Modelling of Cryocoolers

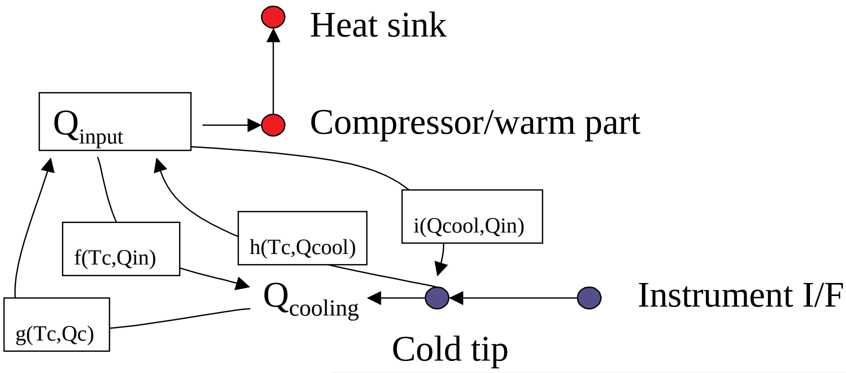
Introduction

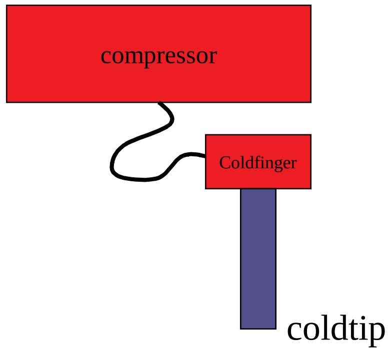
- *Current cryocooler models in ESATAN make use of polynomial fit functions in combination with boundary nodes*
- *This limits the number of free parameters (e.g heat sink temperature)*

therefore

- *Leading to a conservative design only considering worst cases*
- *It is difficult to perform sensitivities or assess the impact of sub-systems (e.g. compressor performances)*
- *A correct heat balance is not always obtained*

Stirling/ Pulse Tube models





$h(T_c,Q_{cool})$:

$$Q_{input} = a\,Q^2_{cool} + b\,Q_{cool} + c$$

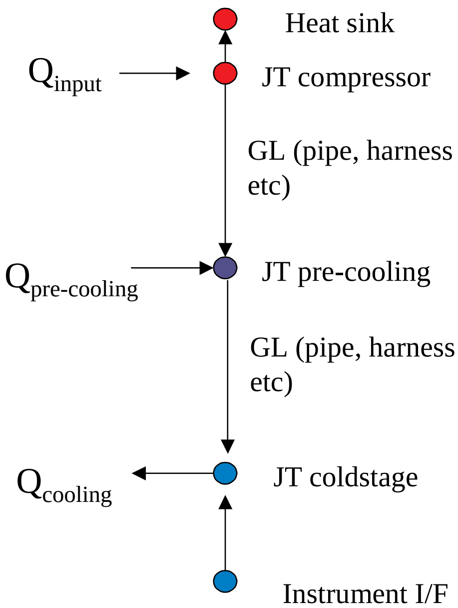
$$a = a_1\,T^2_{cold\ tip} + a_2\,T_{coldtip} + a_3$$

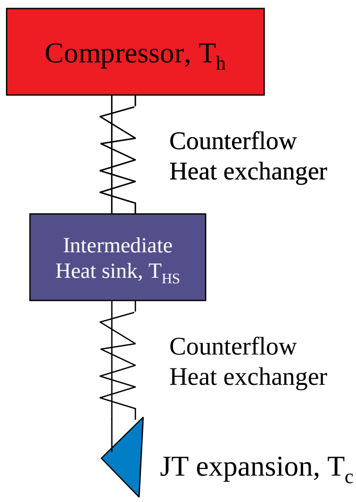
$$b = b_1\,T^2_{cold\ tip} + b_2\,T_{coldtip} + b_3$$

