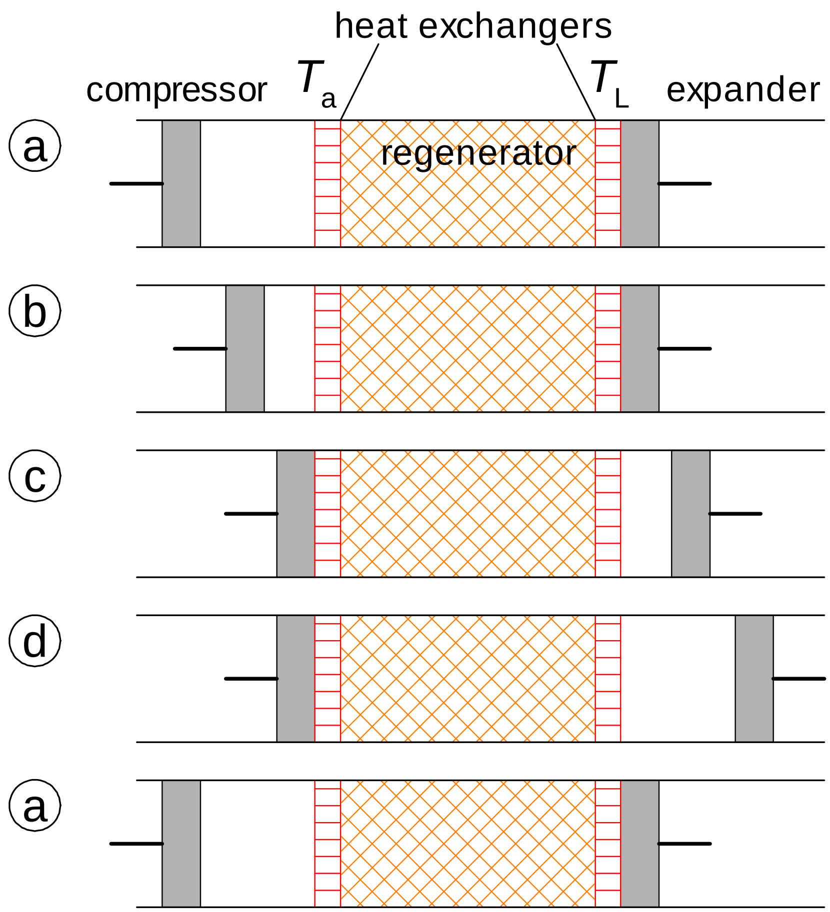
Cryocoolers (AC)

