Study of a 35 K Regenerator Performance Operating at High Frequency

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ABSTRACT

The objective of this paper is to observe the regeneration performance of three different regenerator materials including stainless steel screen, lead screen and lead sphere at 35 K and at a high operating frequency. A systematic comparison of the three different materials' performance including effects of COP, the pressure ratio and the cold-end temperature was carried out using REGEN3.2. Calculation results indicate that the performance of stainless steel screen is better than that of lead sphere and #500 mesh stainless steel screen satisfies the design requirement of a regenerator at a frequency of 40 Hz and a low pressure ratio at 35 K. Moreover, lead screen matrix performs best at 20 K; #500 mesh lead screen has a COP double that of a stainless steel screen.

INTRODUCTION

The regenerator is one of the key components of regenerative cryocoolers. Regenerator loss caused by the defects in the regenerative matrix and its structure accounts for a considerable proportion of the total losses. Such losses increase significantly when the cooling temperature decreases below 80K.[1]

The efficiency of the regenerator is largely dependent upon the ratio of the volumetric specific heat capacity of the regenerator matrix to that of helium. As shown in Figure 1, the volumetric specific heat capacity of lead is larger than that of stainless steel at a temperature lower than 80 K, so Gifford McMahon (GM) cryocoolers which use lead sphere as regenerator matrix have better refrigerating effects than those using stainless steel screen as the regenerator matrix.[2-4]

The situation is different in high frequency pulse tube cryocoolers. The experiments show that the lowest no-load cooling temperature obtained when lead spheres, which have a larger volumetric specific heat capacity, is used as the regenerator matrix is 5-6 K[5] higher than when stainless steel screens are used. This result demonstrates that the cooling temperature depends not only upon the volumetric specific heat capacity of regenerator matrix, but also upon the degree of heat transfer between the gas and the regenerator matrix, and upon the pressure drop in regenerator.

In order to obtain a better understanding and to compare the mechanism of lead sphere and stainless steel screen used as regenerator materials at 35 K, simulation calculations of the regeneration performance of the three regenerator materials: stainless steel screen, lead screen and lead sphere [5-11] in high frequency pulse tube cryocoolers working at 35 to 80 K were carried out using REGEN3.2.[12] The loss associated with the expansion phase in a pulse tube is assumed to be con-

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stant, accounting for 20% of the gross cooling power in the calculation. Hence, the regeneration performance of the three different regenerator materials is determined by COP.

Calculation results indicate that the performance of the lead sphere is worse than that of the stainless steel screen and the lead screen when they are used as the regenerator matrix at 35 K and 40 Hz This means that lead spheres are not an ideal regenerator material at high frequency and low temperature compared with other materials, though it has a larger volumetric specific heat capacity and a lower Debye temperature. This conclusion is in accordance with the experimental result in Yang, et. al.[5]

THERMAL PENETRATION DEPTH OF REGENERATOR MATRIX

The requirements of the regenerator matrix includes sufficient specific heat capacity and heat transfer surface area at a working temperature to facilitate heat transfer between the matrix and gas, small flow resistance and axial heat conduction. As shown in Fig. 1, the volumetric specific heat capacity (ρC_p) of lead and stainless steel decreases in proportion to T^3 as the working temperature decreases. Furthermore, since lead has a lower Debye temperature than stainless steel, it has a larger volumetric specific heat capacity than stainless steel at low temperature. On the other hand, the volumetric specific heat capacity of helium increases as the temperature decreases. Since both lead and stainless steel have larger volumetric specific heat capacities than helium, they both fulfill the requirement of large volumetric specific heat capacity of regenerator matrix at 35 K.

On the other hand, a regenerator matrix is at an unsteady heat transfer and fluid flow state during the working process in a regenerator. Consequently, a large thermal diffusivity in the regenerator matrix is necessary to ensure that the heat transfer from the gas to the surface of the regenerator matrix can transfer to the inside of the solid, and then transfer to the gas again. From the analysis above, we can see that the thermal diffusivity is an essential issue in designing the regenerator of a high frequency cryocooler.

