Performance study on ST/JT hybrid cryocoolers working at liquid helium temperature

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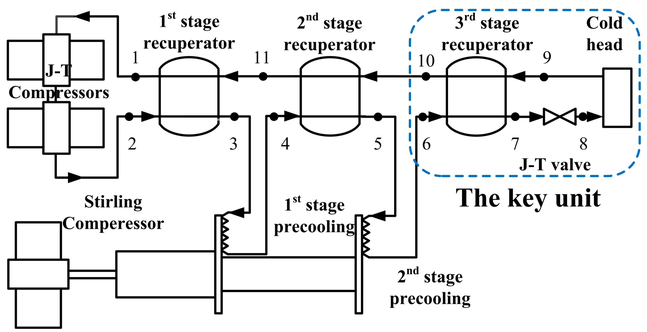
Introduction

- The hybrid space cryocooler, which consists of a Stirling cryocooler and a J-T loop, has become the main cooling technology at liquid helium temperature (around 4 K) in the long-life space mission. It is usually used to directly cool the detectors or precool the other cryocoolers which work at lower temperature.
- There is little detail about the design and the performance analysis of the hybrid cryocoolers in the published literatures.
- For the required cooling power, better performance means less power consumption, which may reduce the weight and volume of the crycoolers and the power equipment. It is meaningful to the space missions.

Conclusion

- The effective ways to improve the overall COP are enhancing the performance of the J-T compressors with lager pressure ratio and the precooler at lower temperature.
- How P_H , T_{pre2} , and ε affects the cooling power has been illustrated with P-h map and thermodynamic calculation.
- For fixed T_{pre2} , $P_{H,opt}$ exits; for fixed P_H , reducing T_{pre2} above the turning point has a significant positive effect on the cooling power (shown in part 3).
- The optimal P_H and T_{pre2} can be calculated out with the actual performance of the J-T compressors and the precooler.

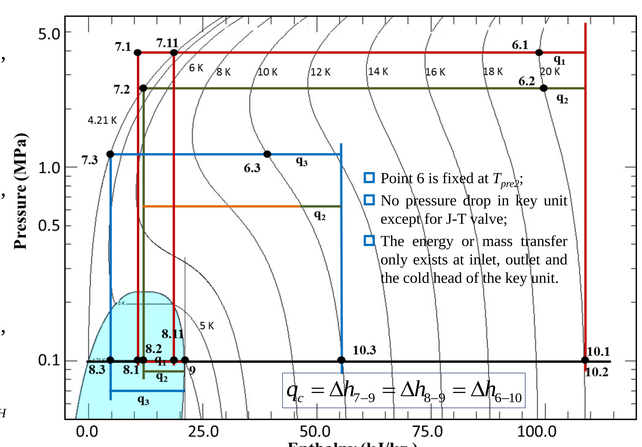
1. Common process and key unit



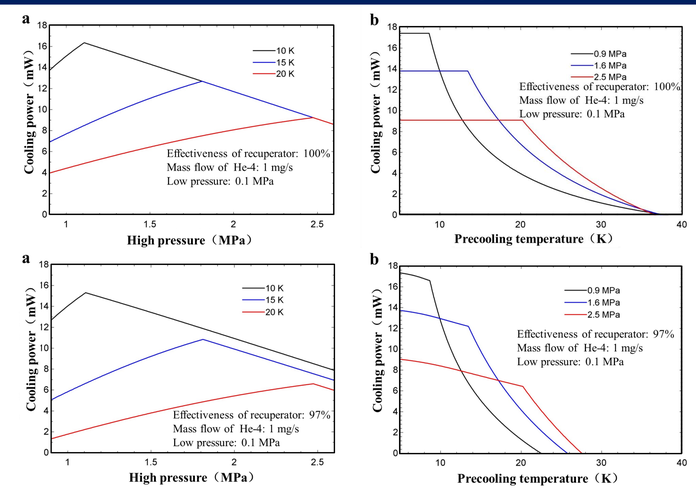
- The key unit can reach liquid helium temperature as long as the precooler is powerful enough.
- Ineffectiveness of the last (3rd) stage recuperator has no compensation provider.
- T_{pre2} has great impact on the cooling power.
- The function of the upper stages is reducing the precooling load of the last stage.