1. Stirling coolers

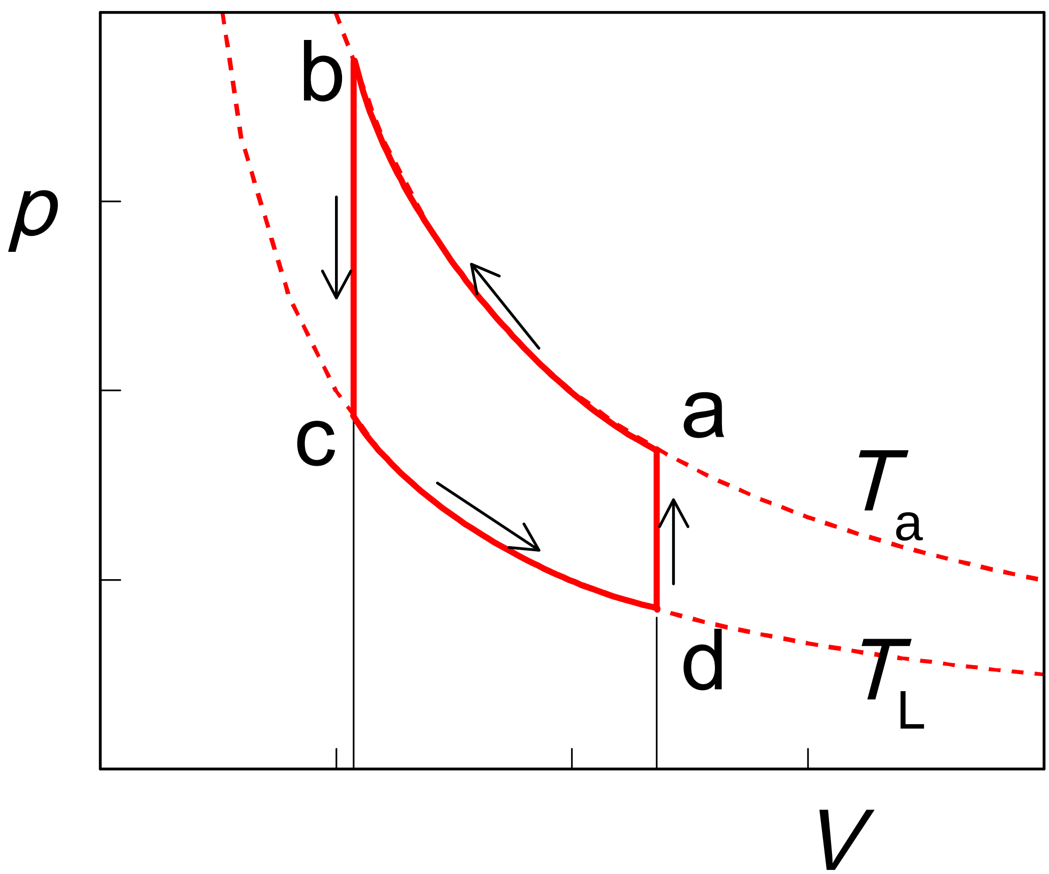
2. Gifford-McMahon (GM)-coolers

3. pulse-tube refrigerators

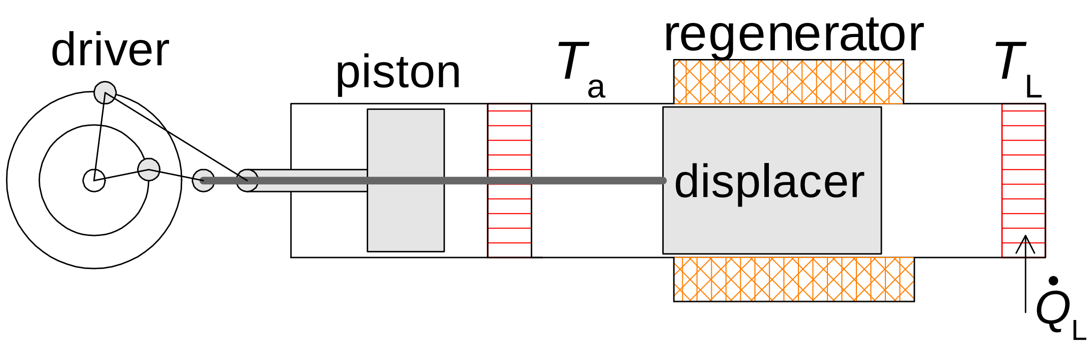
Stirling Coolers

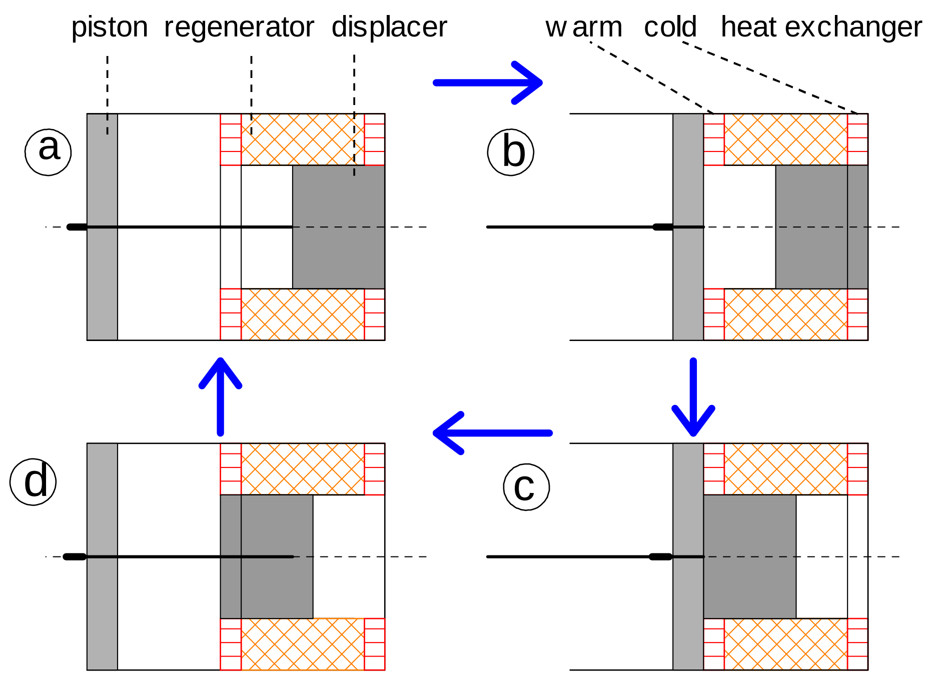


$$\xi = \frac{T_{\mathsf{L}}}{T_{\mathsf{a}} - T_{\mathsf{L}}}$$

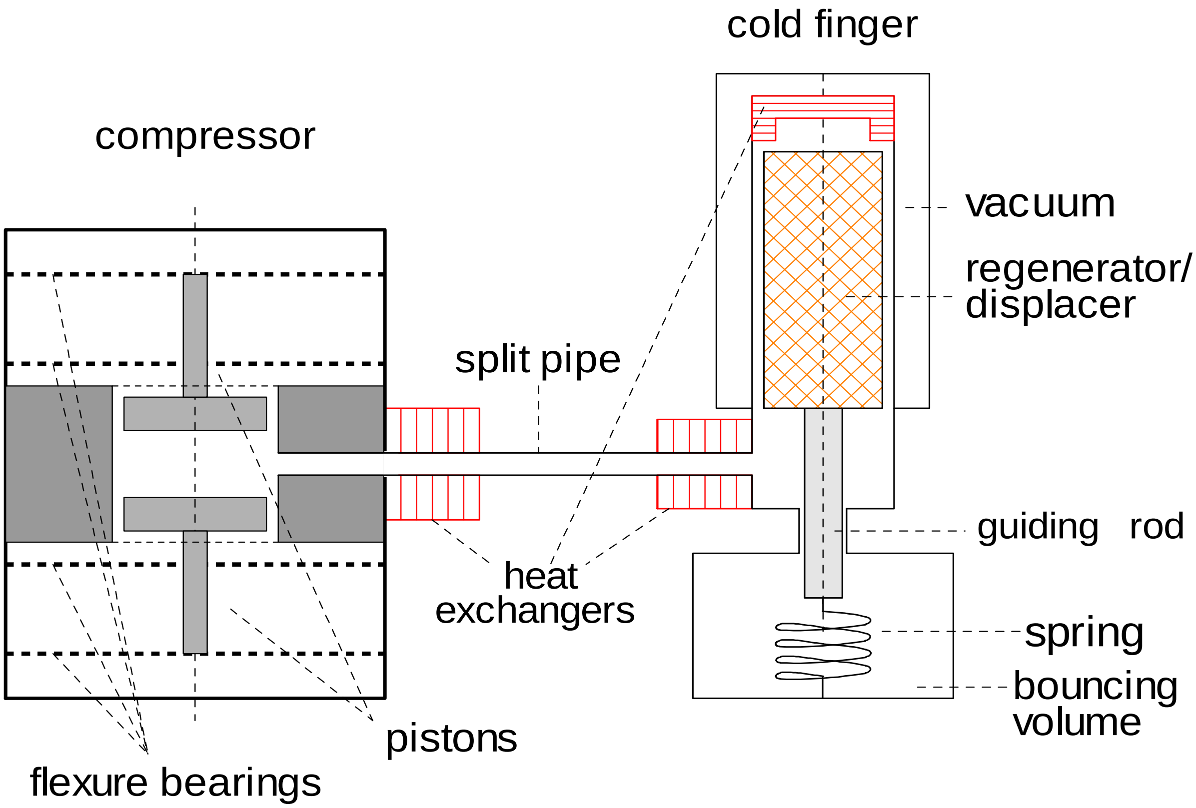