Consider specific heat capacity and thermal conductivity, thermal diffusivity a is given by:

$$a = \frac{k}{\rho C_p} \tag{1}$$

where k is thermal conductivity; ρCp is heat capacity. Eqn. 1 indicates that the rate of heat transfer between the regenerator matrix and the gas is related to the system frequency. The adaptation of the size and shape of the regenerator matrix and the working frequency are investigated to choose high frequency regenerative material.

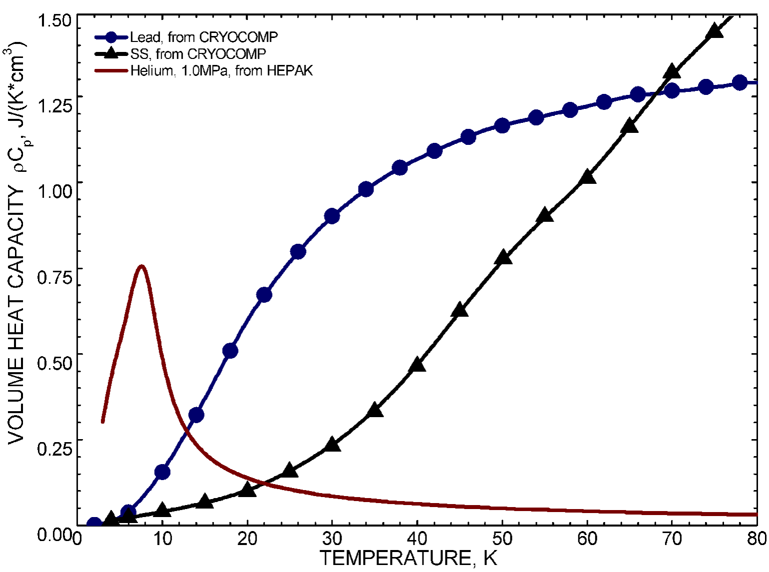

Figure 1. Volumetric specific heat capacity of lead, stainless steel and helium

Assuming the regenerator material is a semi-infinite body with a initial temperature T_0; the surface temperature changes periodically as $T_1\cos(2\pi f t)+T_0$, and the amplitude of inner part temperature of solid decreases exponentially as the distance from the surface x increases. The temperature amplitude at a distance x from the solid surface is:

$$A = T_1 \exp\left[-x\left(\frac{\pi f}{a}\right)^{\frac{1}{2}}\right] \tag{2}$$

where a is thermal diffusivity; f is the vibration frequency of temperature; T_1 is the temperature amplitude at the surface. Define the distance at which the temperature amplitude is T_1/e is thermal penetration depth L_d,

$$L_d = \left[a/(\pi f)\right]^{1/2} \tag{3}$$

From the Eqn. 3, we can see the higher temperature vibration frequency f will yield a smaller thermal penetration depth L_d, which means the effective portion of solid participated in heat transfer is smaller.

Figure 2 shows the relation between the heat penetration depth of helium-4 and temperature at 1.0 MPa and a series of frequencies of 1.4 Hz, 30 Hz, 40 Hz and 60 Hz, respectively. The equivalent diameters of spheres with different diameters (0.06-0.3 mm) and screens with different mesh (#200-#635 mesh) are also shown in the figure. From the figure, we can see that for GM cryocoolers or GM-type pulse tube cryocoolers working at a low frequency of 1.4 Hz, the minimum heat penetration depth of helium-4 is 83.39 μm, which is larger than the equivalent diameter of lead sphere with a diameter of 0.2 mm (81.72 μm). This guarantees the heat transfer between gas and matrix. As a result, the sphere matrixes with diameters at 0.2-0.3 mm is proper at 4 K.

Similarly, the heat penetration depth of helium-4 at 35 K and a working frequency range of 30-40 Hz is 77.72 μm and 67.31 μm, respectively. As shown in the Figure 2, to guarantee sufficient heat transfer between the helium gas and the matrix, the suitable screens are #325 mesh, #400 mesh, #500 mesh and #635 mesh and the suitable diameters for spheres are less than 200 μm.

