Experimental investigation on regenerator materials of Stirling-type pulse tube refrigerator working at 20 K
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\textbf{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 \(\leq 40\) 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\(_3\)Ni, 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.

\textbf{Outline}

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

\textbf{Results}

\textbf{The volumetric heat capacity}

\begin{itemize}
  \item SS represents stainless steel wire-mesh and Pb. Er\(_3\)Ni, HoCu\(_2\), always appear in the form of spheres.
  \item At low temperature, the volumetric heat capacity of different materials decreases rapidly.
  \item The heat capacity of lead spheres dominate in value over a large temperature range.
\end{itemize}

\textbf{The flow resistance}

\begin{itemize}
  \item 20.4 K no-load temperature with SS as regenerator materials.
  \item 1 W cooling power at 33 K with 230 W input power at 35 Hz.
\end{itemize}

\textbf{Conclusion}

\begin{itemize}
  \item Er\(_3\)Ni, with a large ratio of \(C_p\) to \(\lambda\), is proved to be a most promising material to replace stainless steel wire-mesh to improve the refrigerator performance.
  \item 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.
  \item 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 coaxial pulse tube refrigerator.
\end{itemize}

\textbf{Materials}

The no-load temperature shares the same trend with the thermal diffusivity. Er\(_3\)Ni owns the largest ratio of \(C_p\) to \(\lambda\) 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.

\textbf{Schematics of the STPTR}

We define the thermal penetration depth \(\delta\) as the depth where the amplitude of the temperature is 1/4 of the temperature oscillating amplitude at the solid surface

\[ T(x,t) = T(\infty,t)e^{-\frac{x^2}{4 \delta^2}} \]

Where \(C_p = \lambda/\rho C_v\) is thermal diffusivity

\begin{table}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Material & \(C_p\) & \(\lambda\) & \(\rho\) & \(\delta\) \\
\hline
HoCu & 0.1 & 0.245 & 0.61 & 0.244 \\
\hline
Pb & 0.95 & 0.605 & 95.0 & 0.928 \\
\hline
Er\(_3\)Ni & 2.0 & 0.555 & 23.0 & 0.140 \\
\hline
\end{tabular}
\end{table}

\textbf{The flow resistance}

\begin{itemize}
  \item 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.
  \item 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.
\end{itemize}

\begin{thebibliography}{1}

\bibitem{1} \textsuperscript{b}We choose 8.5mm-filling length, 0.055-0.07mesh Er\(_3\)Ni as the regenerator at the position closest to the cold head.

\bibitem{2} \textsuperscript{b}The length of the second-segment regenerator is 25mm 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.

\bibitem{3} \textsuperscript{b}The Er\(_3\)Ni regenerator gets the better performance with a lower optimum operating frequency than SS regenerator.

\bibitem{4} \textsuperscript{b}Afterwards, the size of multipass is adjusted to the optimum value, then, the no-load temperature with Er\(_3\)Ni regenerator can reach 14.7 K with 250 W input power, while the temperature of the multi-bypass flange is 79 K.

\end{thebibliography}