p
b
a
c
d
T_a
T_L
V

crank-driven Stirling



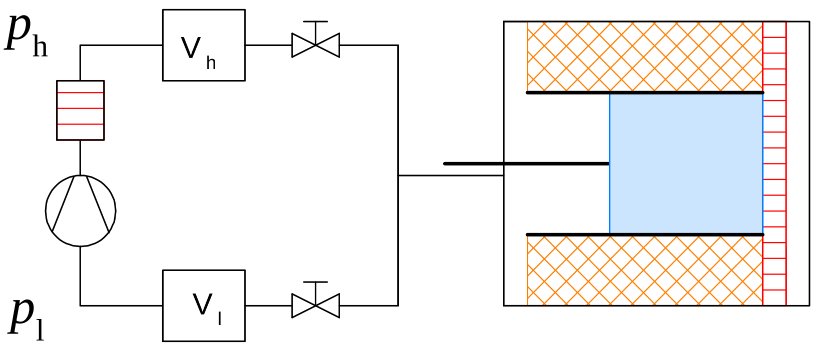


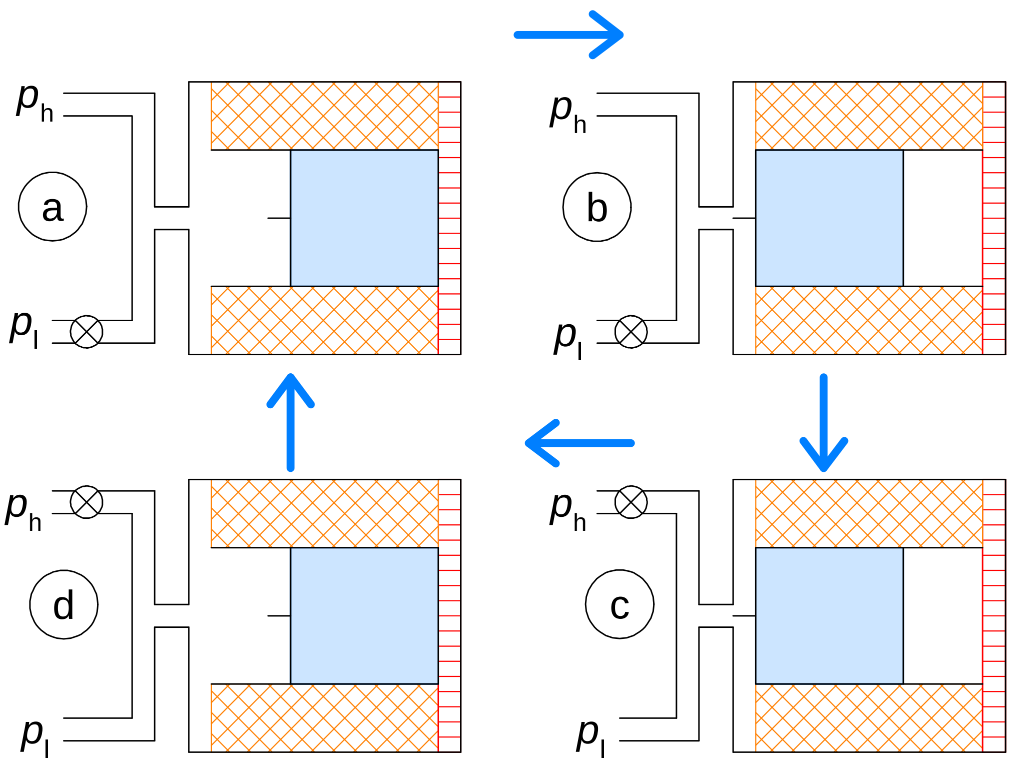
free-piston Stirling cooler



StThalesst.tc

Gifford-McMahon (GM)coolers

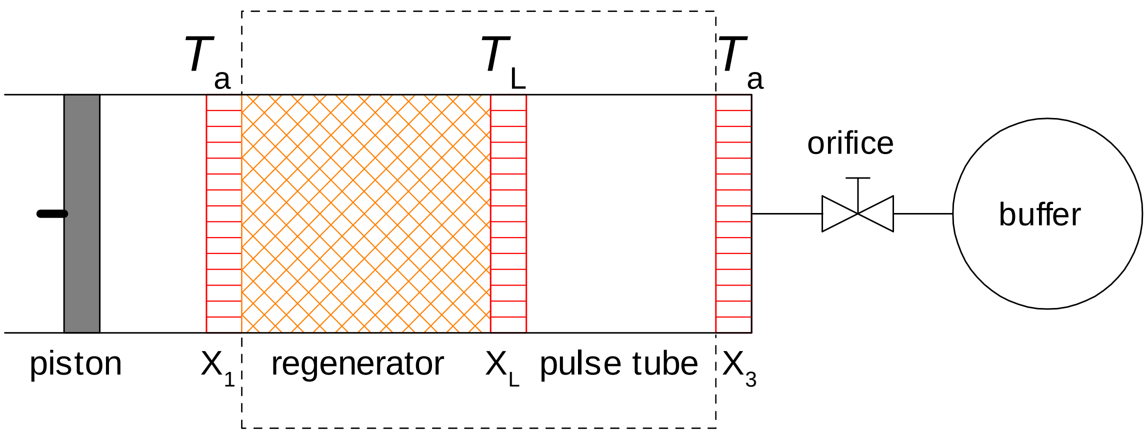


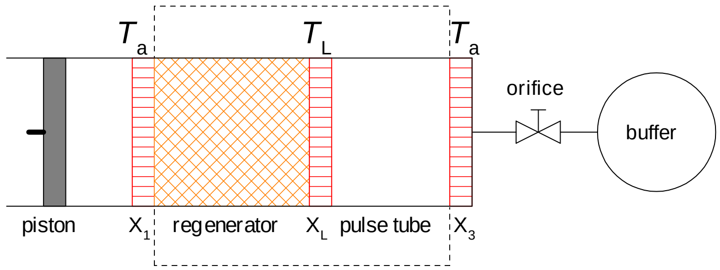