In summary, the characteristics of heat transfer and flow through a regenerator matrix of stainless steel screens with #400 mesh, #500 mesh and #635 mesh, the lead spheres with 100 μm, 150 μm and lead screens with #400 mesh, #500 mesh has been investigated. The lead screen actually

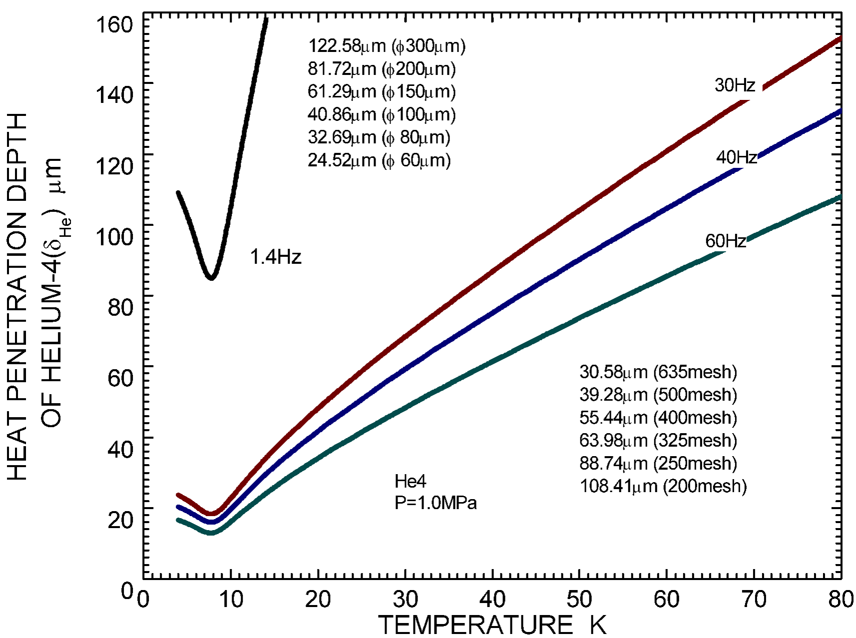

Figure 2. Effect of temperature and frequency on thermal penetration depth

used is thin stainless steel or phosphor bronze screen on which lead is plated. However the lead screen discussed here refers to the lead screen woven by pure lead, which is an ideal assumption.

FLOWABILITY OF REGENERATOR

In order to estimate the effect of the porosity of the regenerative matrix and the pressure on the performance of the regenerator, the loss associated with the expansion phase in the pulse tube is assumed to be constant and accounts for 20% of the gross cooling power, and the regeneration performance of the three different regenerative materials are measured by COP (i.e. the ratio of net cooling power at 35 K to the PV work at the entrance of regenerator at which the temperature is 80 K).

Figure 3 shows the results obtained from studies of the relationship between the COP and the ratio of the flow area of gas to mass flux at cold end of the regenerator when stainless steel screens with different mesh and lead spheres with different diameters are used as the regenerative matrix at 35 K. As shown in Figure 3, the performance of the stainless steel screens is better than lead spheres within the range of mass flux at 35 K. Furthermore, the mesh of the stainless steel screen and the diameter of the lead spheres also influence the performance of the regenerator. Among the matrixes, #500 mesh stainless steel screen, which has a COP 17% higher than lead spheres with diameter of 150 μm, performs best, and #635 mesh stainless steel screen comes in second; lead spherse with a diameter of 200 μm performs worst. This result is contrary to the result obtained from the low frequency condition.

Figure 4 shows the change curves of COP for the three different matrixes at 40 Hz as cold-end pressure ratio changes. As shown in Figure 4, lead spheres perform worse than the stainless steel screen when the cold-end pressure ratio is lower than 1.5; lead spheres have a better performance than the stainless steel screen when the cold-end pressure ratio is higher than 1.5. Though the conclusion is obtained at 40 Hz, it also works for low frequency and large pressure ratio condition. For example, lead sphere performs better than stainless steel screen in GM cryocoolers which work at large pressure ratio and low frequency while the situation is just the opposite when high frequency is applied. This result fully confirms the importance of cold-end pressure ratio of the regenerator.

