Experimental investigation on regenerator materials of Stirling-type pulse tube refrigerator working at 20 K

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Background

Stirling-type pulse tube refrigerator (STPTR) manifests itself a good choice in cooling devices for space use. Nowadays, STPTR has been developed to work at a temperature below 4.2 K. At low temperature (＜ 40 K), the specific heat capacity of regenerator materials decreases rapidly, which leads to a poor performance of regenerator.

The sphere materials, such as lead, Er_3Ni, and $HoCu_2$ possess a relatively high specific heat capacity and are employed in our lab-made STPTR working at liquid-hydrogen temperature. This paper will discuss the performances of different regenerator materials.

Outline

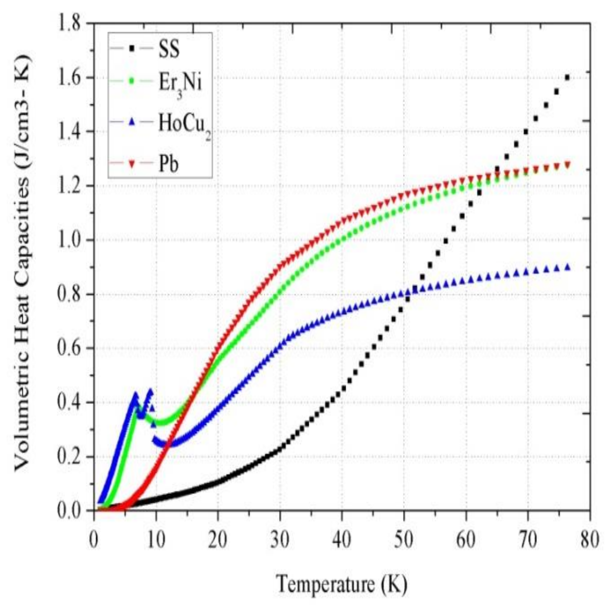
- To demonstrate the principle to choose the suitable regenerator materials of different specific heat capacity and thermal conductivity.
- To clarify the different performances between wire-mesh and sphere regenerator materials in term of flow resistance.
- To introduce briefly the STPTR of a no-load temperature 14.7 K.

Conclusion

- Er_3Ni, with a large ratio of C_p to λ, is proved to be a most promising material to replace stainless steel wire-mesh to improve the refrigerator performance.
- The flow resistance of sphere materials is proved to be greater than that of wire-mesh by measurement both on steady flow condition directly and oscillating flow condition indirectly.
- Choosing the appropriate materials, together with some tricks to lower the flow resistance, we achieve a remarkable no-load temperature 14.7 K with Stirling-type one-stage co-axial pulse tube refrigerator.

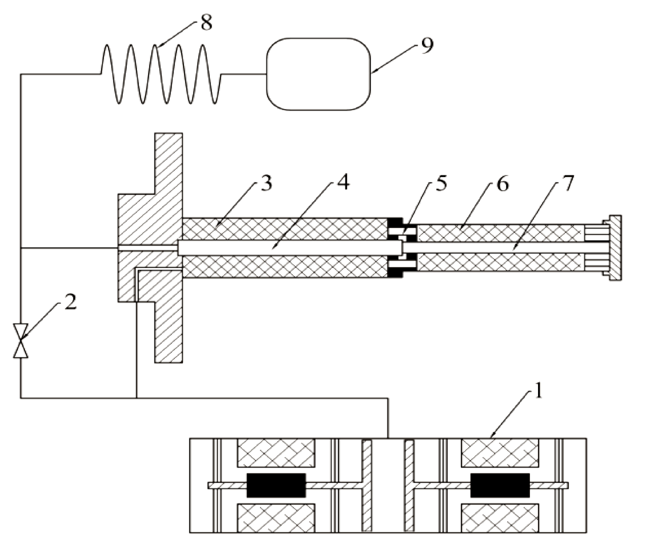
Materials

The volumetric heat capacity



- ✓ SS represents stainless steel wire-mesh and Pb, Er_3Ni, $HoCu_2$ always appear in the form of spheres.
- ✓ At low temperature, the volumetric heat capacity of different materials decrease rapidly.
- ✓ The heat capacity of lead spheres dominate in value over a large temperature range.

