Oct. 1

<u>Introduction to course.</u> ME 323 - Thermo II.

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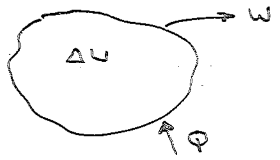
(HW grading & labs)

Question: How many got Thermo I @ → Community college? → Ch.E. 260? → ME 320? } ⇒ Some duplication here.

Focus of Therm I was theory ⇒ Applications were simple.
In 323, no new theory (except Ch. 11)
→ Application to real problems.
⇒ This is where you really learn the Thermo I stuff!

Overview of where we are:

1st Law

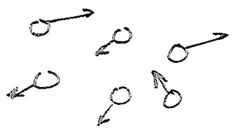


$$Q - W = \Delta U$$

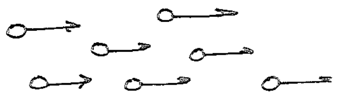
Just keeping track of energy: Just like a checking account.
$\$_{in} - \$_{out}$ = Change in balance.

2nd Law In first law, no distinction between Q and W

<u>Thermal Energy</u>



<u>Organized or Mechanical Energy</u>



- Random molecular motion
- Prime measure is temperature
- Transferred ~~by~~ as heat

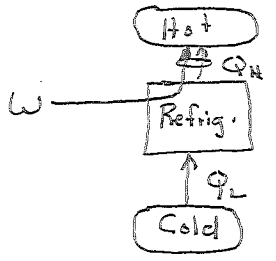
- e.g. car going 60 mph
- All molecules going in same direction.
- Transferred as work

- Work is more useful because we can directly do things with it.
- Mechanical Energy $\xrightarrow{100\%}$ Thermal Energy.
- Thermal Energy $\xrightarrow{<100\%}$ Mechanical Energy
- Thermal Energy at a <u>higher</u> temperature is more valuable than thermal energy at lower T.

} Lost some of the <u>utility</u> of the energy

} All real processes go in a direction that degrades the utility of energy

⇒ Heat flows from hot to cold.



} Best possible refrig cycle:

→ Utility <u>gained</u> by Q_L exactly equals Utility <u>lost</u> by W <u>becoming</u> thermal energy at T_H.

⇒ <u>Reversible cycle</u>!

→ Real cycle, more utility lost than gained.

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Course largely focuses on Energy Conversion.

Raw Forms,
- Fuels
- Heat (geothermal, solar)

$\Longrightarrow$

Useful forms
- Mechanical
- Electrical

↑ Identify and fix inefficiencies.

Course Organization:

Schedule:

	M	W	Th.	F
10:30			L	
~~#~~ 11:30	L	L	o	L

} L = 4 hrs/wk.

- Exams
- Power Plant tour
- Lab outside of class.

Two Labs: Described on Handout.

Grades:

2 midterms @ 100 pts	200
Labs	100
HW	150
Final	150
	600 pts.

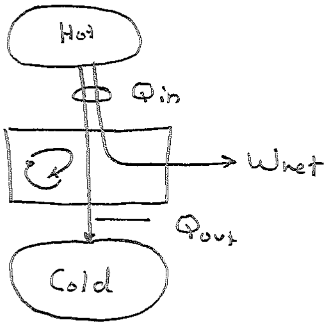
- No hard formula or curve.
- Class mean based on how you perform
- Your grade depends on where you are relative to mean

⇒ Grades based on rank, but ↳ all 4.0 possible!

HW: Assigned on web (1st is out there, due Friday).
→ Solutions go onto web after class, so no late!
→ Turn in at start of class (don't want any active study groups).
⇒ You learn the best by doing something with what you hear and read on your own.

Web: Outline, HW/solutions, handouts, labs, exam learning objectives, lecture notes.

Power Cycles



First Law: $Q - W = \cancelto{0}{\Delta U}$

$\Rightarrow \Sigma Q = \Sigma W = W_{net}$

Second Law:

$$\begin{bmatrix}\text{Increase in utility of} \\ \text{thermal energy converted} \\ \text{from } T_H \rightarrow W_{net}\end{bmatrix} = \begin{bmatrix}\text{Decrease in utility of} \\ Q_{out} \text{ going from } T_H \text{ to} \\ T_L\end{bmatrix}$$

⇒ This is reversible, so real cycle will give less W and more Q_{out}.

Vapor Cycles

- Two phases present:
- Gas part is not ideal gas:

No $PV = mRT$

No $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$

No $\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{K-1/K}$

Use tables for all.

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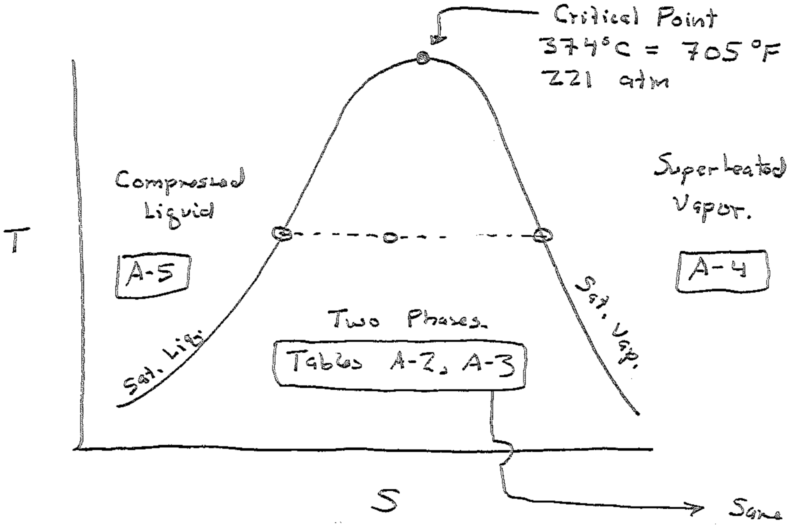
Rankine cycle: ~ 80% of electricity generation

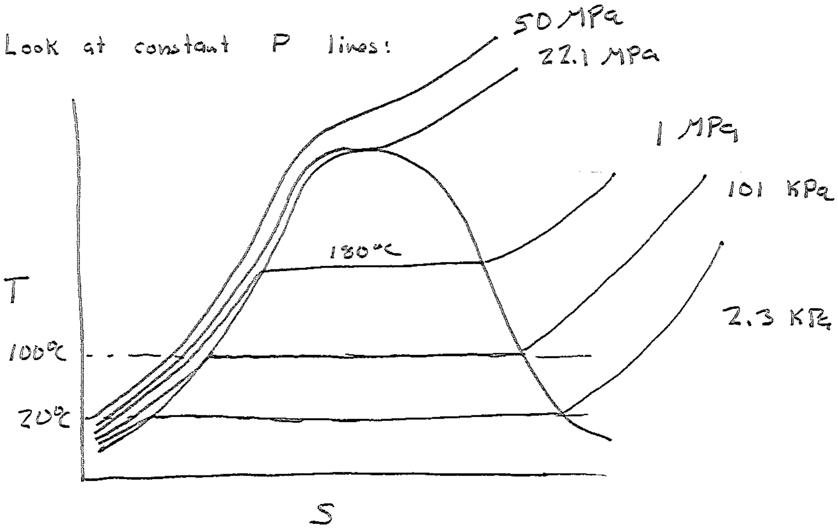
Revisit T-s dome for main features:



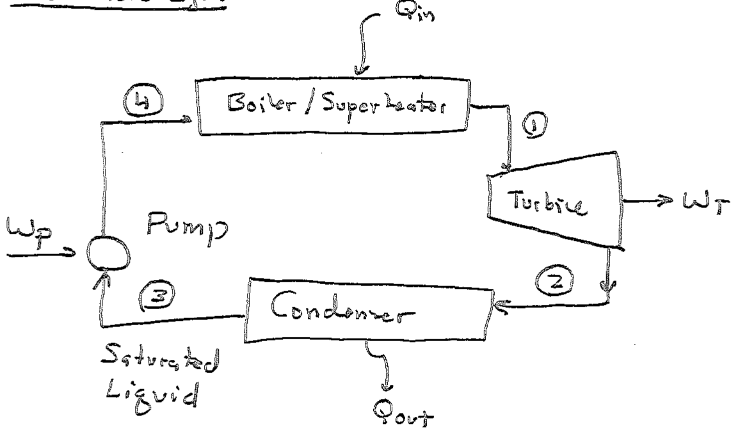
1. Dome
2. Sat. Liq/Vap.
3. Two - Phases.
   (inc. dashed line)
4. Comp. Liq.
5. Superheated vapor
6. Critical Point.
7. No phase change.

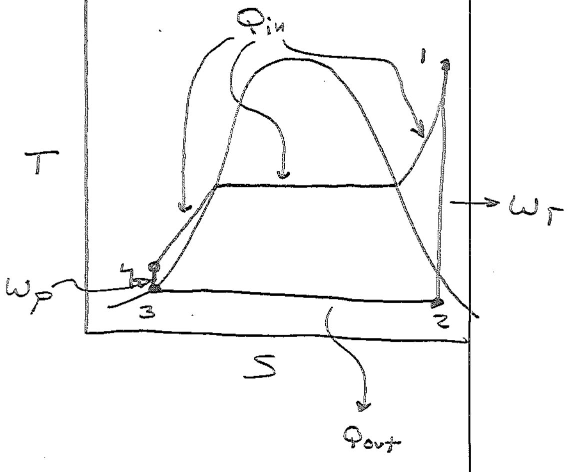
→ Same info, just even T vs. P intervals.