2. Pressure-Enthalpy map analysis

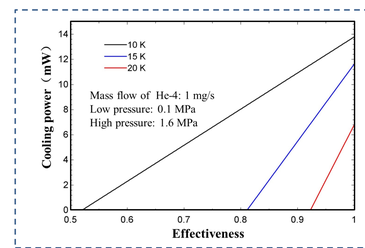
- The 1st process: 6.1-7.1-8.1-9-10.1, T_6=20 K:
  - violate the 2nd law of thermodynamics
  - $q_c = \Delta h_{8.11\text{-}9} < \Delta h_{6.1\text{-}10.1}$
  - $T_{10} < T_6$
- The 2nd process: 6.2-7.2-8.2-9-10.2, T_6=20 K
  - $q_{c,max}$ with $P_{H,opt}$ around 2.5 MPa
  - $T_{10} = T_6$
  - As P_H goes lower, q_c decrease with $\Delta h_{6\text{-}10}$
- The 3rd process: 6.3-7.3-8.3-9-10.3, T_6=10 K:
  - larger $q_{c,max}$ with lower $P_{H,opt}$ around 1.1 MPa
  - same q_c as $q_{c,max}$ of the 2nd process with P_H around 0.6 MPa



3. Thermodynamic calculation of the key unit

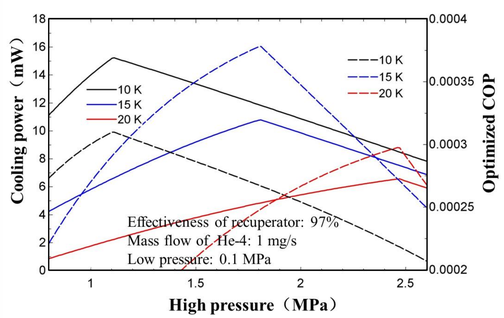


- Effectiveness of the recuperator ε = 100%:
  - q_c have the maximum value at $P_{H,opt}$ with fixed T_{pre2}
  - $P_H > P_{H,opt}$, h_7 limited by $T_7 = T_9$, $T_{10} < T_6$
  - $P_H < P_{H,opt}$, h_7 limited by fixed $\Delta h_{9\text{-}10}$, $T_{10} = T_6$
- Effectiveness of the recuperator ε = 97%:
  - ε does not affect the $P_{H,opt}$
  - lower cooling power and T_{pre2} at zero q_c point



The key unit with the higher T_{pre2} has the more stringent requirement on ε, which is usually higher than 97%

4. COP optimization of the ST/JT hybrid cryocooler



- Dotted lines: optimized COP as the function of P_H , with the optimization parameter T_{pre1}.
- Solid lines: corresponding cooling power of the optimized COP.

- The maximum value of optimized COP (COP_{max}) exists at the $P_{H,opt}$ with fixed T_{pre2}.
- The corresponding cooling power behaves the same as the key unit.
- Optimal T_{pre2} can be found.

References

[1] Gan ZH, Wang B, Liu DL, et al. Status and development trends of space mechanical refrigeration system at liquid helium temperature. Journal of Zhejiang University (Engineering Science, in Chinese). 2012, 46(12): 2160-2177.

[2] Lemmon EW, Huber ML, Mclinden MO. NIST Standard ReferenceDatabase 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP. 9.0. 2010.

[3] Klein SA, Alvarado FL. Engineering equation solver. F-Chart Software, Box. 2002, 44042.

[4] Liu DL, Tao X, Sun X, et al. The analysis and optimization of the cryogenic system on JWST/MIRI. Cryogenics(in Chinese). 2014: in press.

[5] Ladner DR. Performance and Mass vs. Operating Temperature for Pulse Tube and Stirling Cryocoolers. Cryocoolers 16. Boulder, 2011: 633-644.

[6] Sato Y, Sawada K, Shinozaki K, et al. Development status of the mechanical cryocoolers for the Soft X-ray Spectrometer on board Astro-H. Cryogenics. 2014: in press.

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