Schematic of the STPTR

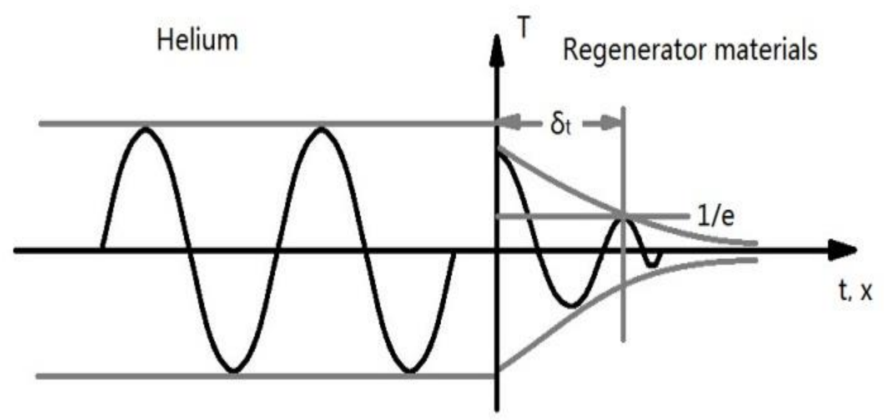


1 compressor; 2 double-inlet; 3 first-segment regenerator; 4 first-segment pulse tube; 5 multi-bypass flange; 6 second-segment regenerator; 7 second-segment pulse tube; 8 long-neck tube; 9 gas reservoir.

✓20.4 K no-load temperature with SS as regenerator materials.

✓1 W cooling power at 33 K with 230 W input power at 35 Hz.

The materials choosing principle



Temperature contribution of regenerator materials

Assume

$$T(x=0,\ t)=T_1\cos(2\pi ft)$$

After solving the energy equation

$$T(x)=T_1e^{-x\sqrt{\pi f\rho C_p/\lambda}}$$

We define the thermal penetration depth δt as the depth where the amplitude of the temperature is 1/e of the temperature oscillating amplitude at the solid surface

$$T(\delta_t)=T_1/e$$

Then, we obtain

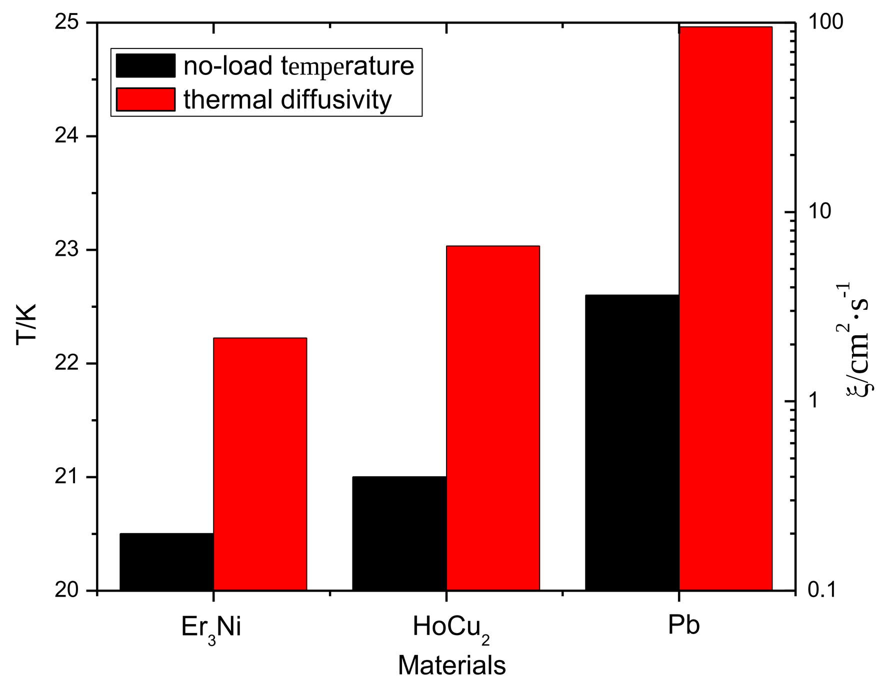
$$\delta_t=\sqrt{\frac{2\lambda}{w\rho C_p}}=\sqrt{\frac{2\xi}{w}}$$

Where $\xi=\lambda/(\rho\cdot C_p)$ is thermal diffusivity

The property of regenerator materials at 2.0 MPa charging pressure, 35 Hz operating frequency, and 20 K

	λ W/(m•K)	C_p J/(cm³•K)	ξ cm²/s	δ_t mm
He	0.0328	0.284	0.115	0.0323
Pb	57.5	0.605	95.0	0.928
Er_3Ni	1.2	0.555	2.16	0.140
$HoCu_2$	2.5	0.378	6.61	0.245

Results



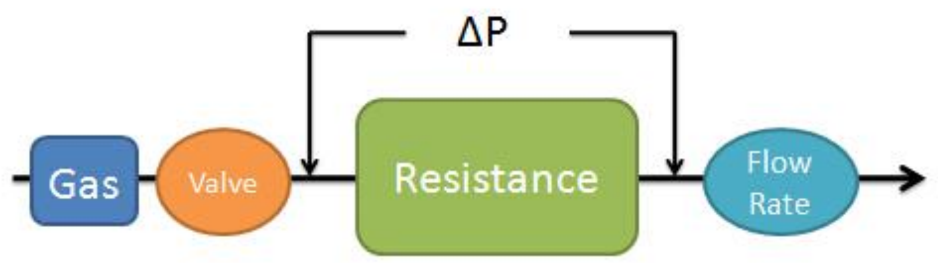
No-load temperature and thermal diffusivity corresponding to different materials

The no-load temperature shares the same trend with the thermal diffusivity.