Look at constant P lines:



The basic cycle:





Review procedures via simple example:

P @ pump inlet = 100 KPa

P @ pump exit = 1 MPa

T after superheating = 350°C

$\Rightarrow$ Find W_{net}, η

① → ② Isentropic expansion to 100 KPa.

→ Finish [inside, outside, on] dome?

→ Don't know, but will find out.

$$\left.\begin{array}{l} 350\,^\circ C \\ 1\ MPa \end{array}\right\} \xRightarrow{A\text{-}4} \begin{array}{l} h_1 = 3157.7\ KJ/kg \\ s_1 = 7.3011\ KJ/kg\text{-}K \end{array}$$

@ ② $P_2 = 100$ KPa

$S_2 = S_1$

⇒ Look at sat tables [A-3] @ 100 KPa $\quad \underline{S_f}$ 1.3026 $\quad \underline{S_g}$ 7.3594

→ Since we are between those, we have a saturated mix.

→ If $S_2 = 7.5$, then we would be superheated → A-4

→ Get h_2 by two-step process:

ⓐ Get quality: $X_2 = \frac{S_2 - S_f}{S_g - S_f} = \frac{7.3011 - 1.3026}{7.3594 - 1.3026} = 0.99$

remember what quality is? $X = \frac{\text{mass vapor}}{\text{mass vapor + liquid}}$

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ⓑ Find $h_2 = h_f + X_2 h_{fg} = 417.46 + [0.99][2258] = 2652.9$ KJ/kg

A-3 @ 100 KPa

$w_T = h_1 - h_2 = 504.8$ KJ/kg

② → ③ Constant P condensation, Think of a pipe

$$③ \left.\begin{array}{l} 100\ KPa \\ Sat.\ Liq \end{array}\right\} \begin{array}{l} h_3 = 417.46\ KJ/kg \\ v_3 = 1.043E\text{-}3\ m^3/kg \end{array}$$

$q_{out} = h_2 - h_3 = 2235.4$ KJ/kg.

③ → ④ Isentropic compression of a saturated liquid.

Could work from compressed liquid tables ⇒ $④ \left.\begin{array}{l} 1\ MPa \\ S_4 = S_3 \end{array}\right\} \Rightarrow h_4.$

But easier to use Eq. 6.53b $\quad [w]_{rev} = -\int_1^2 v\,dP$

For compressed liquid, $v \overset{?}{\doteq}$ constant. $\quad [w]_{Rev} = -v[P_2 - P_1]$

For us:

$w_p = v_3[P_4 - P_3]$ $\quad$ [change sign since we call w_p positive].

$= \left[1.043E\text{-}3\ \frac{m^3}{kg}\right]\left[1000 - 100\ KPa\right] = 0.94\ \frac{KPa\text{-}m^3}{kg} = 0.94\ KJ/kg$

Then $h_4 = h_3 + w_p = 417.46 + 0.94 = 418.4$ KJ/kg.

④ → ① Constant P heat addition. $\boxed{\text{Pipe again}}$

$q_{in} = h_1 - h_4$

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Summarize:

$q_{in} = 2739.3$

$q_{out} =$ ~~[illegible]~~ 2235.4

$w_p = 0.94$

$w_T = 504.8$

$w_{net} = q_{in} - q_{out} = 503.9$

$$\eta = 1 - \frac{q_{out}}{q_{in}} = 18.4\%$$

- Really bad!
- You're out of business.

Efficiency is Key:

Trojan was 1150 MW

Retail Revenue: $\frac{1{,}150{,}000\ \text{KW}\ \big|\ 0.07\ \$\ \big|\ 8760\ \text{hr}}{\quad\big|\ \text{KW-hr}\ \big|\ \text{yr}} = 705.2\text{E+}6\ \$/\text{yr}$.

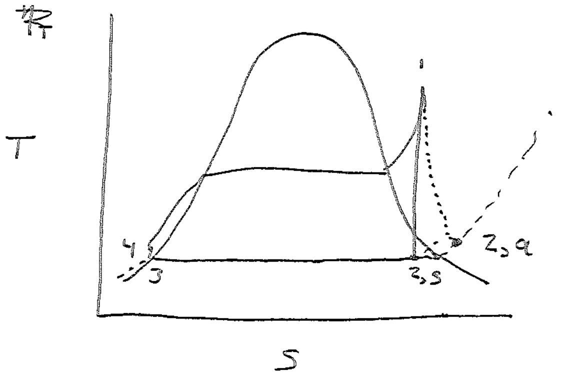
Average nuclear plant $\eta \cong 30\%$. If 31% ~~[illegible]~~

$\Delta = 23.5\text{E+}6\ \$/\text{yr}$

So small numbers make a big difference.
Look at sources of inefficiency.

And it only gets worse because we have assumed a perfect turbine.

How do we handle finite turbine η?



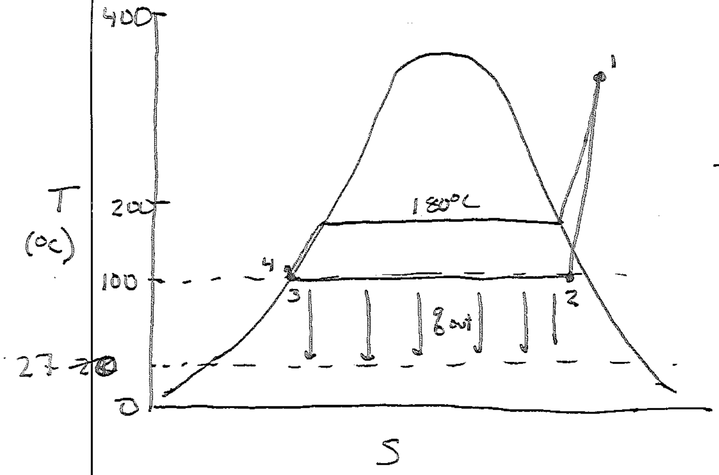
- ~~[illegible]~~ Drops to same pressure, but has higher S

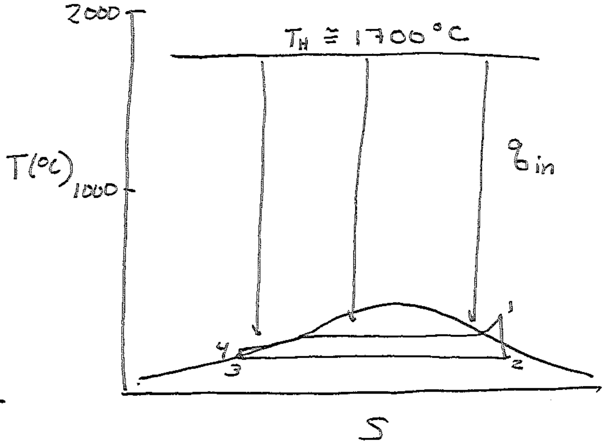
$$\eta_T \equiv \frac{w_a}{w_s} = \frac{h_1 - h_{2,a}}{h_1 - h_{2,s}}$$

- If given $\eta_T \Rightarrow h_{2,a}$
- Note that $h_{2,s}$ is just an intermediate value with no real significance

- Suppose you needs S_2 for a calc?
  - → Now $S_{2,a} \neq S_1$
  - → have P_2, $h_{2,a} \longrightarrow S_{2,a}$

Superheat → Interpolate
Mix → $X_{2,a}$ from $h_{2,a}$
→ $S_{2,a}$ from $h_{2,a}$





- Heat flowing from hot to cold is irreversible
  $\Rightarrow$ losing work potential.
- What to do?
  - ⓐ Insert cycle between T_H and steam [Combined cycle]
  - ⓑ ~~Config~~ Configure steam to reduce ΔT.

- We know W_{max} for this situation can be obtained from Carnot.
- <u>Irreversibility</u> is a way of apportioning this missing work to the different parts of the cycle.
  $\Rightarrow$ Lets you decide where to put your capital \$.

To get there we need to introduce some concepts from Ch. 7

See Web Handout

We get work from resources that are out of thermal, mechanical, or chemical equilibrium with the environment.

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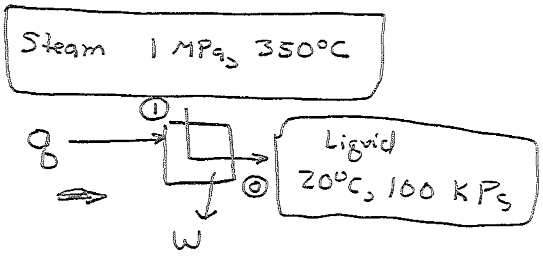


2nd Law says will get W_{max} if
ⓐ Move steam to environmental conditions (20°C, 100 KPa, liquid)
ⓑ Do this reversibly.

Once here, no more work can be removed.

- Process will either absorb or reject heat.

- W_{max} easy to get — No need to specify the process.

1st Law: $q - W = h_o - h_1 \Rightarrow W = h_1 - h_o + q$ [now we need q]

$$S_{gen} = \Delta S_{sys} + \Delta S_{surr} = \Delta S_{sys} + \frac{Q_{surr}}{T_{surr}}$$

$$\underset{(rev)}{0} = S_o - S_1 + \frac{Q_{surr}}{T_o} \Rightarrow Q_{surr} = T_o(S_1 - S_o)$$

$$\Rightarrow Q_{sys} = T_o(S_o - S_1)$$

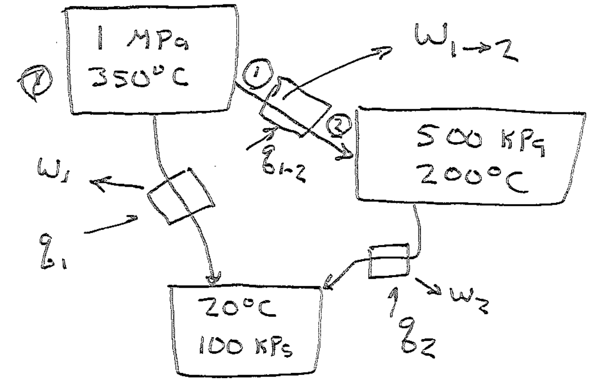
~~1st Law $Q - W = h_o - h_1 \Rightarrow W = h_1 - h_o + Q$~~

$$\Rightarrow \boxed{W_{max} = h_1 - h_o - T_o(S_1 - S_o)}$$

For those who have seen this before, this is Gibbs Free Energy.

