $HoCu_2$ spheres, the virtual capillary structure achieves superior performance below 10 K compared to using $HoCu_2$ alone. As shown in the loss analysis, the improvement stems from reduced heat transfer losses between gas and solid. However, as the cold-end temperature approaches 4 K, the rate of improvement decreases, where real-gas effects become dominant and cannot be mitigated by simply increasing th matrix heat capacity[1].

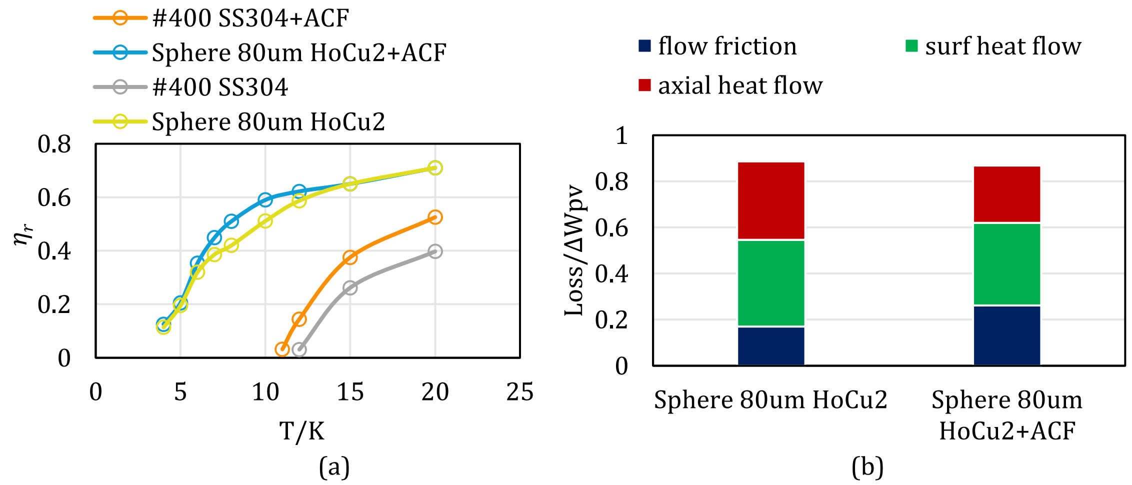


Figure 6. Simulation results for combined $HoCu_2$ sphere and activated carbon fiber regenerators

(a) Relative Carnot Efficiency of Two Axial Segmental Packing Configurations; (b) Loss Breakdown at 4 K ("Loss/ΔW_{pv}" denotes the ratio of each loss component to the consumed acoustic power)

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3.3 Activated carbon fiber

Similarly, to address the limited heat capacity of ACF above 15 K, two axial segmental packing configurations were examined. The first configuration employed #400 stainless steel mesh in the warm section and ACF in the cold section, while the second used 80 μm $HoCu_2$ spheres in the warm section, again paired with ACF in the cold section. The performance of these two configurations is shown in the Figure 6.

The results show that combining ACF with stainless steel mesh offers limited improvement, as both materials exhibit insufficient heat capacity between 15 K and 30 K. In contrast, the configuration using $HoCu_2$ spheres with ACF delivers a noticeable performance enhancement. Around 10 K, the volume packing fraction of the ACF section is approximately 20%, increasing to about 50% near 4 K, with the transition occurring roughly between 10 K and 12 K.

4. Conclusion

This study numerically examined three regenerator configurations—coated wire mesh, open capillary tubes, and activated carbon fiber—each representing a distinct approach to addressing the challenge of insufficient heat capacity in regenerators of cryocoolers operating below 20 K.

Simulations and optimizations conducted using Sage indicate that coated wire meshes provide moderate improvements, primarily due to their limited increase in heat capacity. When used together with $HoCu_2$ spheres, ideal capillary tubes can surpass the performance of pure $HoCu_2$ spheres below 10K, but their application is currently limited by their oversized dimensions. In contrast, activated carbon fiber can be fabricated with appropriate dimensions. Therefore, when combined with other high volumetric heat capacity materials, it yields considerable performance enhancement below 10 K.

From a practical perspective, both coated meshes and capillaries present fabrication challenges and high costs, whereas ACF is more accessible and scalable, though its long-term stability requires further study. Overall, adsorption-based regenerators such as ACF exhibit the greatest potential and warrant continued investigation.

Acknowledgments
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