in reality regenerator and displacer are combined and rotary valves are used

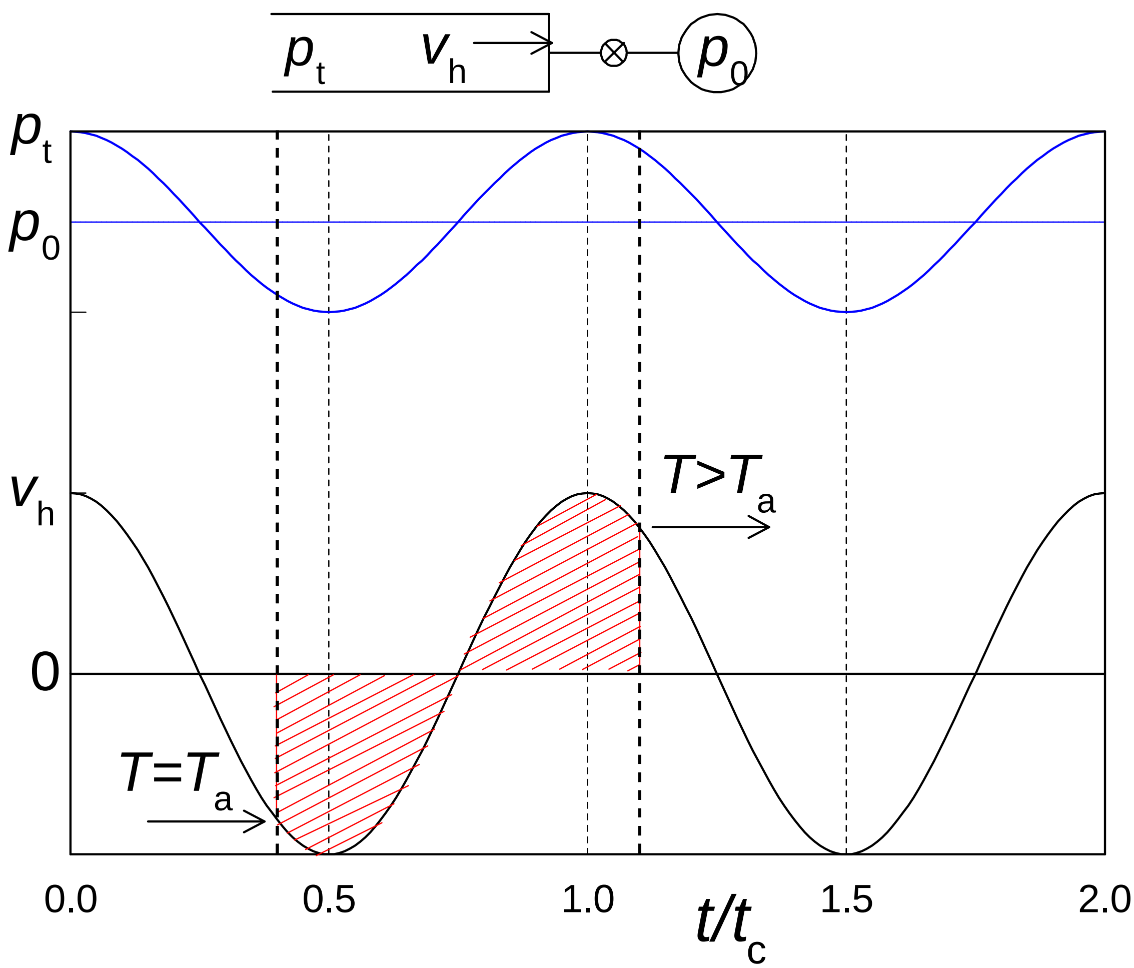
pulse-tube refrigerators

Stirling-type single-orifice PTR

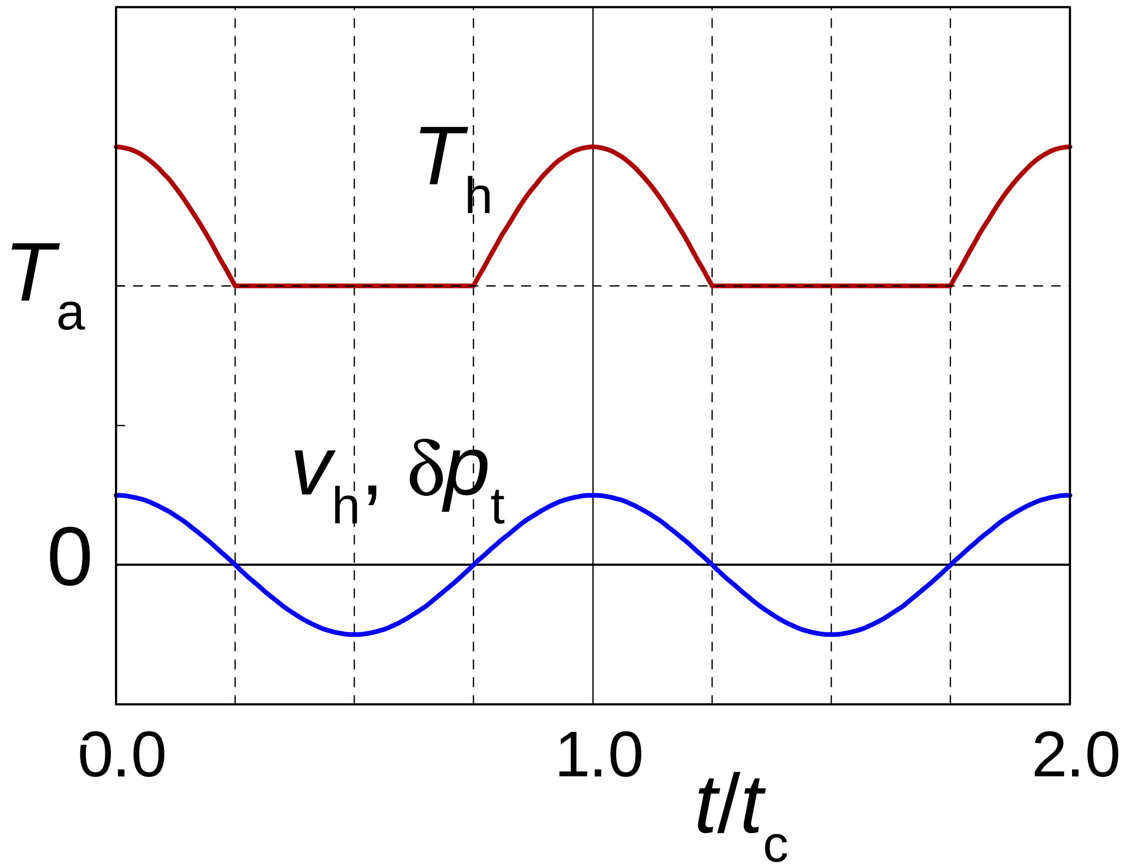




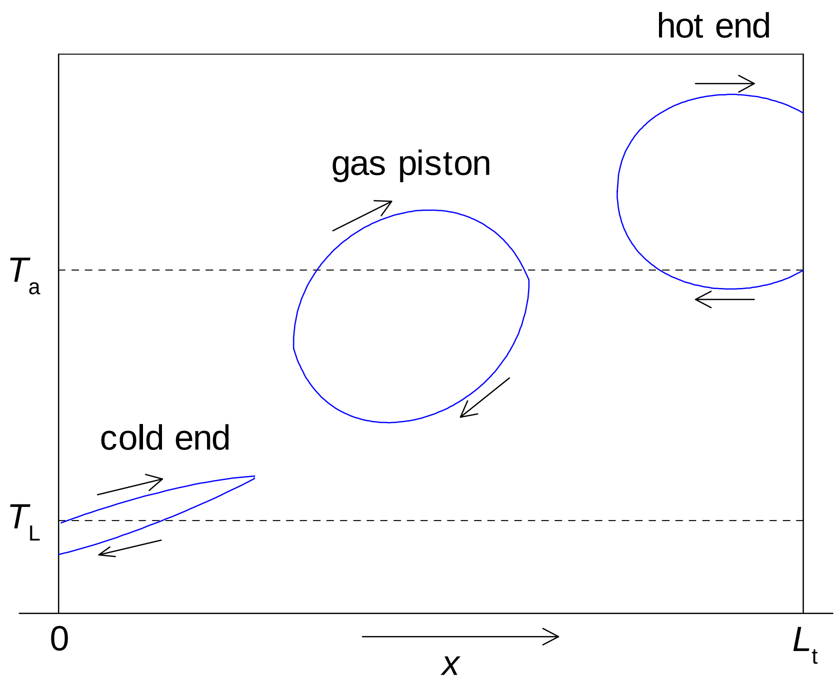
T a
T L
T a
orifice
buffer
piston
X1
regenerator
XL