Max work we can possibly get from processing 1 kg of steam through process.

Next question: What is W_{max} for going between two states that are neither the dead state?



- rev. work between any two states is the same.

$$\Rightarrow W_1 = W_{1\to 2} + W_2$$

$$\text{or } W_{1\to 2} = W_1 - W_2$$

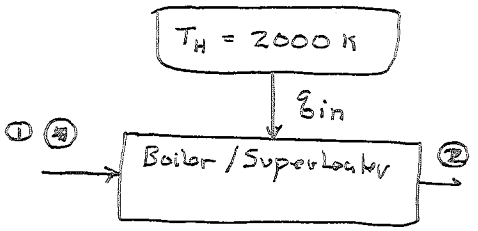
But W_2 is just maximum work for state 2

$$\Rightarrow W_{1\to 2} = \left[h_1 - h_o - T_o(S_1 - S_o)\right] - \left[h_2 - h_o - T_o(S_2 - S_o)\right]$$

$$\Rightarrow \boxed{W_{1\to 2} = h_1 - h_2 - T_o(S_1 - S_2)}$$

Finally, look real process going between ① → ② ⇒ W_{actual}.
What is the lost work potential?
$i = W_{max} - W_{act}$?

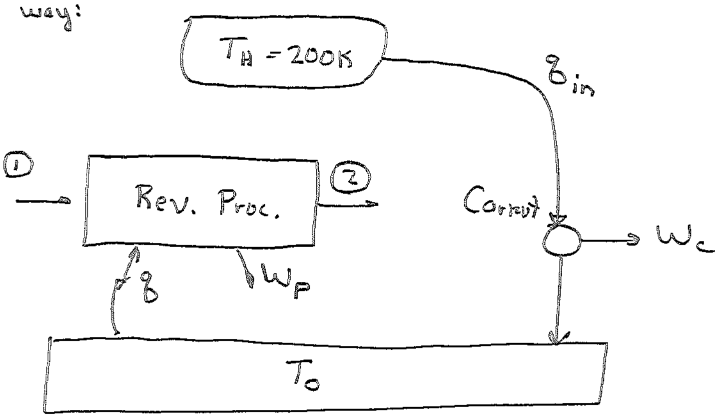
Look at heat addition step:



Here $W_{act} = 0$
$\Rightarrow$ Get W_{max}.

Need to construct a reversible means of ⓐ Doing the boiling, and
ⓑ Extracting q_{in} from reservoir.

Here is one way:



From above: $w_p =$ ~~$h_2 - h_1 - T_0(S_2 - S_1)$~~ $h_1 - h_2 - T_0(S_1 - S_2)$

For Carnot $w_c = q_{in}\left[1 - \frac{T_0}{T_H}\right]$

so: $w_{max} = \underbrace{h_1 - h_2}_{\times} - T_0(S_1 - S_2) + \underbrace{q_{in}}_{\times} - q_{in}\frac{T_0}{T_H}$

But 1^{st} law on original process: $q_{in} = h_2 - h_1$ so indicated terms cancel.

Also: Customary to write q_{in} relative to reservoir, so:

$$w_{max} = T_0(S_2 - S_1) + \frac{q_R T_0}{T_R}$$

$$\boxed{i = T_0\left[(S_2 - S_1) + \frac{q_R}{T_R}\right] = T_0 S_{gen}}$$

Now we are ready to go $\frac{P}{8}$.

Sign = ?

$i_{1\to2} \overset{?}{=} 0 \qquad q = 0,\ S_2 = S_1$

$i_{2\to3} = T_0\left[S_3 - S_2 + \frac{q_R}{T_R}\right] = (300\text{ K})\left[\left(\overset{13026 - 7.3011}{\cancel{7.3011 - 1.3026}}\right) + \frac{2235.4}{300}\right]$

$= 435.8$ KJ/kg.

$i_{3\to4} \overset{?}{=} 0 \qquad q = 0,\ S_4 = S_3$

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$$i_{4\to1} = T_0\left[s_1 - s_4 + \frac{q_R}{T_R}\right] = (300\,K)\left[(7.3011 - 1.3026) + \frac{-2739.3}{1973}\right]$$

$$= 1383 \text{ kJ/kg}$$

⇒ So by far the biggest problem is on the hot side.

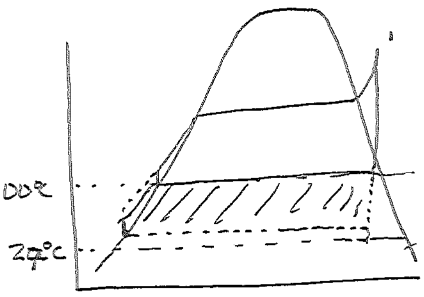
Look at max efficiency: $\eta_{max} = \frac{w_{net} + \Sigma i\text{'s}}{q_{in}} \cong \frac{504.8 + 435.8 + 1383}{2739.3} = 84.8\%$

Compare to Carnot $\eta_c = 1 - \frac{T_0}{T_H} = 1 - \frac{300}{1973} = 84.8\%$!

i can be thought of as where Carnot cycle work is missed.
(actually much broader than this and can be used to get away from Carnot as standard).

Now we have to address our $\eta_c = 18.4\%$ problem.

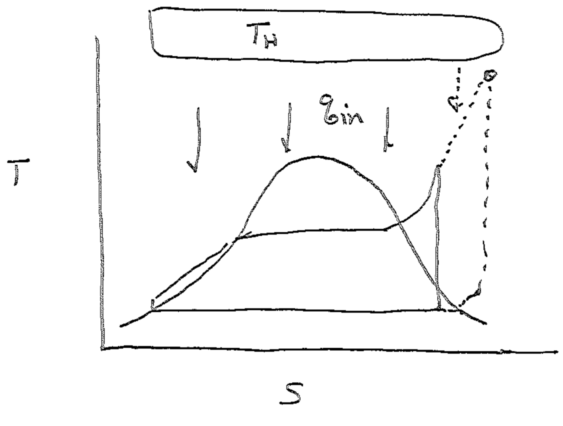
First look at q_{out}:



- Approaches to reducing ΔT ?
  - → Lower condenser T
  - → Reduce condenser P to a vacuum.
- Go as low as your cooling medium allows.
- Since system is closed, there's nothing magic about 100 KPa
- In practice, run about ~3 psia.
- This solves the $i_{condenser}$ problem. (Rankine's strong point).

Next look at q_{in}:

1. <u>Increase steam superheat</u>:



- New q_{in} added at higher T.
  - → Increases average T for q_{in}
  - → Better η
- But $T_{max} \cong 620°C$
  - → H_2O becomes corrosive to boiler tubes and turbine blades.

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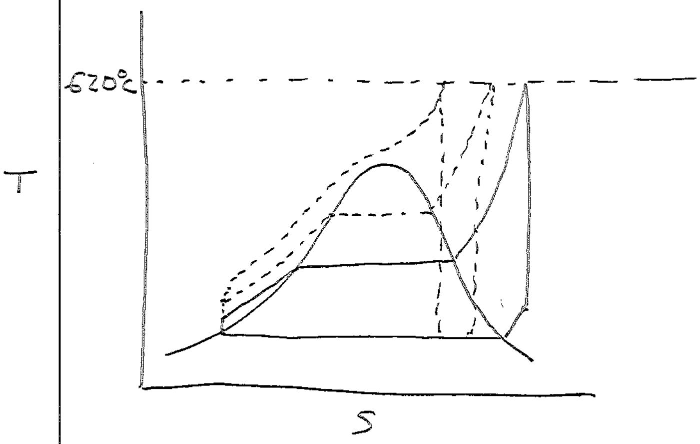
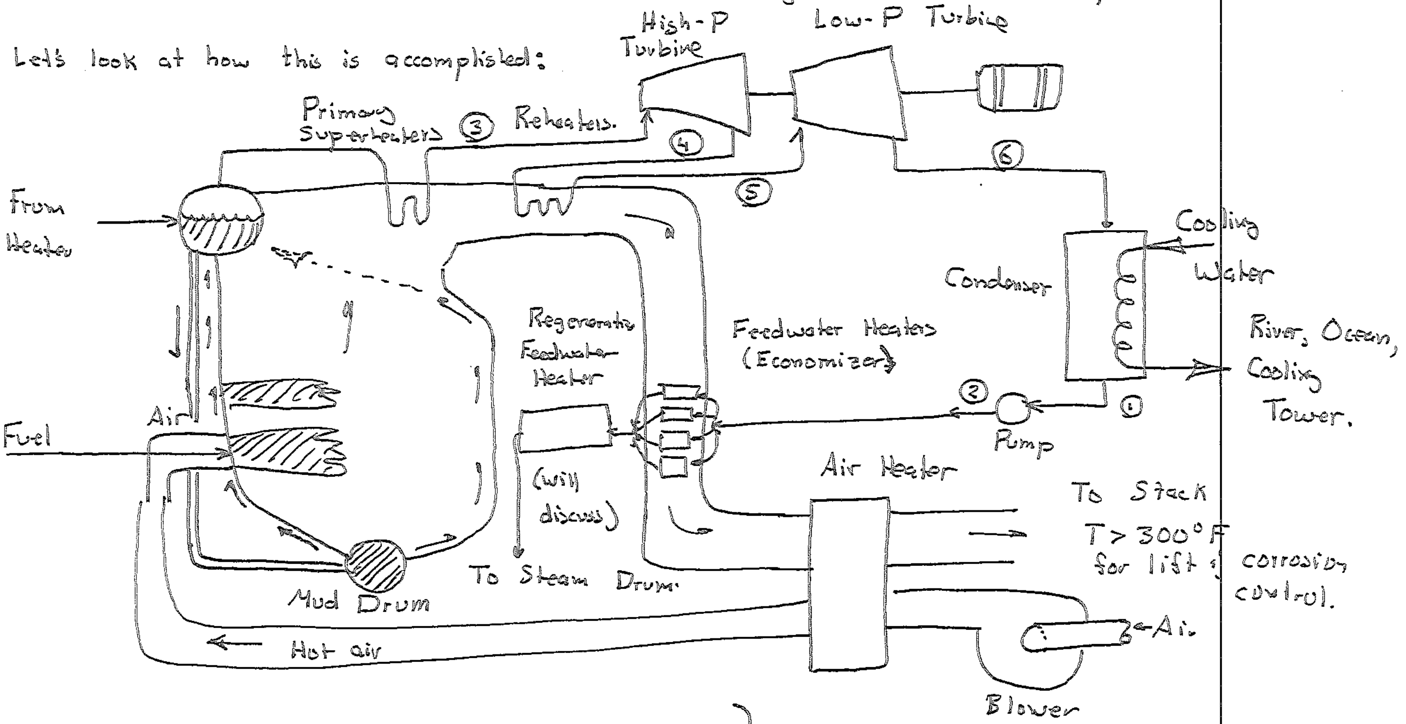
2. Increase boiler P.



