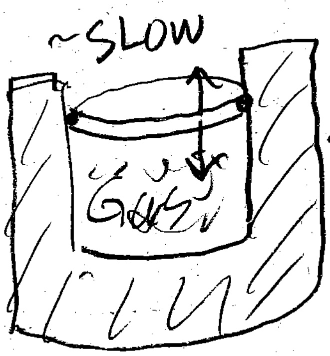
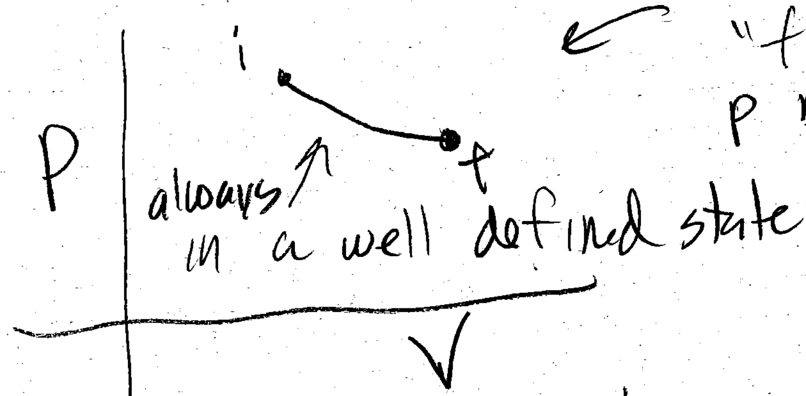
Reversible : (Technicality, can be import.)

- No Friction (no loss of energy)
- SLOW enough so no turbolence.



Insulator (Adiabatic) or Thermal Bath (Isothermal



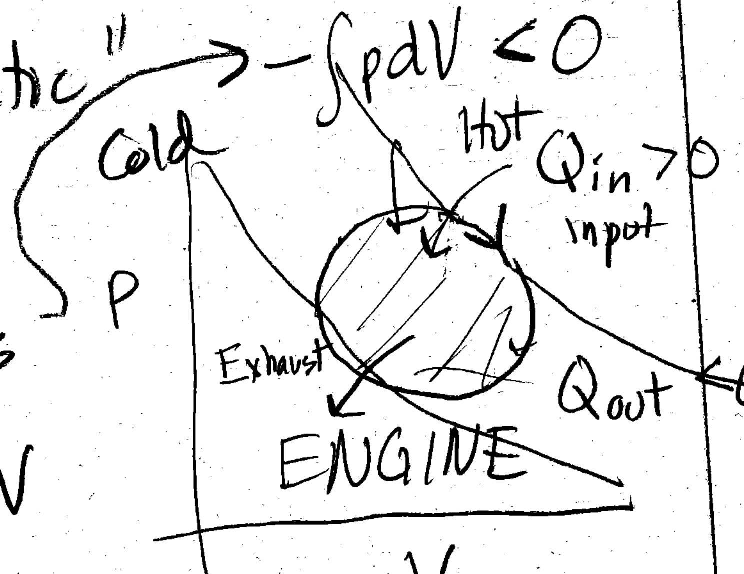
if gas "flowing", p not "equilibrated"

Also "Quasistatic"

Cycle :

Heat → Work by gas

Clockwise on pV



$$W = Q_{in} - |Q_{out}|$$

$$0 \leq e < 1$$

$$e \equiv \frac{W}{Q_{in}} = 1 - \frac{|Q_{out}|}{Q_{in}}$$

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Second Law of Thermodynamics: $|Q_{out}| > 0$

or... $e < 1$

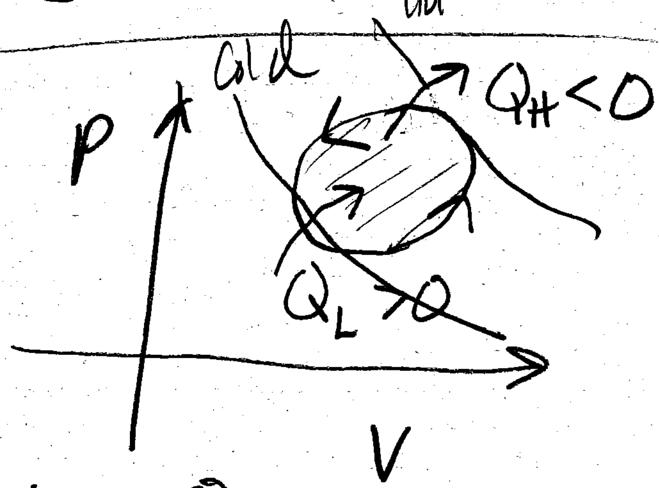
"Kelvin-Planck"

$|Q_{out}|$ causes global warming...