pulse tube
X3



pt
vh
p0
pt
p0
vh
0
T>Ta
T=Ta
0.0
0.5
1.0
1.5
2.0
t/tc



T_h
T_a
v_h, δp_t
0
0.0
1.0
2.0
t/t_c

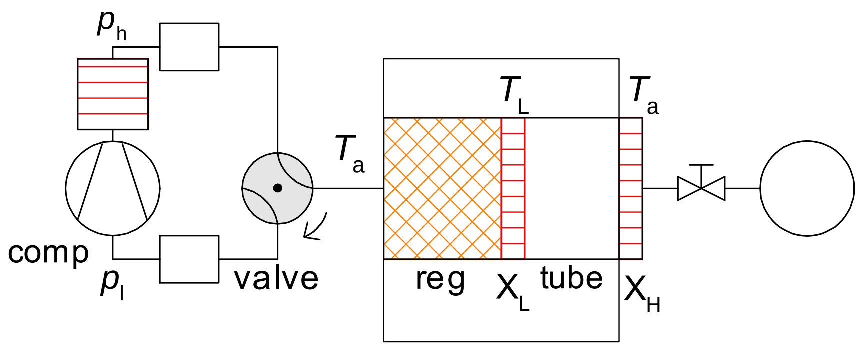


$$\overset{*}{V}_{\mathsf{L}} = \overset{*}{V}_{\mathsf{h}} + \frac{V_{\mathsf{t}}}{\gamma p_{\mathsf{t}}} \frac{\mathsf{d} p_{\mathsf{t}}}{\mathsf{d} t}$$