- Higher - P ⟶ Higher average T for q_{in}
- Still must stop heating at 620°C
- But: Too much condensate in last turbine stages.
  ⟶ Get around by partially expanding the steam and then reheating before final expansion.
- Many modern units are supercritical.

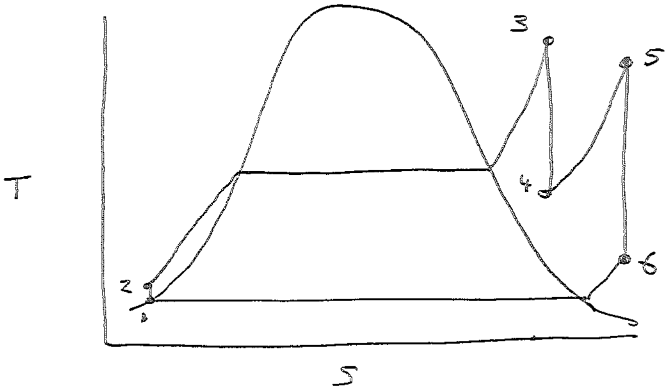
Let's look at how this is accomplished:



- Boiler: - Flame boils water on walls tubes.
  - ~~Natural~~ Steam rises into drum
  - Pulls water down external downcomer

} Natural circulation pattern

Build T-s



$$q_{in} \overset{?}{=} (h_3 - h_2) + (h_5 - h_4)$$

$$q_{out} \overset{?}{=} (h_6 - h_1)$$

$$W_{net} = q_{in} - q_{out}.$$

Note: If we preheat the water, it enters boiler hotter
⇒ Higher average T for q_{in} ⇒ Higher η
⇒ Use steam from cycle to do this.

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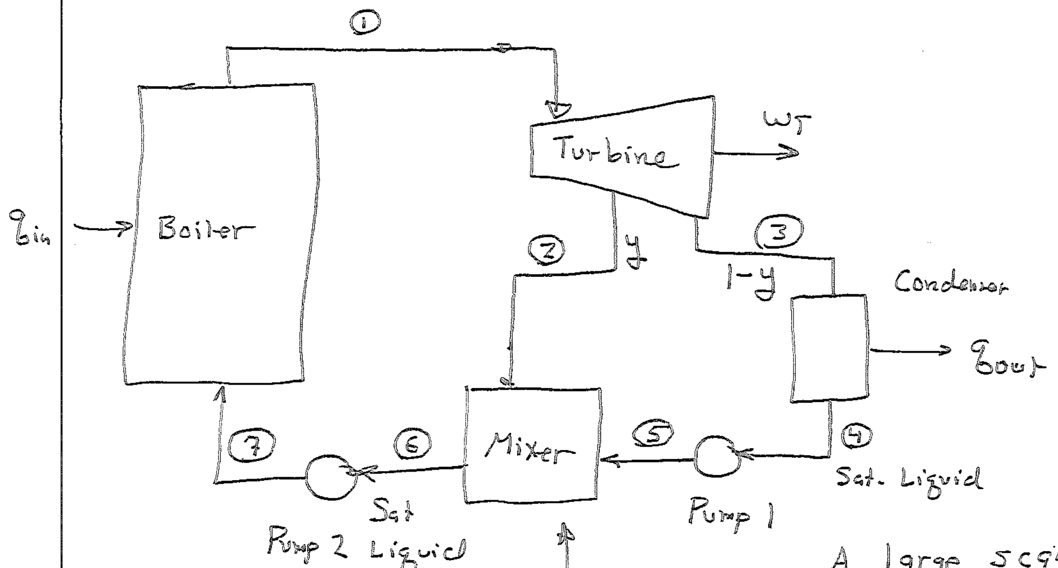
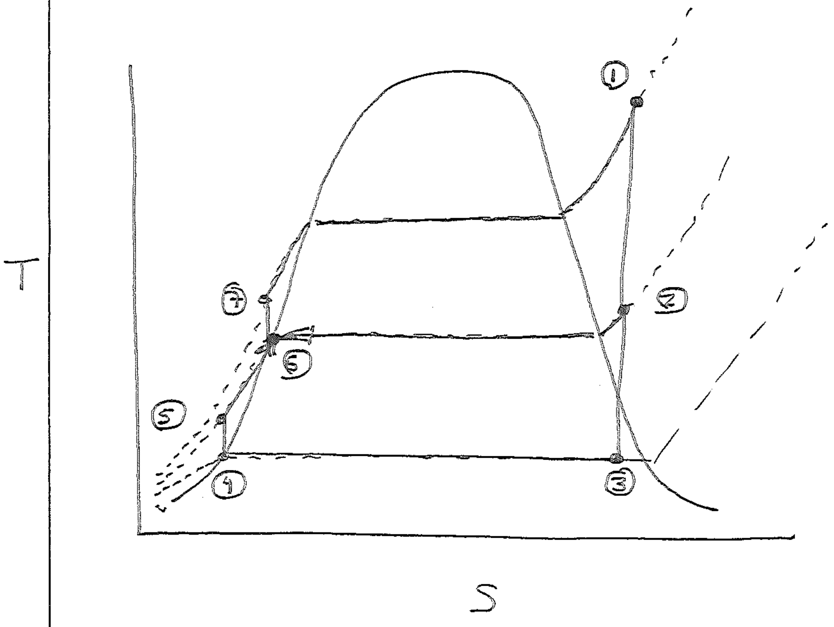
This is regeneration. ⇒ Two Kinds (open vs. closed) → Also formerly. in PP.
Power plant

Basic Open System.



A large scale Latte Steamer!

y = fraction of total flow removed $= \dfrac{\dot m_2}{\dot m_1}$ so $1-y = \dfrac{\dot m_3}{\dot m_1}$



Mixing ⑤ + ② → ⑥

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General Approach:

① P_1, T_1 known $\longrightarrow h_1, S_1$
② $P_2, \; S_2 = S_1 \longrightarrow h_2$
③ $P_3, \; S_3 = S_1 \longrightarrow h_3$
④ Sat Liq @ $P_4 \longrightarrow h_4$
⑤ $w_{p_1} = v_4 (P_5 - P_4), \; h_5 = h_4 + w_p$
⑥ Sat. Liq @ P_6
⑦ $w_{p,2} = v_6 (P_7 - P_6), \; h_7 = h_6 + w_{p,2}$

Last unknown is $y \longrightarrow$ How to get it?