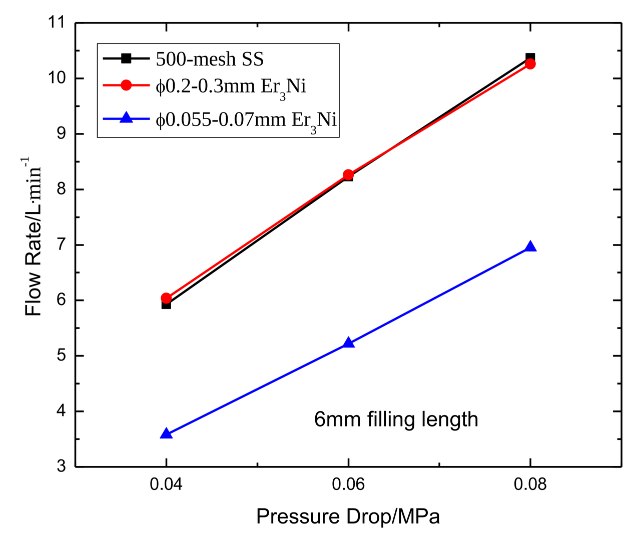
Er_3Ni owns the largest ratio of C_p to λ and achieves the best performance which approaches the 500-mesh SS very closely.

The performance of Pb is the worst even though it possesses the highest value of C_p, which can be attributed to higher thermal conductivity resulting in larger regenerator axial conducting loss

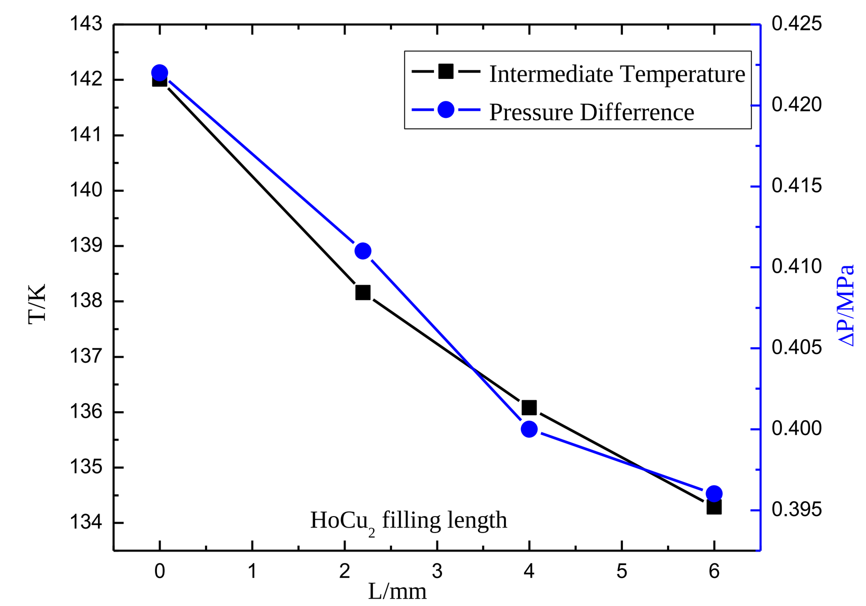
The flow resistance



Schematics of steady flow resistance measurement



The measured stead-flow resistance



The amplitude of pressure oscillating decreases as the filling length of $HoCu_2$ increasing, convincing the larger flow resistance leads to larger pressure drop when gas flows through the regenerator.

The intermediate temperature of the flange at the multi-bypass position decreases with the enhancing filling length. We estimate that more gas passes through the multi-bypass hole and enter the pulse tube to provide refrigeration to cool the stage to lower temperature.

14.7 K STPTR

The performance with different regenerators

Regenerator materials	no-load temperature	Optimum frequency
/	K	Hz
500-mesh SS	17.4	35.5
500-mesh SS+Er_3Ni	16.5	31.5

✓We choose 8.5mm-filling length, 0.055-0.07 mesh Er_3Ni as the regenerator at the position closest to the cold head.

✓The length of the second-segment regenerator is 35mm and we increase the ratio of regenerator area to pulse tube area from 3.5 to 3.9 to lower the mass flow in the regenerator in order to decrease the flow resistance.

✓The Er_3Ni regenerator gets the better performance with a lower optimum operating frequency than SS regenerator.

✓Afterwards, the size of multi-bypass is adjusted to the optimum value; then, the no-load temperature with Er_3Ni regenerator can reach 14.7 K with 250 W input power, while the temperature of the multi-bypass flange is 79 K.

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