$$c = c_1\,T^2_{cold\ tip} + c_2\,T_{coldtip} + c_3$$

Joule Thomson coolers

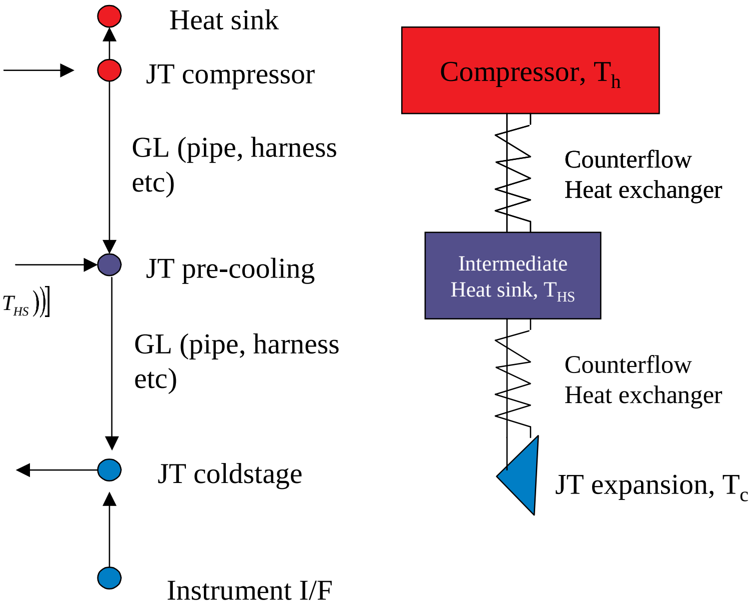
$Q_{pre-cooling}$ and $Q_{cooling,}$ depending on the Hx efficiency and the fluid, are provided only by polynomial fits





Joule Thomson coolers including Physics

Q_{input}



$$Q_{pre-cooling} = \dot{m}\left[\left(H\left(p_{high},T_{high}\right)-H\left(p_{high},T_{HS}\right)\right)-\varepsilon\left(H\left(p_{low},T_{high}\right)-H\left(p_{low},T_{HS}\right)\right)\right]$$

$$Q_{cooling} = \dot{m}\left[H\left(p_{high},T_{HS}\right)-\varepsilon H\left(p_{low},T_{HS}\right)\right]$$

Requirements for Cooler models

- *In most cases the coldtip temperature is specified by the system (coming from detector needs etc)*
- *The required cooling power is obtained by the TMM*
- *For sizing the thermal system the cooler model must provide* $Q_{input} = f(T_{coldtip}, Q_{cooling})$
- *For transient verification, the cooler model must be able to calculate* T_{cold} *for a given* Q_{input}. *The following function is required within a TMM:* $Q_{cooling} = g(T_{coldtip}, Q_{input})$

Requirements for Cooler models

- Cooler model shall consider as a minimum the following parameters:
  - For single stage cooler $T_{heat\ sink}$, $T_{coldtip}$, Q_{input}, $Q_{cooling}$
  - For multistage coolers, the influence of the intermediate cooling stages for different operating conditions needs to be implemented
- This can not be handled by polynomial fits or would require a large amount of data points at specific conditions (e.g. isothermal points)

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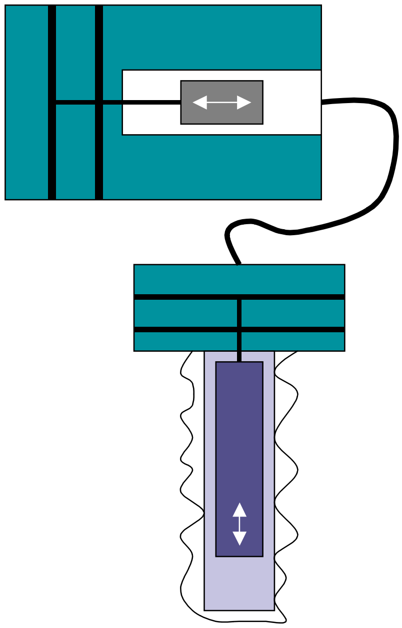
Requirements for Cooler models

- Overall heat balance needs to be correct
  - Common approach is: $Q_{dissipated} = Q_{input}$
  - For Stirling, PT and reverse Turbo-Brayton correct approach is: $Q_{dissipated} = Q_{input}+Q_{cooling}$
- Use of boundary nodes shall be limited, where required link them correctly with the TMM
- Shall be simple, fast and robust

Stirling cooler

- *Compressor transform electrical Energy into pneumatic Work (pV work). For high efficient space coolers one can assume: $pV = Q_{in} - I^2R$*
- *Pressure wave generated passes through a regenerative heat exchanger (= Regenerator)*
- *At the cold end the pressure wave and massflow wave are shifted such, that the following cooling occurs: $q_{gross} = T_{cold}/(T_{hot} - T_{cold})*pV$*
- *The available cooling power is: $q_{net} = q_{gross} - losses$*
- *Main losses are: conductive, radiative, regenerator and shuttle losses*