$\longrightarrow$ When you're lost, look for something to put first law around $\Rightarrow$ Mixer.

$$\cancel{\dot{Q}}^{0} - \cancel{\dot{W}}^{0} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i$$

$\Rightarrow$ exit = inlet.

$$\Rightarrow \dot{m}_6 h_6 = \dot{m}_2 h_2 + \dot{m}_5 h_5 \quad ; \quad \text{divide by } \dot{m}_6$$

$$\Rightarrow h_6 = \underbrace{\frac{\dot{m}_3}{\dot{m}_6}}_{=y} h_2 + \underbrace{\frac{\dot{m}_5}{\dot{m}_6}}_{=1-y} h_5 \quad \Rightarrow \quad h_6 = y h_2 + (1-y) h_5$$

$$\Rightarrow y = \frac{h_6 - h_5}{h_2 - h_5}$$

Why do we need this?

$$\eta = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{h_3 - h_4 \; \cancel{h_1 - h_7}}{h_1 - h_7} \Rightarrow \text{But this is wrong! Why?}$$

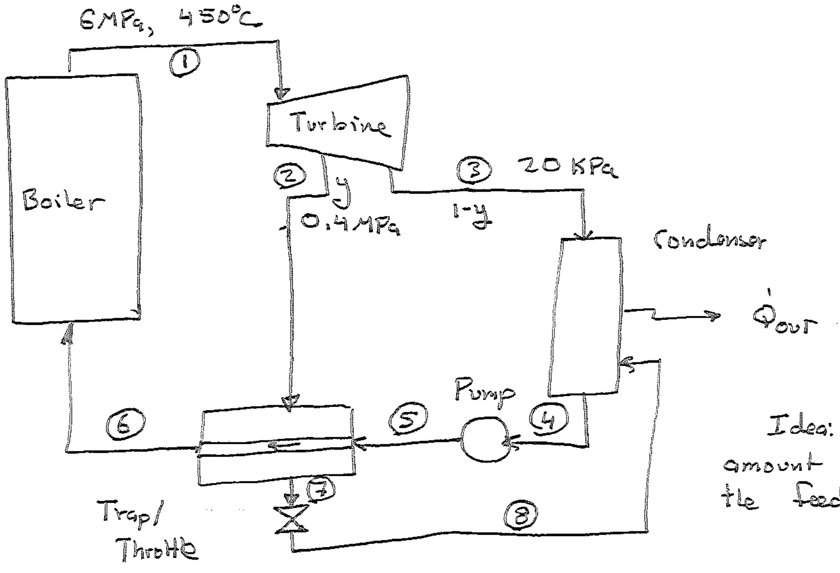
$$\dot{Q}_{in} = \dot{m}_1 [h_1 - h_7] \quad ; \quad \dot{Q}_{OUT} = \dot{m}_4 (h_3 - h_4)$$

$$\eta = 1 - \frac{\dot{m}_4 (h_3 - h_4)}{\dot{m}_1 (h_1 - h_7)} = 1 - (1-y)\frac{(h_3 - h_4)}{(h_1 - h_7)}$$

} All flow goes through boiler; Only part through condenser.

One important function of open heaters is clearing air out of condensate.
$\longrightarrow$ See power plant.

Second major system is the <u>Closed Feedwater Heater</u>

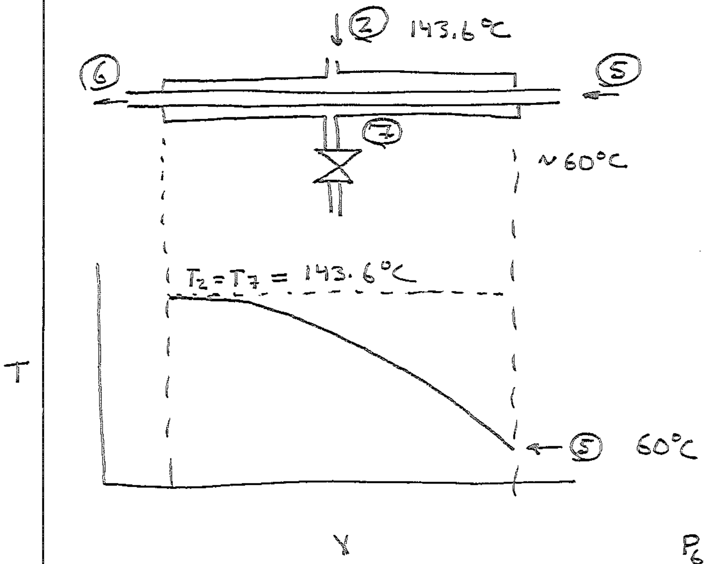


Idea: Grab a small amount of steam to heat the feedwater.

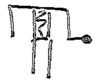
Scorecard:

	P(MPa)	What else?	⟹	h (kJ/kg)
1	6	450°C		3301.4
2	0.4	$s_2 = s_1$		2664.9
3	20 kPa	$s_3 = s_1$		2211.7
4	20 kPa	Sat. Liq.		251.4
5	6	$h_5 = h_4 + w_p$, $w_p = v_4(P_5 - P_4)$		257.5
6	6	?		
7	0.4	Sat. Liq.		604.74
8	20 kPa	$h_8 = h_7$		604.74

Look at point ⑥



- Trap will only pass liquid, not vapor. (one in each room).
- Similar to toilet stopper.



→ low liquid level keeps it shut, high floats it open.

⟹ If exchanger is long enough, what would T_6 be? ⟹ 143.6°C

$$\left.\begin{array}{l} P_6 = 6\text{ MPa} \\ T_6 = 143.6°\text{C} \end{array}\right\}$$ Approximate as h_f @ 143.6°C $= 604.7\cancel{3}^{4}$ kJ/kg.

(p has little influence on h for liquids

Now get y: First law on Heat Exchanger

$$\cancel{\dot Q}^{0} - \cancel{\dot W}^{0} = \sum \dot m_e h_e - \sum \dot m_i h_i$$

$$\dot m_6 h_6 + \dot m_7 h_7 = \dot m_2 h_2 + \dot m_5 h_5$$

but $\dot m_6 = \dot m_5$, $\dot m_7 = \dot m_2$ so collect terms:

$$\dot m_6 (h_6 - h_5) = \dot m_7 (h_2 - h_7)$$ Divide by $\dot m_6$

$$(h_6 - h_5) = \underbrace{\frac{\dot m_7}{\dot m_6}}_{y}(h_2 - h_7) \qquad y = \frac{h_6 - h_5}{h_2 - h_7} = 0.1685$$

To finish off, lets assume a <u>basis</u> of 1 kg steam through the boiler.

$$\Rightarrow \frac{\dot Q_{in}}{\dot m_1} = \cancel{(1\text{ kg})}(h_1 - h_6) = 2696.66 \text{ kJ/kg Boiler}$$

How to get $\dot Q_{out}$? not just $h_3 - h_4$ due to stream ⑧

⟹ First Law:

$\dot{Q}_{out} = \dot{m}_4 h_4 - \dot{m}_3 h_3 - \dot{m}_8 h_8$

Divide by $\dot{m}_1$

$$\frac{\dot{Q}_{out}}{\dot{m}_1} = \underbrace{\frac{\dot{m}_4}{\dot{m}_1}}_{1} h_4 - \underbrace{\frac{\dot{m}_3}{\dot{m}_1}}_{1-y} h_3 - \underbrace{\frac{\dot{m}_8}{\dot{m}_1}}_{y} h_8 = 251.4 - (1-0.1685)(2211.7) - (0.1685)(604.74)$$

$$\frac{\dot{Q}_{out}}{\dot{m}_1} = 1689.53 \ \mathrm{KJ/Kg} \text{ Boiler.}$$

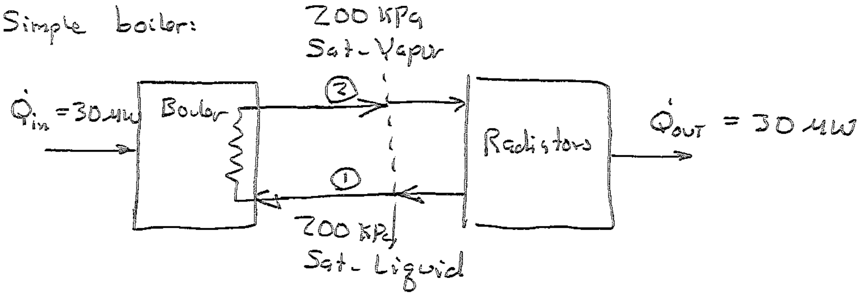
$$\eta_c = 1 - \frac{\dot{Q}_{OUT}}{\dot{Q}_{in}} = 1 - \frac{1689.53}{2696.66} = \underline{\underline{37.4\%}}$$

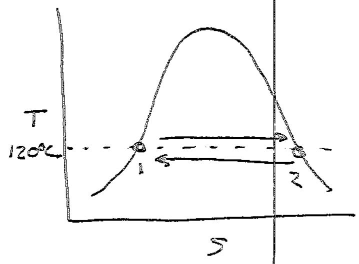
Same cycle without regeneration? 35.6% ⇒ Δ2.2% or > 30 M$/yr @ Trojan.

Last topic: Cogeneration: "When you have a required heating load, why not make some electricity on the side?"

