National Aeronautics and
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Performance Characteristics Comparison of Major Types of Mechanical Cryocoolers for Aerospace Applications

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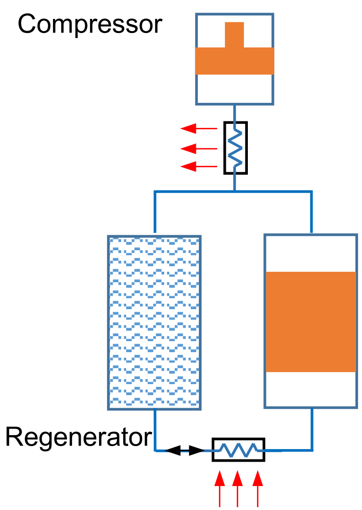
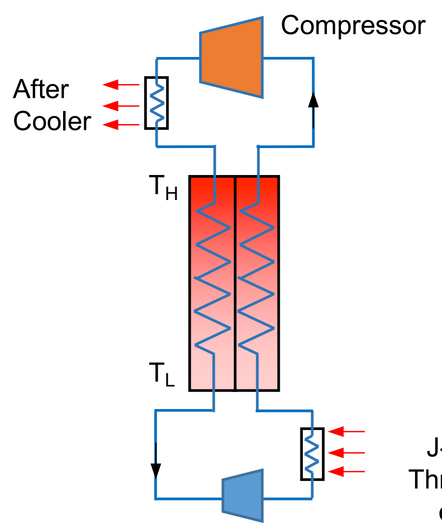
Introduction

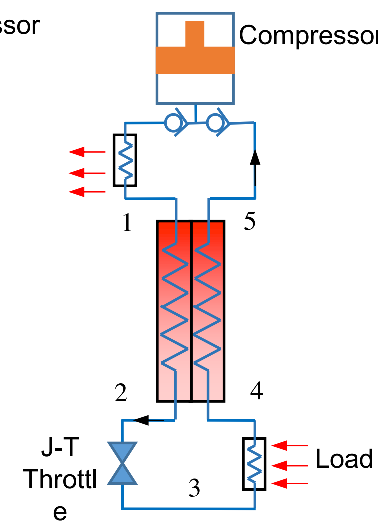
- Mechanical cryocoolers are a critical enabling technology for
  - Aerospace imaging and sensing applications
  - In-space propellant zero boil-off storage
- Major types aerospace mechanical cryocoolers
  - Stirling/pulse tube, Reverse-Brayton (RB), and Joule-Thomson (J-T)
- Similar operating principle in all mechanical coolers
  - Compress gas and reject heat to heat sink
  - Recuperation/regeneration to cool compressed gas to cold end temperature
  - Expand compressed gas to produce cooling
- Efficiency and specific mass of these coolers, however, can differ from each other significantly



•Stirling/Pulse Tube



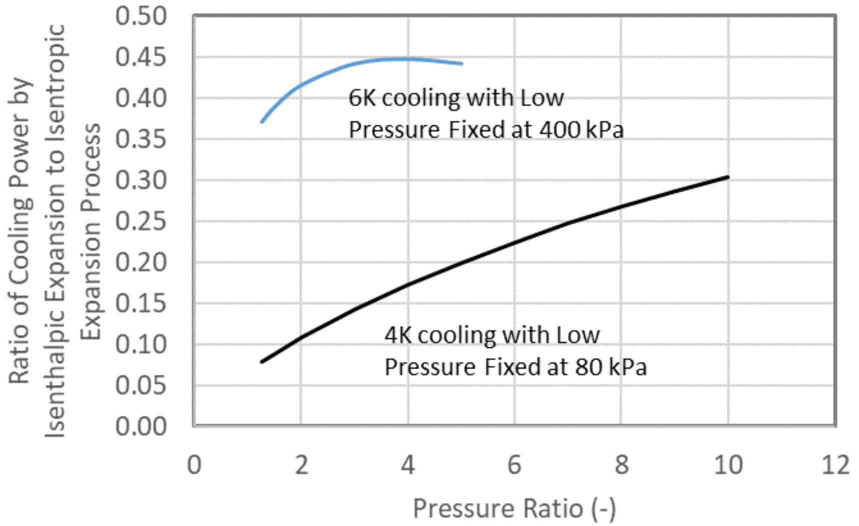
•Reverse Brayton



•Joule-Thomason

General Performance Features (1/2)

- **Stirling coolers**
  - Most efficient coolers for >20K cooling
  - For <20 K cooling, need exotic materials to stabilize regenerator temperature
  - Inability to provide remote distributed cooling
- **RB coolers**
  - High power density at high capacity
  - Much larger HX than other types of coolers for medium capacity cooling need
  - Challenging features and fabrication tolerances for compressors
- **J-T coolers**
  - High vulnerability to system contamination
  - Efficiency is low except for near 6 K applications
    - Isenthalpic expansion can achieve 45% of cooling power by isentropic expansion
  - For 4 K applications, Isenthalpic expansion can only achieves < 25% of (at PR=5) cooling power by isentropic expansion



General Performance Features (2/2)