Stirling cooler losses

- *Conductive/radiative losses are equal to parasitic loads of a non-operating cooler.*
- *Regenerator losses: $Q_{regenerator} = dm/dt * c_p *(T_{hot} - T_{cold})\ (1-\varepsilon)$ with $dm/dt \sim pV/T_{hot}$*
- *Shuttle losses $Q_{shuttle} \sim (T_{hot} - T_{cold})/stroke$*

Stirling cooler equation

- *It should be possible to describe the Stirling cooler with the following equation:*

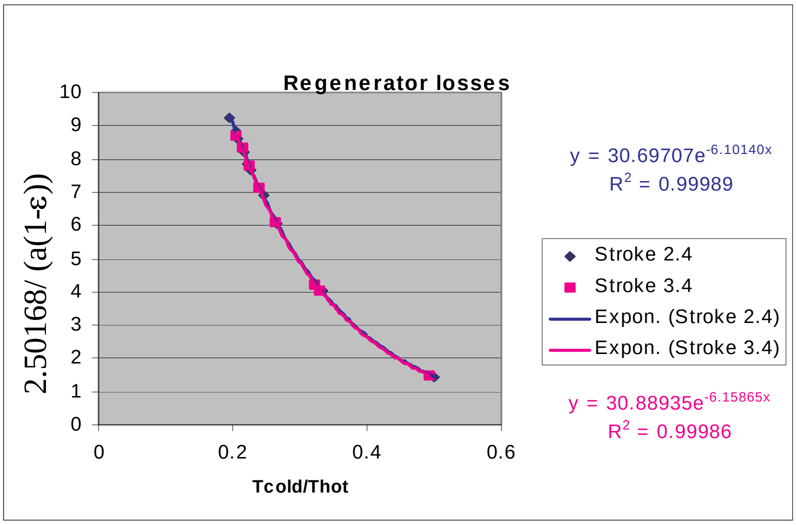
$$\frac{T_{cold}}{T_{hot}-T_{cold}}\,pV - c\left(T_{hot}-T_{cold}\right) -$$

$$a\left(1-\varepsilon_{reg}\right)\frac{pV}{T_{hot}}\left(T_{hot}-T_{cold}\right) - b\,\frac{T_{hot}-T_{cold}}{stroke} - q_{net} = 0$$

- *Approach has been tested with MIPAS 50-80k Astrium cooler data, assuming a constant compressor efficiency (due to the lack of I^2R data)*

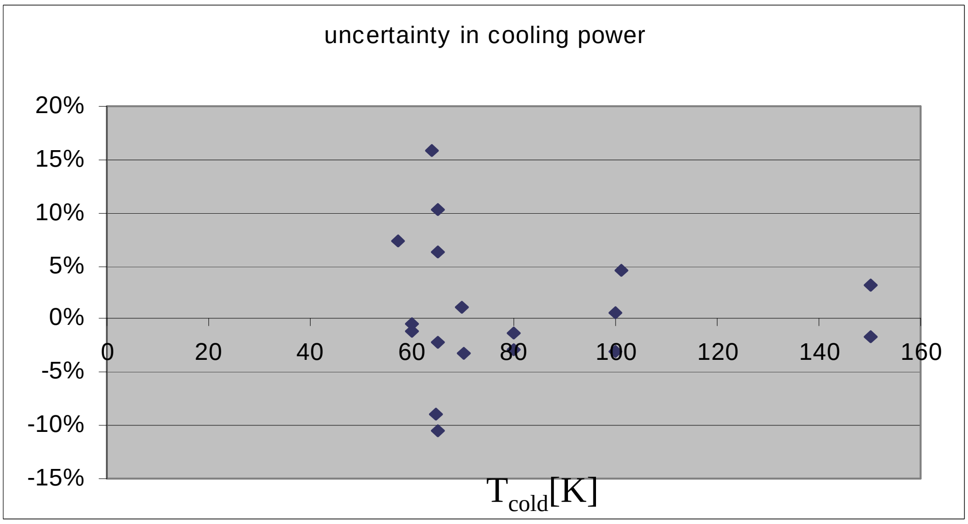
Stirling cooler extrapolation

- *Dataset includes 18 measurements from 57-150K and -10°C to 40°C heat sink*
- *$pV = 0.8 * Q_{in}$*
- *C = 220 mW /193K from parasitic measurements, refined during interpolation*
- *Distinguishing between regenerator and shuttle loss not possible, but regenerator loss as a function of displacer stroke*