⇒ Suppose you have a heating load of 30 MW

① Simple boiler:

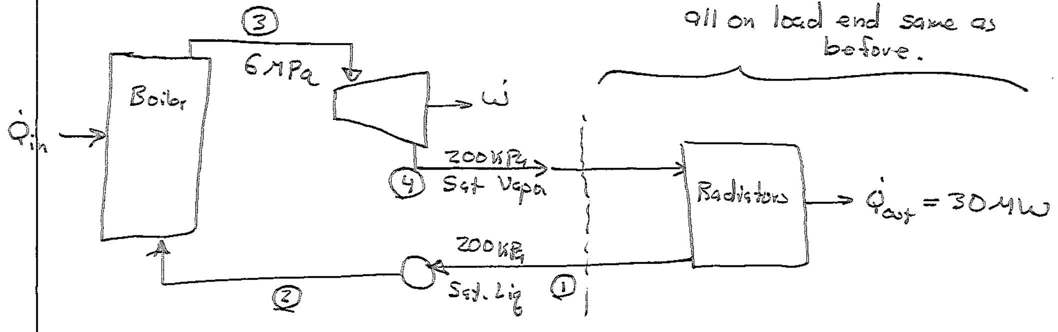


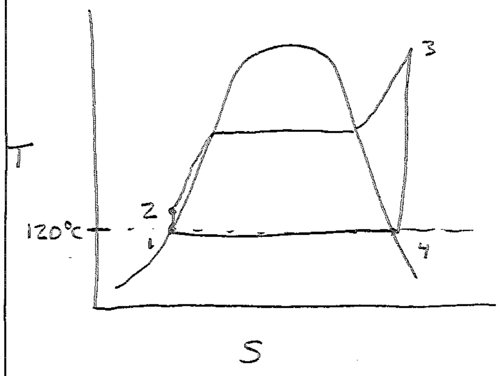


$$\dot{m}_{steam} = \frac{\dot{Q}}{h_{fg} @ 200\,\mathrm{KPa}} = \frac{30{,}000 \ \mathrm{KJ}}{\mathrm{s}} \left| \frac{\mathrm{Kg}}{2201.9 \ \mathrm{KJ}} \right. = 13.6 \ \mathrm{Kg/s}$$

$$\text{Cost: } \frac{30{,}000 \ \mathrm{KJ}}{\mathrm{s}} \left| \frac{\$3}{10^6 \ \mathrm{KJ}} \right| \frac{3600\,\mathrm{s}}{\mathrm{hr}} \left| \frac{24\,\mathrm{hr}}{\mathrm{day}} \right. = \$7800/\mathrm{day}.$$

② Cogeneration:





By our usual methods we get:

$h_1 = 504.7 \text{ kJ/kg}$

$h_2 = 510.85$

$h_4 = 2706.7, \quad s_4 = 7.1271 \text{ kJ/kg-K}$

$$③ \left.\begin{array}{l} 6 \text{ MPa} \\ s_3 = s_4 \\ \text{(going backward)} \end{array}\right\} h_3 = 3624.0$$

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$\dot{Q}_{in} = \dot{m}(h_3 - h_2) = 42.3 \text{ MW}$

$\dot{Q}_{out} = 30 \text{ MW}$

$\dot{W}_{net} = 12.3 \text{ MW}$

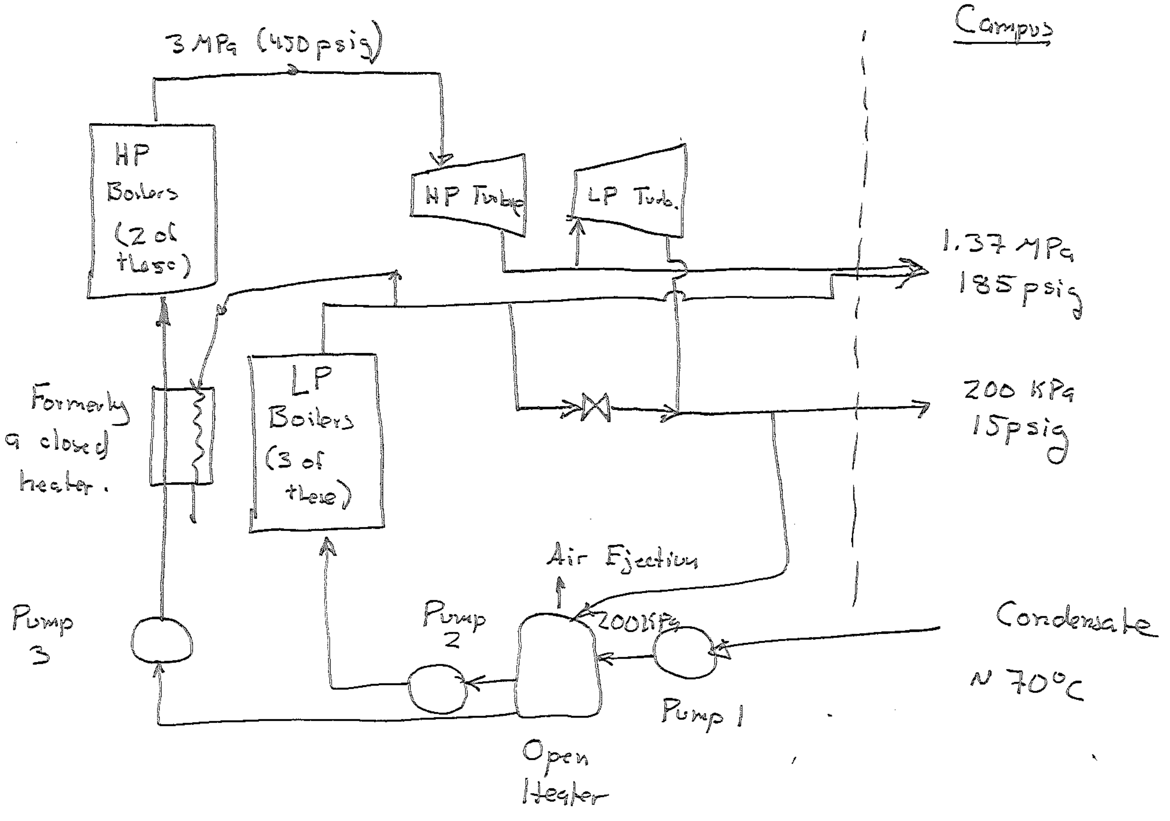
Higher gas cost: 42.3 MW rather than 30 $\Rightarrow$ \$10,950/day.

Value of electricity: $\dfrac{12{,}300 \text{ kW}}{} \left|\dfrac{0.07\,\$}{\text{kW-hr}}\right| \dfrac{24 \text{ hr}}{\text{day}} = \$20{,}700/\text{day}.$

So I increased my gas cost by \$3150/day, but I now recover \$20,700/day in electricity.

Idea is cycles are not 100% efficient, but if I have a required heating load ($\dot{Q}_{out}$), can design system where incremental fuel $\xrightarrow{100\%}$ electricity.

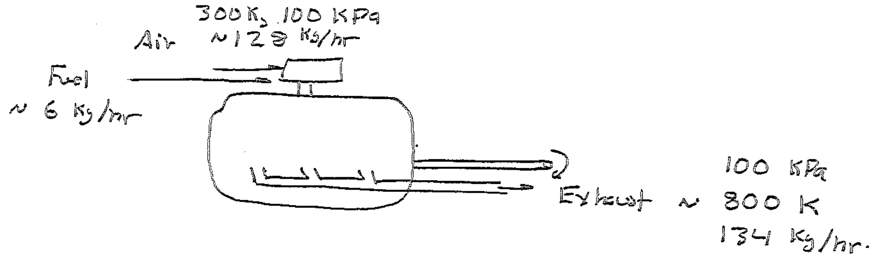
<u>UW Plant in a nutshell</u>



Will discuss how modern power generation fits together after doing Brayton cycles.

Chapter 9 - Gas Cycles

Look at auto engine at cruise:



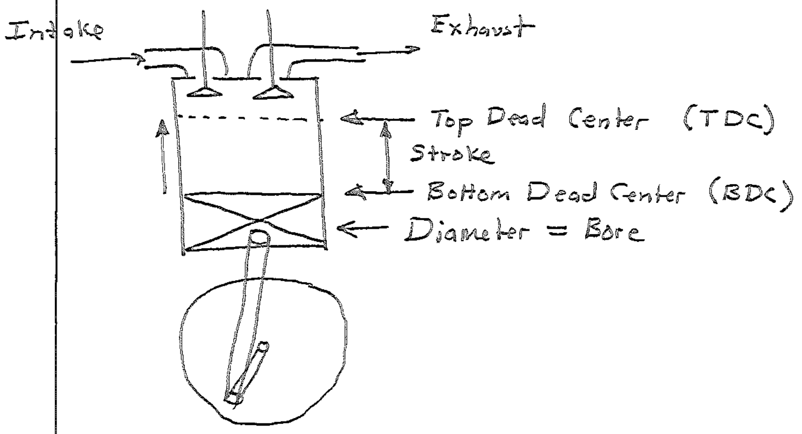
- Analyzing this as an open cycle is complex due to chemistry and change in mass.

- We can capture most of the performance issues with following assumptions:

1. Ignore fuel mass (it's small)
2. Replace energy provided by fuel with equivalent Q_{in}.
3. Route exhaust through heat exchanger to return to 300 K. (since we burn no fuel, no problem reusing air.

} Air Standard Assumptions

<u>Engine terminology.</u>



V_{min} = Cyl. Vol @ TDC
V_{max} = Cyl. Vol @ BDC

Displacement Volume
$= V_{max} - V_{min}$

Compression ratio =
$r = \frac{V_{max}}{V_{min}}$ (~ 8-10)
[Volume, not pressure]