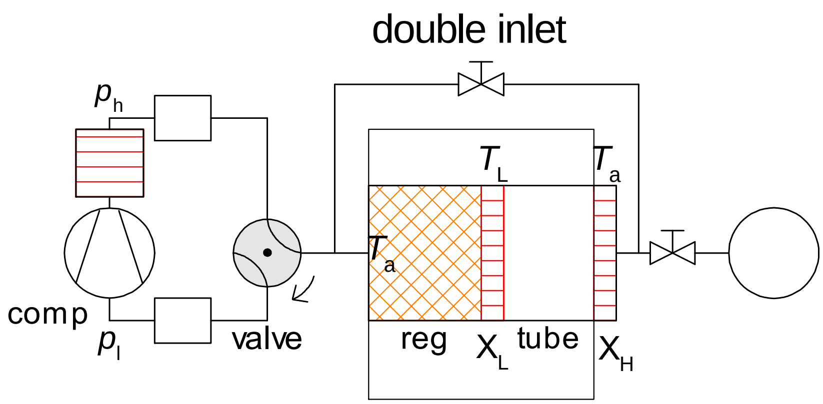
only the $\overset{*}{V}_{\mathsf{h}}$ component contributes to the cooling power

the second contribution reduces the COP

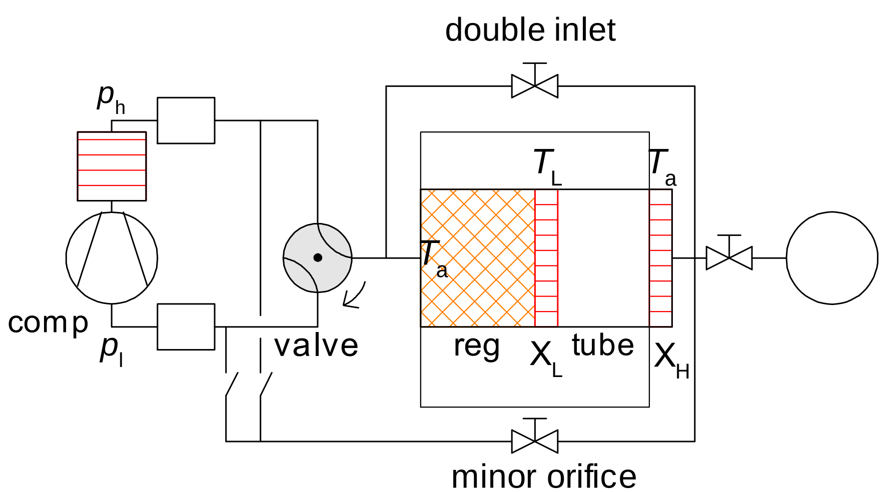
second orifice, inertance, active buffer, ...



p_h
comp
p_l
valve
T_a
T_L
T_a
reg
X_L
tube
X_H

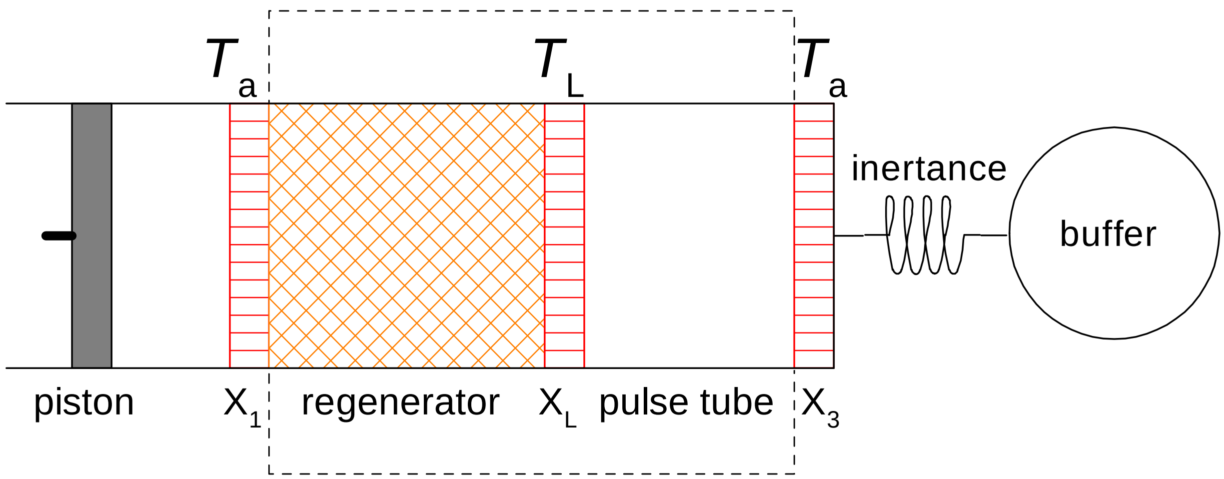


double inlet
p_h
comp
p_l
valve
T_a
T_L
T_a
reg
X_L
tube
X_H



double inlet
p_h
comp
p_l
valve
T_a
T_L
T_a
reg
X_L
tube
X_H
minor orifice

inertance



T_a
T_L
T_a
inertance
buffer
piston
X_1
regenerator
X_L
pulse tube
X_3

with

$$p_{\mathsf{t}} = p_0 + p_1 \cos \omega t$$

in first order with only orifice $\overset{*}{V}_{\mathsf{h}} = C_{\mathsf{o}} p_1 \cos \omega t$ so with