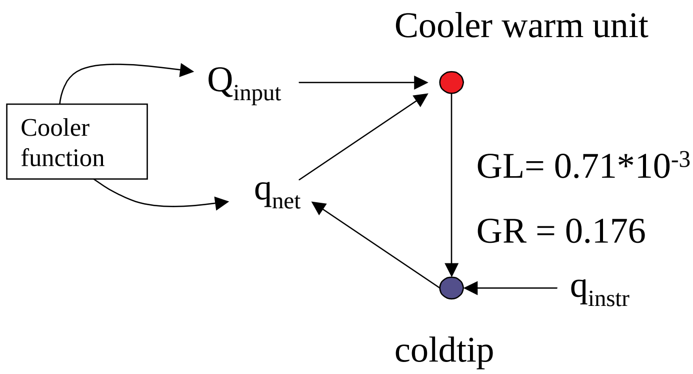


Stirling cooler extrapolation uncertainty

Strong deviations from measurements above 150K, additional correction for these temperatures required



Stirling cooler model



Result TMM:

(300mW q_{instr},Cooler Wu 263K)

T_{cold} = 64.9K -> 12.19W input

Q_{in} = 11.17W -> 66.1K T_c

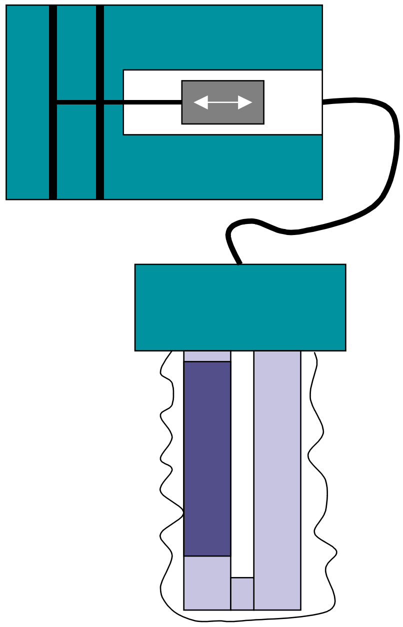
Cooler function:

$$0.8 * Q_{input}\left[\frac{T_{cold}}{T_{hot}-T_{cold}} - \frac{2.50168}{30.697}\, e^{6.101\, T_{cold}/T_{hot}}\, \frac{1}{T_{hot}}\left(T_{hot}-T_{cold}\right)\right] - q_{net} = 0$$

Note: not valid for temperatures below 50K and above 150K

Pulse Tube cooler

- *Compressor transform electrical Energy into pneumatic Work (pV work). For high efficient space coolers one can assume:* $pV = Q_{in} - I^2R$
- *Pressure wave generated passes through a regenerative heat exchanger (= Regenerator)*
- *At the cold end the pressure wave and massflow wave are shifted such, that the following cooling occurs:* $q_{gross} = T_{cold}/T_{hot})*pV$
- *The available cooling power is:* $q_{net} = q_{gross} - losses$
- *Main losses are: conductive, radiative, regenerator and pressure losses*



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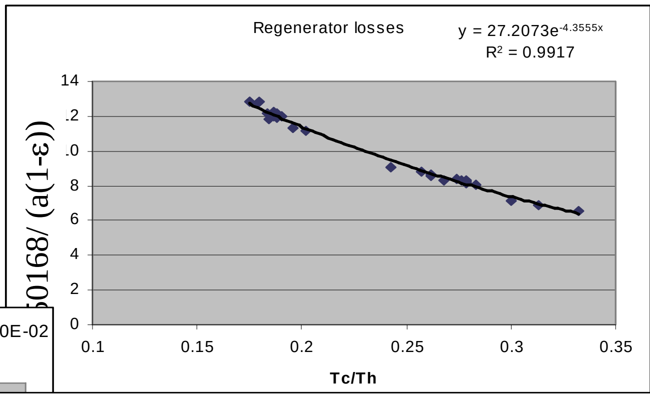
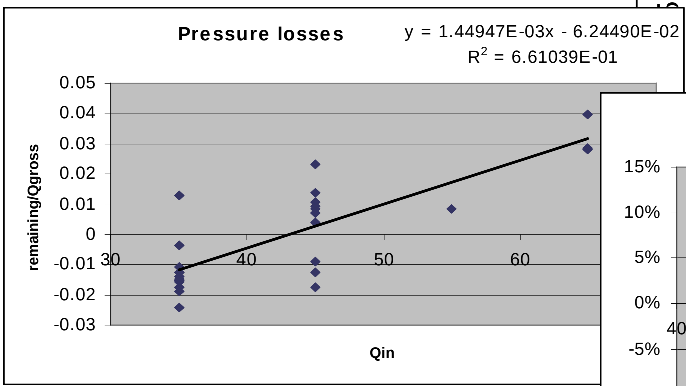
Pulse Tube cooler losses