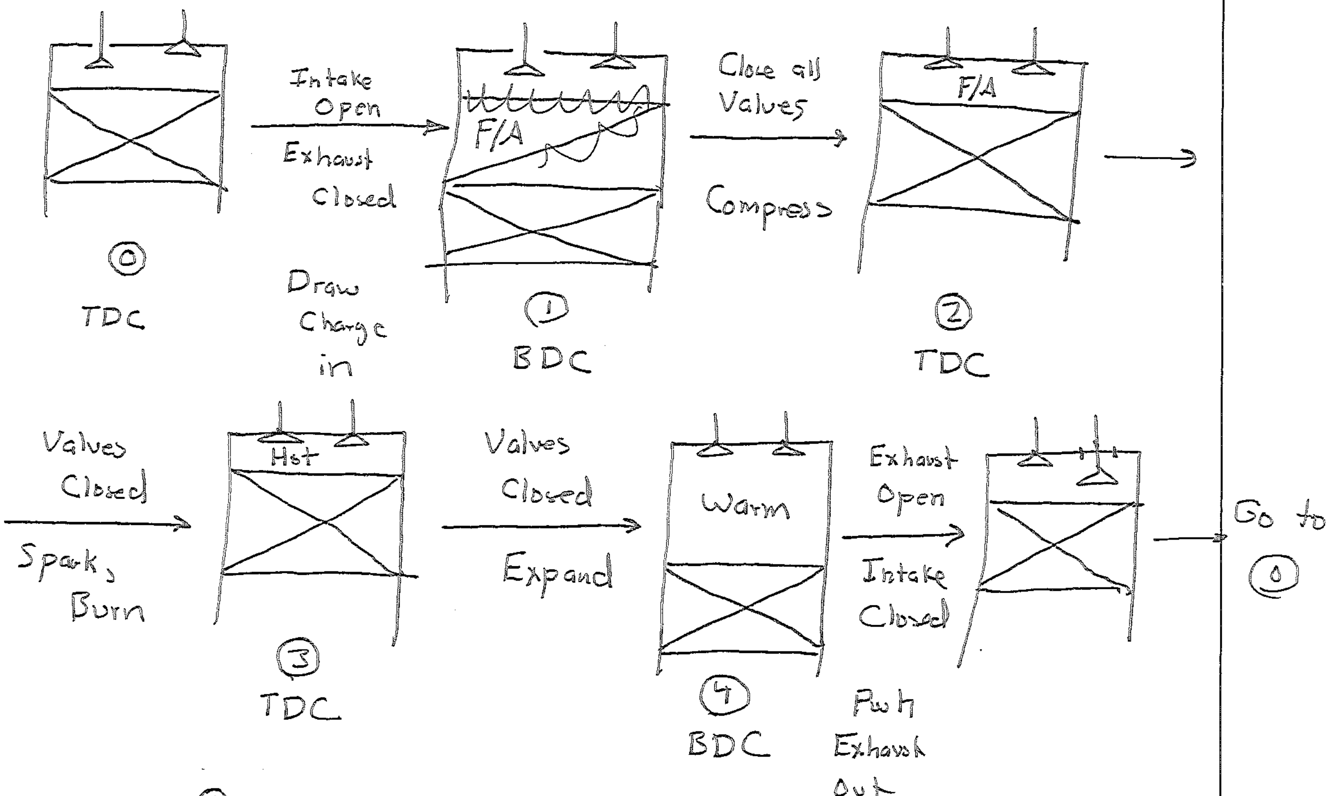
Common terminology: 5-liter engine or 305 in^3 V-8.

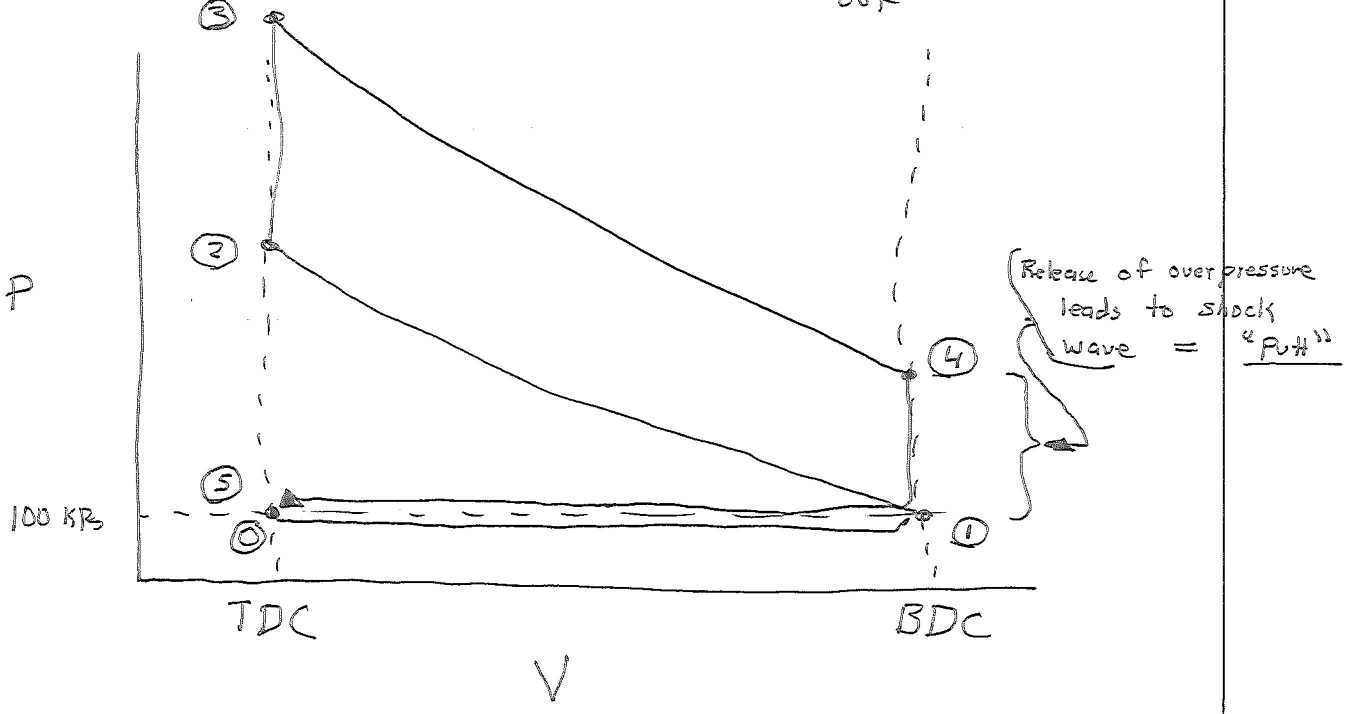
$\Rightarrow 5\ell = 8(V_{Displacement}$ for one cylinder).

Note: Given
- V_{disp}
- bore
- r

} Can define entire engine geometry.

Briefly walk through cycle:





In real life this is a complex process

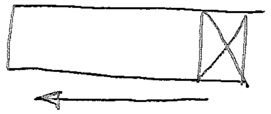
- Valves overlap piston movement
- Burning takes time: Starts before TDC, ends after.
- Lots of heat loss to walls.

⇒ Cannot be accurately modeled without detailed calcs.

⇒ First step is <u>Air Standard Assumptions</u>

Air standard assumptions:

① Working fluid is air (how do we justify this?)
② All processes are internally reversible.
- No friction
- Processes go slowly enough so gases can continously adjust.



Compression: How fast must we go to violate?

$< M = 0.3$

6000 RPM, 6" stoke

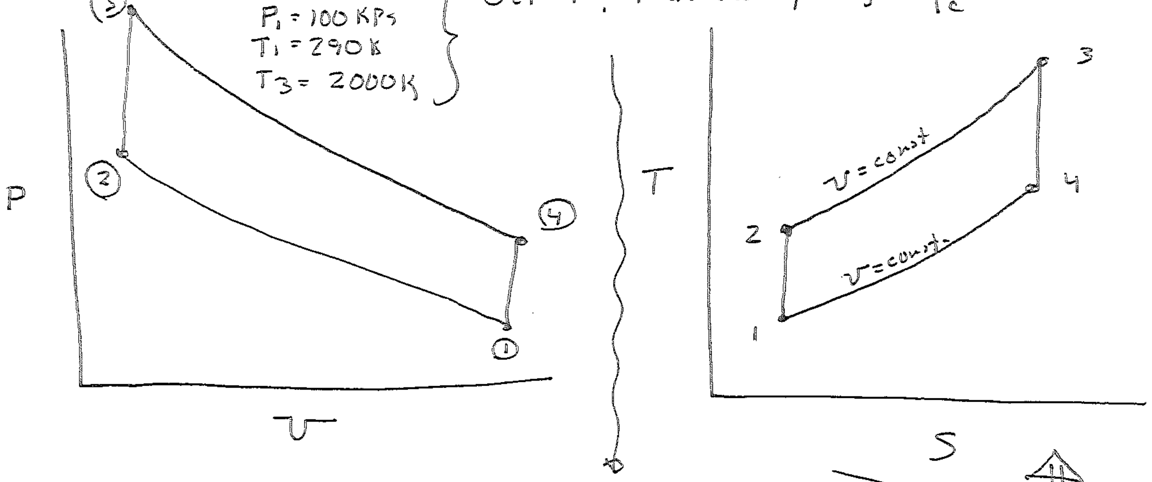
$M \cong 0.1$

③ Replace combustion by $\bar{\bar{Q}}_{in}$
④ Replace exhaust by Q_{out}.

With that said, here's the Otto cycle.

$r = 9.5$
$P_1 = 100$ KPa
$T_1 = 290$ K
$T_3 = 2000$ K

Get P : T at each point, + η_c



- What stays constand during compression? Entropy!
- Why? Reversible/adiabatic:

$$\underset{\text{rev}}{\underset{0}{\cancel{S_{gen}}}} = \Delta S_{sys} + \underset{\text{adiabatic}}{\underset{0}{\frac{\cancel{Q_{surr}}}{\cancel{T_{surr}}}}}$$

$$\Rightarrow S_1 = S_2$$

Scorecard:

	T (K)	u (KJ/kg)
1	290	206.91
2	$\boxed{695}$	508.39 kJ/kg
3	2000	1678.7
4	$\boxed{985}$	746.22+

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1atm value — Deviation from 1 atm.