$$\overset{*}{V}_{\mathsf{L}} = \overset{*}{V}_{\mathsf{h}} + \frac{V_{\mathsf{t}}}{\gamma p_{\mathsf{t}}} \frac{\mathrm{d} p_{\mathsf{t}}}{\mathrm{d} t}$$

we get

$$\overset{*}{V}_{\mathsf{L}} = C_{\mathsf{o}} p_1 \cos \omega t - \frac{\omega V_{\mathsf{t}}}{\gamma p_0} \sin \omega t$$

with inertance

$$\overset{*}{V}_{\mathsf{h}} = C_{\mathsf{o}} p_1 \cos \omega t + C_{\mathsf{I}} \sin \omega t$$

so

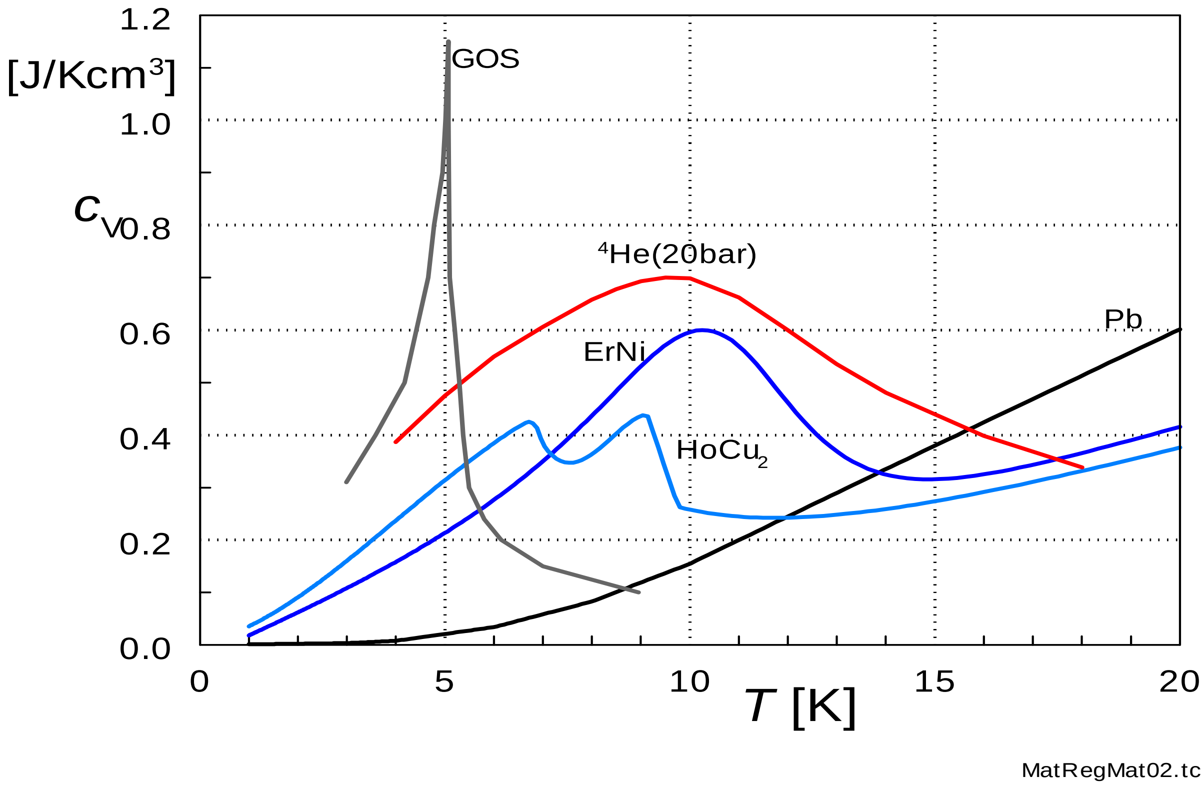
$$\overset{*}{V}_{\mathsf{L}} = C_{\mathsf{o}} p_1 \cos \omega t + \left(C_{\mathsf{I}} - \frac{\omega V_{\mathsf{t}}}{\gamma p_0} \right) \sin \omega t$$

optimum if

$$C_{\mathsf{I}} = \frac{\omega V_{\mathsf{t}}}{\gamma p_0}$$

ideal regenerator

1. heat capacity of matrix $\gg$ gas
2. heat contact between gas and matrix is perfect
3. axial thermal conductivity is zero
4. flow resistance is zero
5. void volume of the matrix is zero
6. gas is ideal



1.2
[J/Kcm3]
1.0
cV
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
T [K]
GOS
4He(20bar)
ErNi
HoCu2
Pb
MatRegMat02.tc

average enthalpy flow in the regenerator

$$\overline{\overset{*}{H}} = \overline{\overset{*}{n} H_{\mathsf{m}}} = \frac{5}{2} R \overline{\overset{*}{n} T} = \frac{5}{2} R T \overline{\overset{*}{n}} = 0$$

ideal gas (helium)