Work → Cooling

"FRIDGE"

Counter clockwise



$$W = -\int p\,dV < 0$$

$$W = Q_L - |Q_H|$$

$$K \equiv \frac{Q_L}{W} = \frac{Q_L}{Q_L - |Q_H|} = \frac{1}{1 - \frac{|Q_H|}{Q_L}}$$

want big!

$$0 \le K < \infty$$

Wish

$$|Q_H| = Q_L$$

NO WAY

Second Law Need non zero work to move heat from cold to hot

"Clausius"

e

$$\varepsilon = \frac{W_{out}}{Q_{in}} = \frac{-W}{Q_{in}} =$$

$$= \frac{P_1 - P_2}{\left[\frac{n_{Dof}}{2}+1\right]P_1 + \left[\frac{n_{Dof}}{2}\right]P_2}$$

$P_1 = 1$ atm $\quad P_2 = \frac{1}{2}$ atm

$n_{Dof} = 5 \quad (N_2)$

$$= \frac{1 - \frac{1}{2}}{\frac{7}{2}\cdot 1 + \frac{5}{2}\cdot\frac{1}{2}}$$

$$= 10.5\%$$

---

make $P_1 = \infty$, $P_2 = 0$

$$\varepsilon = \frac{1}{7/2} = \frac{2}{7} = 28.6\%$$

Backward As a Fridge.

Exhaust $\rightarrow$ Absorbed

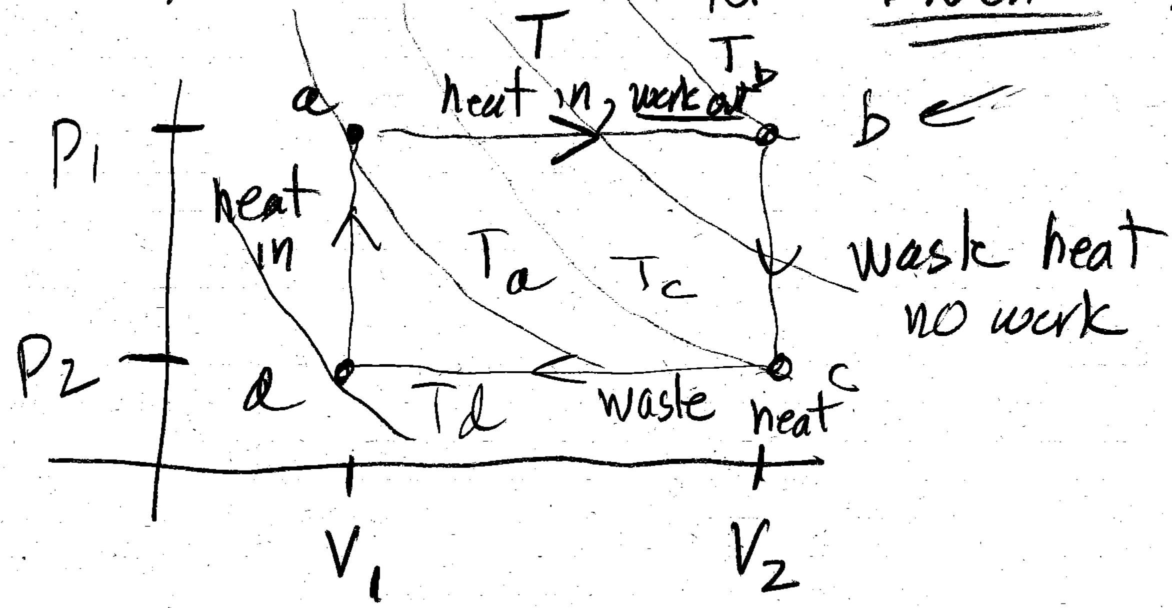
$$K = \frac{Q_{\text{aborbed}}}{W}$$

now, work on

Detail :

Cycle

Q: which point comes after A for ENGINE?



