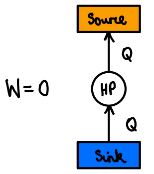
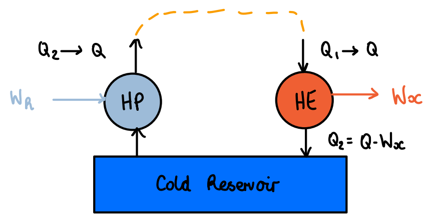


Impossible

would be hot reservoir
but as $Q_{in} = Q_{out}$ it can be
treated as short circuit



From Kelvin-Planck $|W_{HE}| - |W_R| <= 0$

$|W_{HE}| < |W_R|$

Clausius Statement

heat pump

Impossible to construct device that operates in cycle and transfers heat from cooler to hotter body without work being done on system by surroundings

heat engines must exchange heat with ≥2 reservoirs

system exchanging heat with 1 reservoir does 0 work or accepts +ve work from surroundings

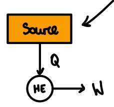
Kelvin-Planck Statement:

heat engine

Impossible for device operating on a cycle to recieve heat from single reservoir and produce a net amount of work

→ engine with no heat rejection impossible

Perpetual motion machine 2nd kind



impossible

2nd Law of Thermodynamics

Reversibility

heat transfer by infinitesimally small temp. differences

forces on moving boundaries only infinitesimally different from external

Reversible: when fluid undergoes process, fluid and surroundings can always be restored to original states

Reservoir

Hot = source
→ e.g sun

Cold = sink
→ e.g lake

if a small amount of heat transfer, the change is negligible

Efficiency

Coefficient of performance for heat pump

$$COP_{HP} = \frac{|Q_1|}{|W|} = \frac{|Q_1|}{|Q_1| - |Q_2|}$$

demands addition of work

HE → HP = inverse

if $|Q_2| > 0$, $\eta < 100\%$

produces work from heat transfer

$$\eta = \frac{|W|}{Q_1} = \frac{|Q_1| - |Q_2|}{|Q_1|}$$

heat engine

$$1 - \eta = \frac{|Q_2|}{|Q_1|} = \frac{T_2}{T_1}$$

→ Carnot Efficiency of Engine

$$\eta = 1 - \frac{|Q_2|}{|Q_1|} = 1 - \frac{|T_2|}{|T_1|}$$

Isentropic Efficiency Compressor

$$\eta = \frac{W'}{W} = \frac{h_2' - h_1}{h_2 - h_1} = \frac{T_2' - T_1}{T_2 - T_1}$$

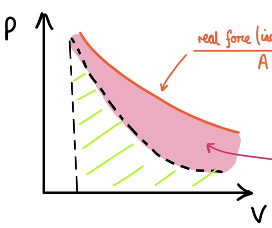
where W' means isentropic work and W is real work

Inverse

Isentropic Efficiency Turbine

$$\eta = \frac{W}{W'} = \frac{h_2 - h_1}{h_2' - h_1}$$

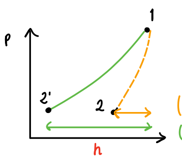
Fluid Friction



real force (inc. friction) / A

difference in work due to friction vs. ideal work

Turbine Friction



Reversible

Irreversible - friction
↘ heating
∴ larger h_2
↘ less work avaliable

$(h_2 - h_1)\dot{m} = \dot{W}$

$(h_{2'} - h_1)\dot{m} = \dot{W}$

Isentropic Efficiency Turbine:

$$\eta = \frac{W}{W'} = \frac{h_2 - h_1}{h_2' - h_1}$$

← inverse →

for compressor, go opposite way along graph:

$$\eta = \frac{W'}{W} = \frac{h_2' - h_1}{h_2 - h_1}$$

ENTROPY

Clausius Inequality

$$\oint \frac{dQ}{T} \leq 0$$

equal when reversible

less than when irreversible

T = temp of fluid supplying heat

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} + \ldots \leq 0$$

- Property, however is always increasing, or may = 0 locally

→ increases when irreversible

→ constant when reversible

↘ reversible local

$$\Delta S = \int_1^2 \frac{dQ_{rev}}{T}$$

Viewpoints change sign e.g heat from fluid to engine:

- engine sees -ve

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_{..}}{T_{...}} \leq 0$$

- fluid sees -ve change

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_{..}}{T_{...}} \geq 0$$

Thermally isolated systems → no heat crosses boundary

$$dU = dQ_{rev} + dW_{rev} = \boxed{Tds - pdv}$$

dividing by mT, rearranging for ds and substituting $du = c_v dT$ and $p = \frac{RT}{v}$ then integrating:

$$s_2 - s_1 = c_v \int_1^2 \frac{dT}{T} + R \int_1^2 \frac{dv}{v} = C_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right)$$

Specific entropy

$$\boxed{\Delta S_{12} = mC_v \ln\left(\frac{T_2}{T_1}\right) + mR \ln\left(\frac{V_2}{V_1}\right)}$$

non-specific

Subbing $\frac{v_2}{v_1} = \frac{T_2}{T_1} \times \frac{p_1}{p_2}$

$$\Delta s_{12} = C_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{p_1}{p_2}\right)$$

$C_v + R = C_p$

$$\boxed{\Delta s_{12} = C_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right)}$$

for isentropic (constant entropy) $s_1 = s_2$

$$\therefore \boxed{\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}}}$$

$\gamma = \frac{C_p}{C_v}$ heat capacity ratio

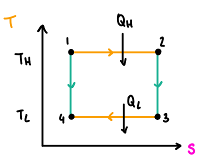
For pure, incompressible liquids: $dv = 0$

∴ distinction between C_v and C_p omitted:

$$ds = \frac{du}{T} + \cancel{\frac{p\,dv}{T}} = c\frac{dT}{T}$$

$$\boxed{\Delta s_{12} = c \ln\left(\frac{T_2}{T_1}\right)}$$

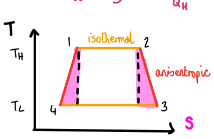
Carnot Cycle



Q_H = area under 1-2

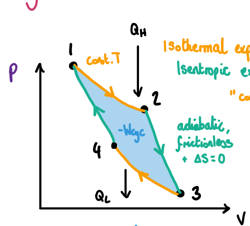
Q_L = area under 3-4

$$\therefore \text{efficiency} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$



irreversible

∴ increased entropy



Isothermal expansion 1→2

Isentropic expansion 2→3

" compression 3→4

" compression 4→1

adiabatic, frictionless + ΔS=0

Net work done = area in curve