$$H_{\mathsf{m}} = C_{\mathsf{p}} T = \frac{5}{2} R T$$

if ideal regenerator

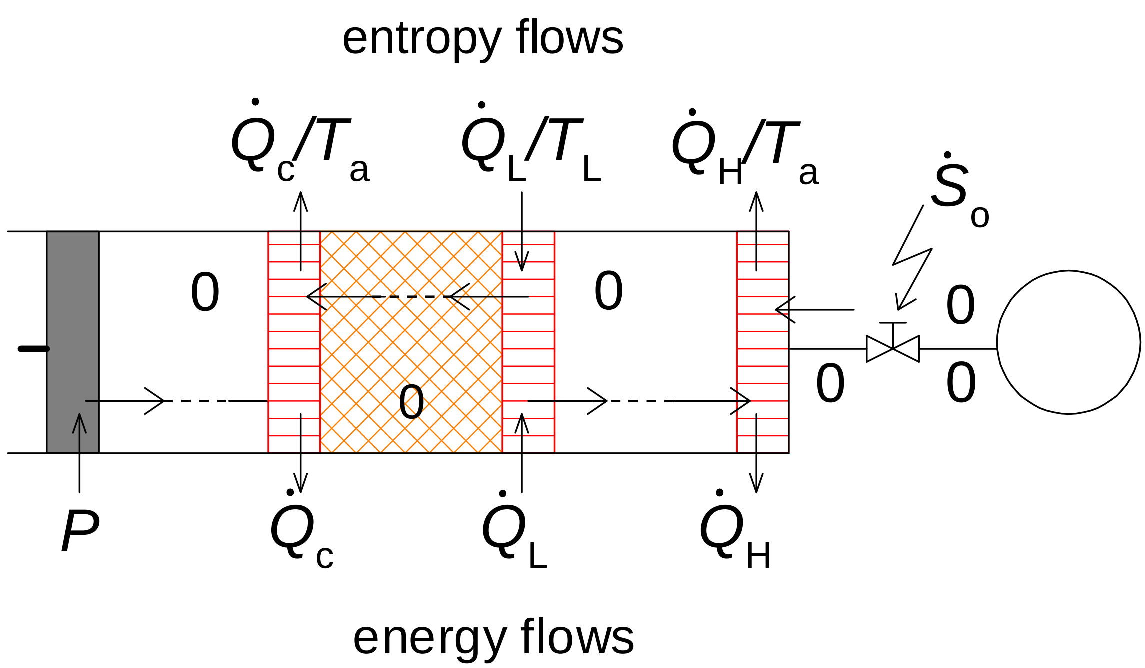
$$T = \text{ constant}$$

steady state

$$\overline{\overset{*}{n}} = 0$$

so, in an ideal regenerator,

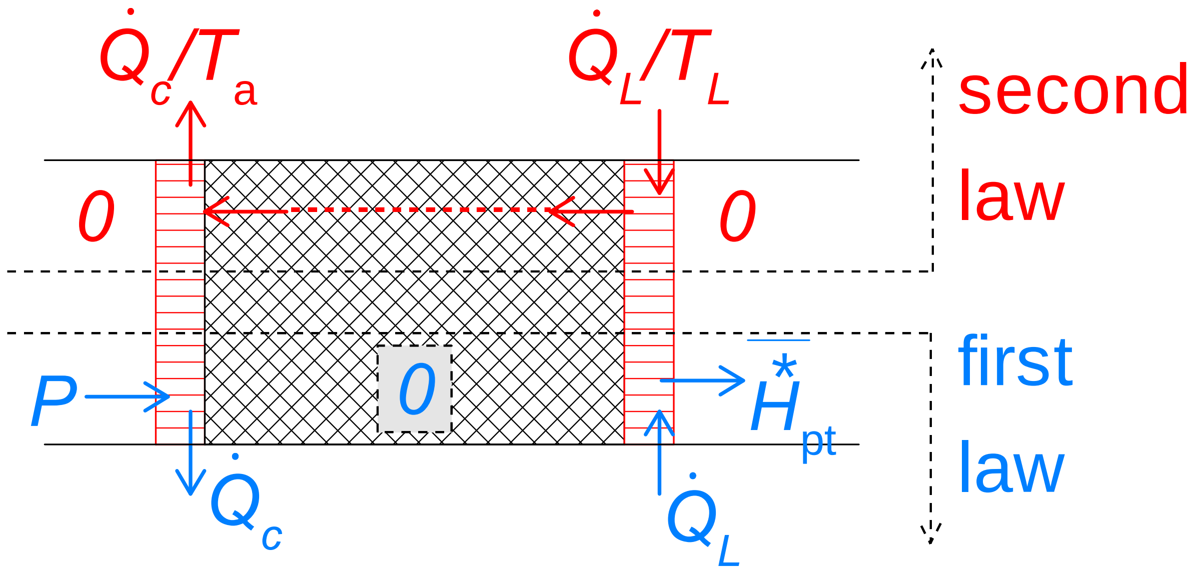
$$\overline{\overset{*}{H}} = 0$$



entropy flows
$\dot{Q}_c/T_a$
$\dot{Q}_L/T_L$
$\dot{Q}_H/T_a$
$\dot{S}_o$
0
0
0
0
0
0
P
$\dot{Q}_c$
$\dot{Q}_L$
$\dot{Q}_H$
energy flows

average enthalpy flow in the regenerator

$$\overline{\overset{*}{H}_{\mathsf{r}}} = 0$$



$$\overline{\overset{*}{S}_{\mathsf{c}}} = \overline{\overset{*}{S}_{\mathsf{t}}} = 0$$

ideal case

$$\frac{\overline{\dot{Q}_{\mathsf{L}}}}{T_{\mathsf{L}}} = \frac{\overline{\dot{Q}_{\mathsf{c}}}}{T_{\mathsf{a}}}$$

Coefficient Of Performance (COP)

$$\xi = \frac{\overline{\dot{Q}_{\mathsf{L}}}}{P}$$

second and first law

$$\frac{\overline{\dot{Q}_{\mathsf{L}}}}{T_{\mathsf{L}}} = \frac{\overline{\dot{Q}_{\mathsf{c}}}}{T_{\mathsf{a}}} = \frac{P}{T_{\mathsf{a}}}$$

so

$$\xi = \frac{T_{\mathsf{L}}}{T_{\mathsf{a}}}$$

Carnot *COP*

$$\xi_{\mathsf{C}} = \frac{T_{\mathsf{L}}}{T_{\mathsf{a}} - T_{\mathsf{L}}}$$