$a \to b$ $\quad Q_{ab} = n C_p (T_b - T_a) > 0$

heat in $\quad = \frac{C_p}{R} p_1 (V_2 - V_1)$

on system $\to$ $W_{ab} = - p_1 (V_2 - V_1) < 0$

$b \to c$ No work!

cooling $\quad Q_{bc} = n C_v (T_c - T_b) < 0$

Exhaust Heat $\quad = \frac{C_v}{R} (p_2 - p_1) V_2 < 0$

$c \to d.$ $\quad Q_{cd} = n C_p (T_d - T_c)$

cooling $\quad = - \frac{C_p}{R} p_2 (V_2 - V_1)$

Exhaust Heat

d

$$W_{cd} = +p_2(V_2 - V_1) > 0 \quad \text{on system}$$

$d \to a \qquad Q_{da} = nC_v(T_a - T_d)$

heat in $\qquad = \frac{C_v}{R}(p_1 - p_2)V_1$

$$W_{da} = 0 \quad \text{no work}$$

Total Work on system $\quad W = -(p_1 - p_2)(V_2 - V_1)$

$$\Delta E_{int} = Q + W$$

know ... $(p_1 - p_2)(V_2 - V_1)$

But... some of Q is WASTE HEAT

Heat in

$$Q_{ab} = \left(\frac{n_{DoF}}{2} + 1\right) p_1 (V_2 - V_1)$$

$$Q_{da} = \frac{n_{DoF}}{2}(p_1 - p_2)V_1$$

$$Q_{in} = p_1\left[\left(\frac{n_{DoF}}{2} + 1\right)V_2 - V_1\right] - p_2 \frac{n_{DoF}}{2} V_1$$

$$\varepsilon = \frac{W_{out}}{Q_{in}} = \frac{(p_1 - p_2)(V_2 - V_1)}{p_1\left[\left(\frac{n_{DoF}}{2} + 1\right)V_2 - V_1\right] - p_2 \frac{n_{DoF}}{2} V_1}$$

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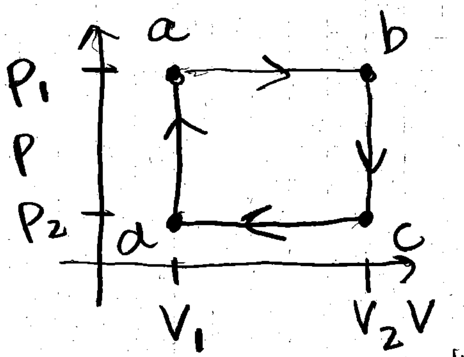


Numbers: $p_1 = 1$ atm $p_2 = 1/3$ atm

$n_{DOF} = 3$ monatomic $V_1 = 0.01\,m^3$ $V_2 = 0.02\,m^3$

	Leg	Q	W (on system)
heat intake	$a \to b$	$\left(\frac{n_{DOF}}{2}+1\right) p_1 (V_2 - V_1) = 2532.5\,J$	$-p_1(V_2 - V_1) = -1013.0\,J$
heat exhaust	$b \to c$	$-\frac{n_{DOF}}{2}(p_1 - p_2) V_2 = -2026.0\,J$	0
heat exhaust	$c \to d$	$-\left(\frac{n_{DOF}}{2}+1\right) p_2 (V_2 - V_1) = -844.2\,J$	$p_2(V_2 - V_1) = 337.7\,J$
heat intake	$d \to a$	$\frac{n_{DOF}}{2}(p_1 - p_2) V_1 = 1013.0\,J$	0
$Q + W = 0$ →	Total	$(p_1 - p_2)(V_2 - V_1) = 675.4\,J$	$-(p_1 - p_2)(V_2 - V_1) = -675.4\,J$
	Qintake	$p_1\left[\left(\frac{n_{DOF}}{2}+1\right)V_2 - V_1\right] - \frac{n_{DOF}}{2} p_2 V_1 = 3545.5\,J$	

gets lower as n_{DOF} ↑ →

$$\varepsilon = \frac{-W}{Q_{intake}} = \frac{(p_1 - p_2)(V_2 - V_1)}{p_1\left[\left(\frac{n_{DOF}}{2}+1\right)V_2 - V_1\right] - \frac{n_{DOF}}{2} p_2 V_1} = 19.0\%$$

Run it as a Fridge

(a) $|W|$ stays same

(b) Now $\underline{Q_{exhaust}}$ is the interesting heat quantity

$$Q_{exhaust} = -\frac{n_{DOF}}{2} p_1 V_2 + \frac{n_{DOF}}{2} p_2 V_2 - \left(\frac{n_{DOF}}{2}+1\right) p_2 V_2 + \left(\frac{n_{DOF}}{2}+1\right) p_2 V_1$$

$$Q_{exhaust} = -\frac{n_{DOF}}{2} p_1 V_2 + p_2\left[\left(\frac{n_{DOF}}{2}+1\right)V_1 - V_2\right]$$