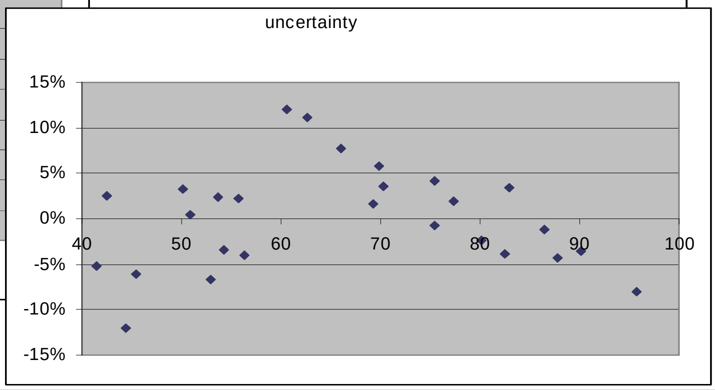
- *Conductive/radiative losses are equal to parasitic loads of a non-operating cooler.*
- *Regenerator losses:* $Q_{regenerator} = dm/dt * c_p *(T_{hot} - T_{cold}) (1-\varepsilon)$ *with* $dm/dt \sim pV/T_{hot}$
- *Pressure losses* $Q_{press} \sim f(p_{ampl}) *T_c/T_h*pV$ $p_{ampl} \sim Q_{in}$
- *Data taken from MPTC Air liquide TRP cooler*

Pulse Tube cooler extrapolation

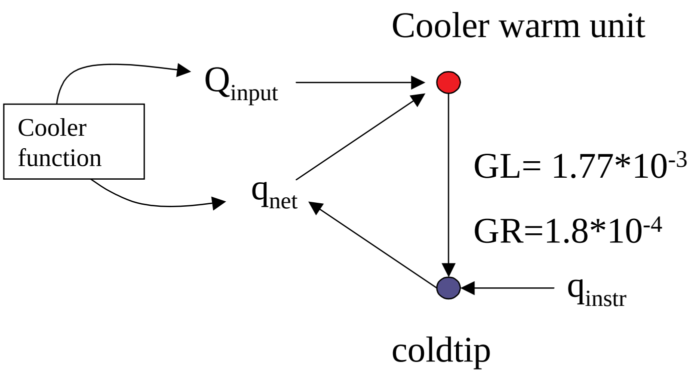
- *Dataset includes 23 measurements from 40-95K and -40℃ to 40℃ heat sink*
- *pV = 0.7 *Q_{in}*
- *C = 465 mW /208K from parasitic measurements*







Pulse Tube cooler model



Result TMM:

T_{cold} = 60.63K , T_{hot}=310K, q_{instr} =0

Q_{in} = 45W -> 58.7 K T_c

T_{cold} = 75.43K , T_{hot}= 273K, q_{instr} = 1W -> 36.3 W

Q_{in} = 35W -> 76.3 K T_c

Cooler function:

$$0.7 * Q_{input}\left[\frac{T_{cold}}{T_{hot}}\left(1.0637 - 1.479 * 10^{-3} * Q_{input}\right) - \frac{2.50168}{27.1518}\, e^{4.327\, T_{cold}/T_{hot}}\, \frac{(T_{hot} - T_{cold})}{T_{hot}}\right] - q_{net} = 0$$

Note: function not valid for input powers below 30W and $T_{coldtip}$ above 100K, not verified for high $T_{coldtip}$

Conclusion

- *Performance predictions of Stirling and PT coolers is feasible by interpolating the various loss mechanisms, requiring much less input data than polynomial fits*
- *Some additional effort is required for high cold tip temperatures, mainly for cool down predictions*
- *In addition to the classical thermal parameters, the compressor efficiency also needs to be measured*

Future work

- *Distinguish between Compressor and warm part of coldfinger and predict dissipated power on each*
- *Modelling of the gas temperature as a function of gross cooling power and I/F temperature (to improve high temperature performance)*
- *Extend model to multistage Stirling and Pulse Tube cooler*