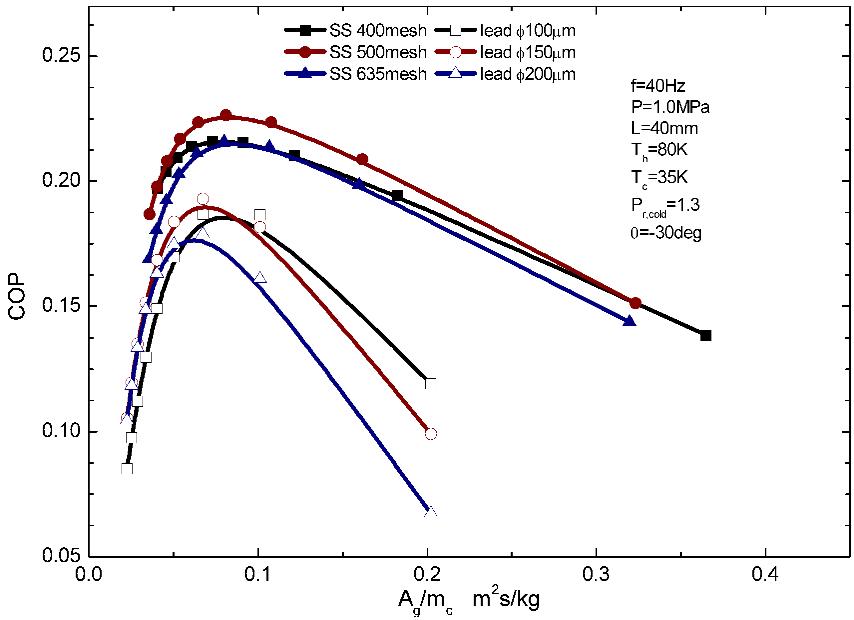

Figure 3. Effect of regenerative materials on the performance of regenerator

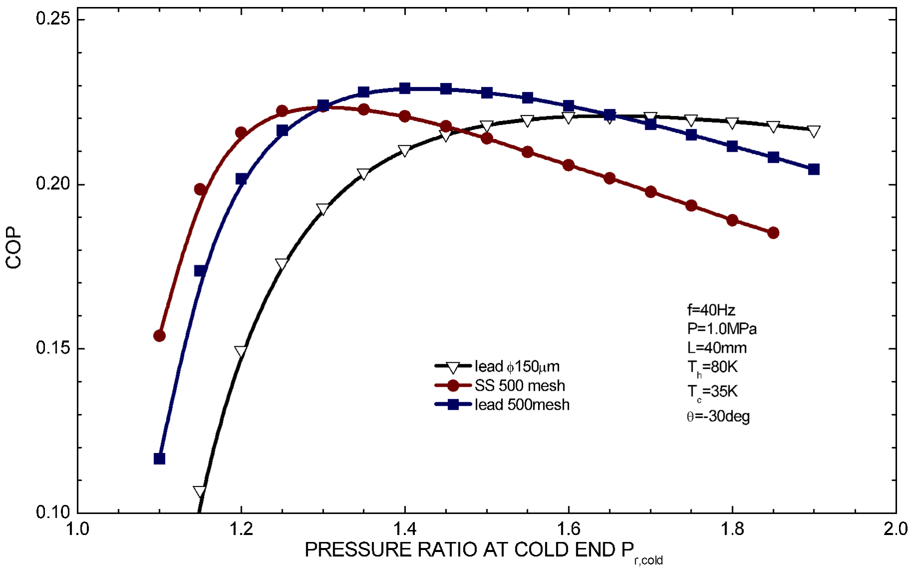

Figure 4. Influence of cold-end pressure ratio of regenerator on the performance of regenerator

Lead sphere has a smaller porosity (generally 36-39%) compared with stainless steel screen (generally 60-70%) and a larger flow resistance, which increases as the diameter of lead sphere decreases. By contrast, the structure of screen mesh is not so sensitive to the change of pressure ratio, which is helpful to decrease the loss associated with pressure drop. Apparently, the larger the pressure drop in regenerator is, the smaller pressure ratio would be obtained at the cold end of regenerator, resulting in a worse performance of regenerator. As shown in Figure 4, lead screen has a larger COP at 35K than lead sphere when the cold-end pressure ratio is lower than 1.3. This is the result of a smaller flow resistance in the screen structure. Furthermore, the COP of lead screen is higher than that of stainless steel screen when the cold-end pressure ratio is in the range of 1.3-1.7, indicating that when the losses associated with pressure drop in lead screen and stainless steel screen are similar, lead screen has a higher volumetric specific heat capacity. However, a cold-end pressure ratio higher than 1.3 is hard to obtain as a result of the limit of a real linear compressor's performance. Therefore, stainless steel screen is the best choice for regenerator matrix at this temperature.