How to go from ① → ② ? (Want T_2)

~~$\Delta S = S_2^o - S$~~ For air $S_1 = \underbrace{S_1^o}_{\text{1atm value}} \underbrace{- R\ln\frac{P_1}{P_0}}_{\text{Deviation from 1 atm.}}$ } Both a pressure and temp influence for ideal gases

~~$S_1 = S_1^o - R\ln$~~

So: $S_2 - S_1 = S_2^o - S_1^o - \left[R\ln\frac{P_2}{P_0} - R\ln\frac{P_1}{P_0}\right]$

$= S_2^o - S_1^o - R\ln\frac{P_2}{P_1}$ } Idea here is simple: Know $\Delta P \rightarrow \Delta S \rightarrow \Delta T$

Now, let $S_2 - S_1 = 0$

$$\Rightarrow \frac{S_2^o - S_1^o}{R} = \ln\frac{P_2}{P_1} \Rightarrow \underbrace{\frac{P_2}{P_1}}_{\text{Depends only on } P} = \underbrace{\exp\left[\frac{S_2^o - S_1^o}{R}\right]}_{\text{Depends only on } T} = \frac{\exp\left[S_2^o/R\right]}{\exp\left[S_1^o/R\right]}$$

Philosophically this is saying that if I change the pressure, there is only one way temperature can change to keep S constant

Define $\exp\left[S_1^o/R\right] = P_{r,1}$, which is tabulated in A-22 (air table).

So, for $\Delta S = 0$ $\boxed{\frac{P_2}{P_1} = \frac{P_{r,2}}{P_{r,1}}}$

But this doesn't help us in our present situation (~~are~~ we have volumes, not pressures).

$$P_2 = \frac{RT_2}{v_2} = \frac{P_2}{P_1} = \frac{T_2}{T_1}\left[\frac{v_1}{v_2}\right] = \frac{P_{r,2}}{P_{r,1}}$$

Define $\underbrace{v_{r,2} \equiv \frac{P_{r,2}}{T_2}}_{\text{Tabulate}}$

$$\Rightarrow \frac{v_2}{v_1} = \frac{P_{r,1}/T_1}{P_{r,2}/T_2} \Rightarrow \frac{v_2}{v_1} = \frac{v_{r,2}}{v_{r,1}}$$

So: $\frac{v_2}{v_1} = \frac{v_{r,2}}{v_{r,1}}$ or $v_{r,2} = v_{r,1}\left[\frac{v_2}{v_1}\right]$

$= 676.1\left[\frac{1}{9.5}\right] = 71.17$

Air Table 290K

Air Table $T_2 = 695\,K$

$u_2 = 508.39\ kJ/kg$

How to get P_2 ? $\frac{P_2 V_2}{T_2 V_2} = \frac{R v_1}{T_1}$ or $\frac{P_2}{P_1} = \frac{P_{r,2}}{P_{r,1}}$?

Both will work! Use first since it involves no table lookup.

$$P_2 = P_1\left[\frac{T_2}{T_1}\right]\left[\frac{V_1}{V_2}\right] = [100\ KPa]\left[\frac{695\ K}{290}\right][9.5] = 2276\ KPa$$

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How about P_3?

$$\frac{P_3 V_3}{T_3} = \frac{P_2 V_2}{T_2} \quad \text{or} \quad \cancel{\frac{P_3}{P_2} = \frac{P_{r,3}}{P_{r,2}}} \rightarrow$$ No – Not an isentropic process!

$$P_3 = P_2\left[\frac{T_3}{T_2}\right] = [2276 \text{ kPa}]\left[\frac{2000}{695}\right] = 6652 \text{ kPa}$$

Finally: ③ → ④ Isentropic expansion.

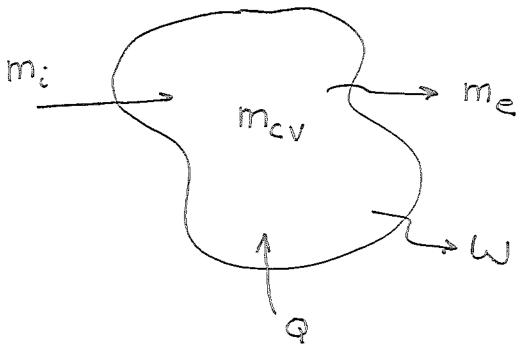
$$v_{r,4} = v_{r,3}\left[\frac{v_4}{v_3}\right] = \underset{\text{Air Table @ 2000 K}}{2.774}\,[9.5] = 26.37 \rightarrow$$ $T_4 = 985$ K
$u_4 = 746.22$ kJ/kg

$$P_4 = P_3\left[\frac{T_4}{T_3}\right]\left[\frac{V_3}{V_4}\right] = [6652 \text{ kPa}]\left[\frac{985}{2000}\right]\left[\frac{1}{9.5}\right] = 345 \text{ kPa}$$
(The "Puff")

$$\eta = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{u_4 - u_1}{u_3 - u_2} = 1 - \frac{746.22 - 206.91}{1678.7 - 508.39} = 54\%$$

Question: Why did we use $Q = m\Delta u$ instead of $m\Delta h$?

Always go back to the general form of the first law:



Start at ①
End at ② } In between you have m_i, m_e, Q, W

$$\underbrace{Q - W = \sum m_e h_e - \sum m_i h_i}_{\text{Energy crossing boundary}} + \underbrace{[m_2u_2 - m_1u_1]_{cv}}_{\text{Change in energy inside.}}$$

For Otto Q_{in}: $m_e = m_i = 0$, $W = 0$, $m_1 = m_2 = m_{cv}$

$Q = m_{cv}(u_2 - u_1)$ or $q = u_2 - u_1$

For steam turbine: $Q = 0$, $u_2 = u_1$, $m_2 = m_1$, $m_e = m_i$

$-W = m[h_e - h_i]$ or $-\dot{W} = \dot{m}[h_e - h_i]$ or $-w = h_e - h_i$

⟹ Always go back to original form if confused.

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Very quickly work the problem with cold air assumptions. (const C_p, C_v).

① → ② Isentropic compression $\frac{P_2}{P_1} = \left[\frac{V_1}{V_2}\right]^K$, $\frac{T_2}{T_1} = \left[\frac{V_1}{V_2}\right]^{K-1}$ $K = \frac{C_p}{C_v} = 1.4$

instead of $\frac{P_2}{P_1} = \frac{P_{r,2}}{P_{r,1}}$, $\frac{V_2}{V_1} = \frac{v_{r,2}}{v_{r,1}}$

$$T_2 = T_1\left[\frac{V_1}{V_2}\right]^{K-1} = [290\text{ K}][9.5]^{0.4} = 714\text{ K}$$

$$P_2 = P_1\left[\frac{V_1}{V_2}\right]^{K-1} = [100\text{ KPa}][9.5]^{1.4} = 2338\text{ KPa}$$

$$P_3 = P_2\left[\frac{T_3}{T_2}\right] = [2338\text{ KPa}]\left[\frac{2000}{714}\right] = 6549\text{ KPa}$$

Finally: ③ → ④ Isentropic:

$\cancel{\frac{P_4}{P_3} = \frac{V_3}{V_4}}$

$$T_4 = T_3\left[\frac{V_3}{V_4}\right]^{K-1} = (2000\text{ K})\left[1/9.5\right]^{0.4} = 813\text{ K}.$$

$$P_4 = P_3\left[\frac{V_3}{V_4}\right]^{K} = (6549\text{ KPa})\left[1/9.5\right]^{1.4} = 280\text{ KPa}.$$

Before: $q_{in} = u_3 - u_2$ but $du = C_v\,dT$

Now: $q_{in} = C_v(T_3 - T_2)$ or $\Delta u = \int_{T_1}^{T_2} C_v\,dT = C_v(T_2 - T_1)$

If constant

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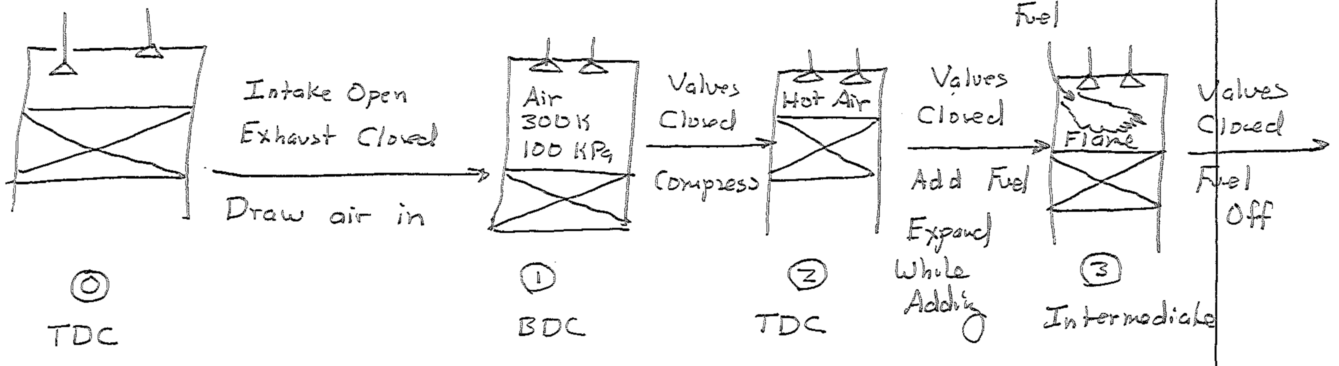
so $\eta = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{\cancel{C_v}(T_4 - T_1)}{\cancel{C_v}(T_3 - T_2)} = \frac{813 - 290}{2000 - 714} = 59\%$

Why cold air? ⟹ 1) It's less accurate than air standard.

2) Can use for a quick/dirty answer.

3) Is only approach available for He, Ar, Ne

Ideal Diesel cycle: Idea was to burn powdered coal, but engines didn't last.



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