Numerically $= 2870.2$ J

$$\boxed{K = \frac{2870.2}{675.2} = 4.25}$$

Note: $0 = Q_{in} + Q_{out} + W \Rightarrow -Q_{out} = W + Q_{in}$

$$K = \frac{-Q_{out}}{-W} = \frac{W + Q_{in}}{-W} = \frac{Q_{in}}{-W} - 1$$

$$\boxed{K = \frac{1}{\varepsilon} - 1} = \frac{1}{0.19} - 1 = 4.25$$

f

First law ...

$$0 = W_R + Q$$

$$W_R > 0, \quad Q < 0$$

$$= -W$$

$$= -W + (-Q_{in} + Q_{absorbed})$$

$$Q_{absorbed} = Q_{in} + W$$

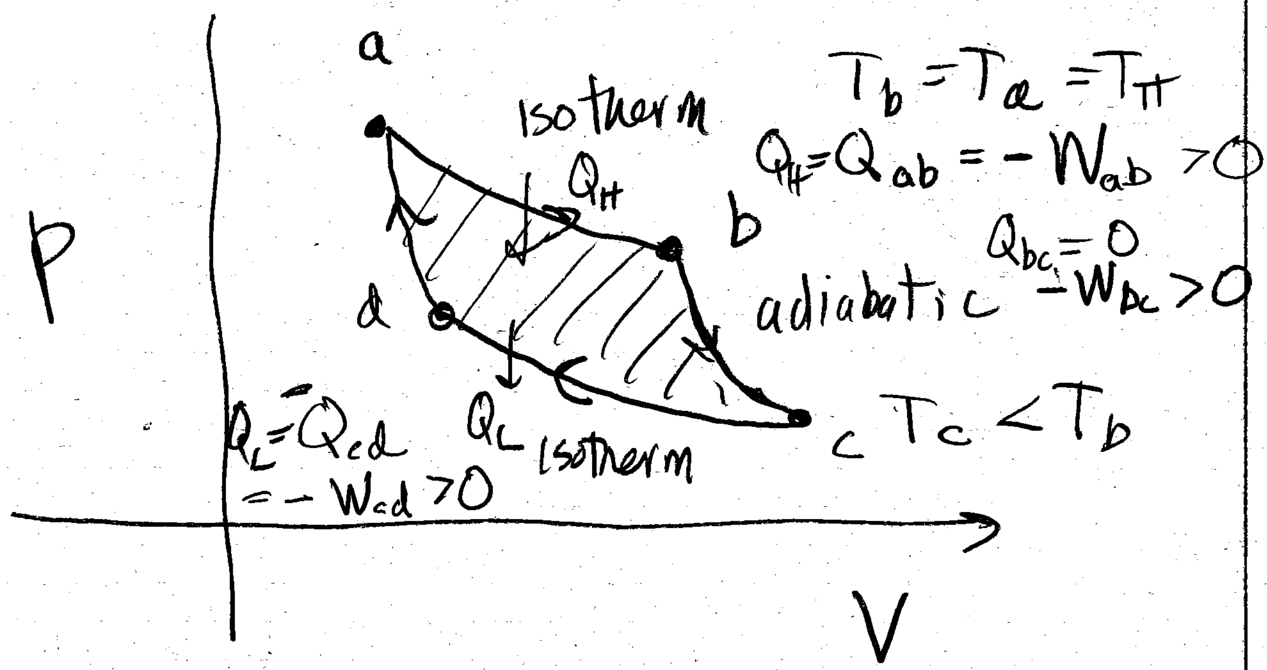
$$K = \frac{Q_{in} + W}{-W}$$

$$K = \frac{1}{\varepsilon} - 1$$

$$= \frac{1}{0.105} - 1 = 8.5$$

Better (more efficient)

Carnot Cycle ...



$$\Delta E_{int} = 0 = \underbrace{Q}_{= Q_H - Q_L} + W$$

$$= Q_H - Q_L + \underset{\substack{\uparrow \\ \text{on system!}}}{\underline{W_{net}}}$$

available work ..

$$-W_{net} = Q_H - Q_L$$

$$\varepsilon = \frac{-W_{net}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

$$Q_H = Q_{ab} = -W_{ab} = nRT_H \ln \frac{V_b}{V_a}$$

$$Q_L = -Q_{cd} = +W_{cd} = nRT_L \ln \frac{V_c}{V_d}$$

$=$