	Stirling/Pulse Tube	Reverse Brayton	J-T
Flow Conf.	AC	DC	DC
Efficiency	High when T_c > 20K	High when input power is large	Modest for < 10K
Compactness	Compact	Relatively large HX	Compact, very small cold finger
Cooling capacity	Medium to low	Medium to high	Low
Exported vibrations	Low	Ultra-Low	Low to Ultra-Low
Remote distributed cooling	No	Yes	Yes
Main applications	Compact, effecicent Single point cooling Upper stage for hybrid cooling	High capacity remote distributed cooling Applications very sensitive to vibrations	Low-temp., low-capacity remote distributed cooling Gyro stabilized gimbal platform

Main Losses in Cryocoolers

- **Compression loss**
  - **Non-isothermal compression process**
    - **Temperature rise increases with pressure ratio**
      - **Mitigated with intercooling in a multistage compression system**
  - **Internal losses associated with motor losses, internal leakage, drag loss**
- **Losses below warm end of recuperator/regenerator)**
  - **Expander gross cooling losses**
    - **Drop in pressure ratio across expander**
    - **Non-isothermal expansion process**
    - **Parasitic loss in expander**
  - **Convective heat leak into cold end**
    - **Gas inlet temperature slightly warmer than old end due to limited convective conductance**
    - **Directly related pressure drop by heat transfer and momentum analogy**
    - $\frac{d(UA)_{stream}}{dP} = 2\frac{j}{f}\frac{1}{dl}\frac{1}{u}c_p {P_r}^{-2/3} D_h dA_s = 8\frac{j}{f}\frac{1}{dl}\frac{P}{\dot{G}RT}c_p {P_r}^{-2/3} dV$
      - **j/f is a is a non-dimensional ratio of heat transfer performance to pressure drop**
        - » **A figure of merit for heat transfer surface**
  - **Axial conduction**

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Overall Carnot Efficiency

- **Efficiency equation is derived for RB cryocoolers with ideal gas flows**
  - **General trends are still applicable to J-T and regenerative coolers**
- **Optimal design needs to have proper balance between pressure ratio drop and HX size**

Loss below HX Warm End

$$\eta_{comp,isothm}\frac{(T_H-T_L)}{T_H}\left[\left(1-\frac{2\,\Delta P/P}{ln(P_{Ratio})}\right)\eta_{exp,isothm}-\frac{\dot{G}^2(T_H-T_L)T_m c_p {P_{r,m}}^{2/3}}{4\frac{j}{f}\frac{\Delta P/P}{\ln(P_{Ratio})}P^2T_L}-\frac{\overline{kAc_{HX}}}{L_{HX}}\frac{(T_H-T_L)}{\dot{m}RT_L ln(P_{Ratio})}\right]$$

Compressor Eff

Not recover expansion work

Reduced P_{Ratio}

Limited convective conductance

Axial Conduction

$$\frac{\dot{m}c_p\Delta T_{HX}}{\dot{m}RT_L ln(P_{Ratio})}=\frac{\dot{m}c_p}{\dot{m}RT_L ln(P_{Ratio})}\frac{\dot{m}c_p(T_H-T_L)}{UA}$$

$$UA=4\frac{j}{f}\,c_pP_{r,m}{}^{-2/3}\frac{{A_c}^2}{\dot{m}}\frac{P^2}{RT_m}\frac{\Delta P}{P}$$

$\dot{G}^2$ and 1/P².

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Implication for Cooler Design and Optimization

- **Overall cooler efficiency is strongly dependent on normalized pressure drop**
  - $\Delta P/P/ln(P_{Ratio})$
- **Loss due to limited convective HT is**
  - **Proportional to $1/P^2$**
    - **A higher P allows a proportionally higher ΔP**
    - **A higher P reduces flow velocity and allows the use of channel with smaller D_h, thus higher HTC**
  - **Proportional to $\dot{G}^2$**
    - **Reducing mass flux proportionally decreases HX heat load thus leads to a smaller HX**
    - **Decreasing mass flux proportionally enhances convective heat transfer for same pressure drop**
- **Nominal P in a regenerative cooler is ~ 10X that in an RB cooler**
  - **Lead to regenerators an order of magnitude smaller than recuperators in RB**
- **Nominal P and ln(P_{Ratio}) in a JT cooler are ~ 5 X those in an RB cooler**
  - **Lead to JT recuperators more than an order of magnitude smaller than RB recuperators**

Compressor Configurations

- Compressor configurations
  - Centrifugal compressors
    - Used in RB coolers
    - Very high power density due to very high operating speeds > 1 kHz
    - Suitable for high volumetric flow rate
      - Thus RB cooler is ideal for high capacity cooling
    - Optimal pressure is low for high compression efficiency
      - Typical low-side pressures: 1 atm
  - Piston compressors
    - Used in regenerative coolers and JT coolers
    - Suitable for operating at high system pressures: ~ 10 bar
    - Large piston diameter will increase challenge for heat removal and reduce resonant frequency
      - Thus input power can only be up to a few hundred watts
- Optimal pressure ratio is
  - Compromise between compression efficiency and cooler size and mass
- The optimal system pressure is most controlled by compressor configuration

Summary

- Comparison of general performance characteristics of three main types of mechanical cryocoolers in aerospace applications
- An analytical expression for a cryocooler's Carnot efficiency is derived using Colburn-Chilton analogy
- Allowable ΔP scaled with $P ln(P_{Ratio})$ for the same thermodynamic efficiency
- Higher P or pressure ratio reduces HX size and mass
- Different compressor technologies employed in coolers cause significantly different system pressures and pressure ratios
  - HX sizes and overall cooler sizes are quite different from each other