EFFECT OF REFRIGERATION TEMPERATURE ON REGENERATOR'S PERFORMANCE

Analyses above with regard to the effect of refrigeration temperature and pressure ratio on the refrigeration performance of the regenerative matrix point out that if a cold-end pressure ratio reached 1.3 or above, lead screen would have benefit from a higher COP due to the small pressure drop and large volumetric specific heat capacity. Figure 5 indicates the relation between COPs of various regenerator matrixes and the ratio of gas flow area to cold-end mass flux of regenerator. As shown in the figure, lead screen and lead sphere both have higher COP than stainless steel screen when the cold-end temperature decreases to 20 K. However, since lead sphere has small porosity and a large pressure drop, the cold-end pressure ratio of the gas driven by a linear compressor decreases when lead spheres are used as the regenerator matrix, so the COP also decreases. The two dashed lines in Figure 5 show the change curves of 150 μm lead sphere's COPs when the cold-end pressure ratio is 1.2 and 1.15, respectively. From the dash lines, we can see that the performance of lead spheres is worse than stainless steel screens. If a #500 mesh lead screen is used as the regenerator matrix, a doubled COP could be obtained compared with that of stainless steel.

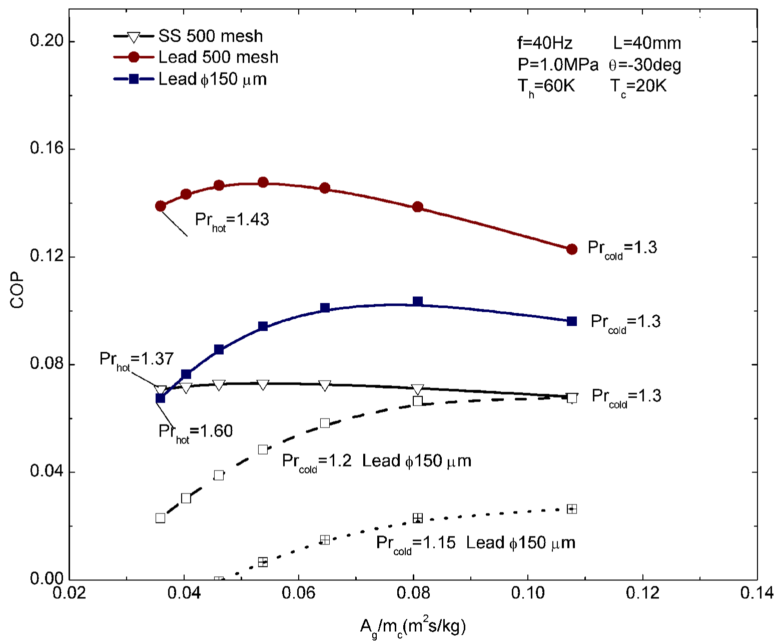

Figure 5. Performance of regenerator at a cold-end temperature of 20 K

CONCLUSION

The calculation results of this paper point out that under the influence of thermal penetration depth and pressure drop, lead spheres with large volumetric specific heat capacity performs worse than stainless steel screens with small volumetric specific heat capacity when they are used as regenerative matrix of cryocoolers at 35 K and a high frequency (40 Hz). #500 mesh stainless steel screen satisfies the design requirements of the regenerator matrix.

Moreover, regeneration performance of lead spheres is better than stainless steel screens at 20 K. Nevertheless, a matix of lead screens achieves the best benefit due to a small pressure drop and large volumetric specific heat capacity. #500 mesh lead screen has a COP one time higher than stainless steel screen when they are used as regenerator matrix at 20 K.

ACKNOWLEDGMENTS

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