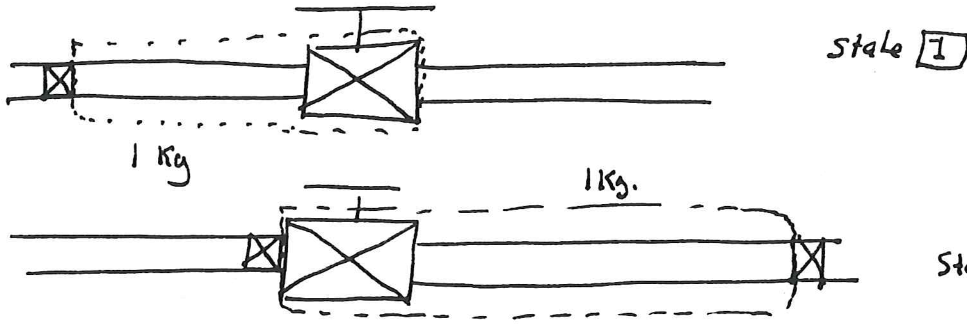
From superheat tables: $P_2 = 100\,KPa$, $h_2 = 3133.7\ KJ/Kg$ $\xrightarrow{\text{Interpolate}}$ $\boxed{T_2 = 329.4\ °C}$

---

An alternate (but not recommended) way to analyze this is as a closed system:

Process 1 Kg.




$$\cancel{Q}^{\,0} - W = \cancel{\Delta H}\ m(u_2 - u_1)$$

$W_{\cancel{net}\ \text{bdy}}$ = Work done by system - Work done on system.

$$= m P_e v_e - m P_i v_i$$

$$-(m P_e v_e - m P_i v_i) = m(u_e - u_i) \Rightarrow \underbrace{u_1 + P_1 v_1}_{h_i} = \underbrace{u_2 + P_2 v_2}_{h_e}$$

April 26

~~Problem is~~ Can evaluate LHS directly ($u_i$, $v_i$ from steam table)

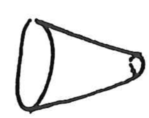
$u_e$, $v_e$ are unknown ⇒ must ~~guess~~ Iterate
⇒ Guess $T_e$ → find $u_e$, $v_e$ → Plug in & see if they work.

With h, the PV term is absorbed & you can forget about it.

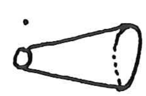
---

Nozzles and Diffusers:

Nozzle: Device for accellarating flow



Diffuser: Device for slowing flow



First law for steady state Control Volume

$$\dot{Q} - \dot{W} = \dot{m}\,(h_e + (KE)_e - h_i - (KE)_i)$$

$$\cancel{\dot{Q} - \dot{W} = \dot{m}(h_e - h_i) + \Delta KE + \Delta PE}$$

Note that we have added these terms.

For nozzle & diffuser:

$$\cancel{\dot{Q}}^{\,0} - \cancel{\dot{W}}^{\,0} = \cancel{\dot{m}}(h_e - h_i) + \cancel{\dot{m}}\left[\frac{V_e^2 - V_i^2}{2}\right]$$

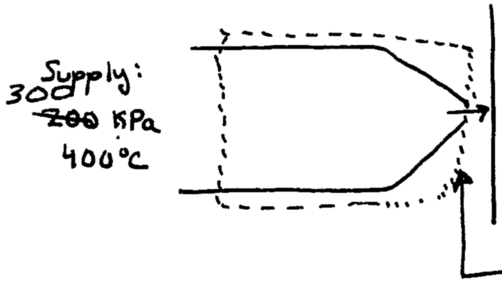
cancels.

How would this simplify?

$$0 = h_e - h_i + \frac{V_e^2 - V_i^2}{2}$$

In words, you are exchanging enthalpy for velocity.

Example: You want to use a steam nozzle in a stripping operation:




Released to ambient:
$P = 100$ kPa
$T_{meas} =$ ~~400°C~~ 360°C
$D = 1.5$ cm

Goals
Want $V = 200$ m/s
$\dot{m} = 1$ kg/min.

Question: How close does this nozzle come to giving this performance?

① First Law:

$$0 = h_e - h_i + \frac{V_e^2 - V_i^2}{2}$$

② Draw control volume

③ Simplify first law: In this case, the KE contribution of $V_i$ will be quite low ⇒ Assume $V_i = 0$ for purposes of first law calculation.

$$i: \begin{cases} P = \cancel{200}\ 300 \text{ kPa} \\ T = 400\,°C \end{cases} \Rightarrow h_i = 3275.0 \text{ kJ/kg}.$$

$$e: \begin{cases} 100 \text{ kPa} \\ T = 360\,°C \end{cases} \Rightarrow h_e = 3195.9 \text{ kJ/kg}$$

$$V_e = \left[-2(h_e - h_i)\right]^{1/2} = \left[\frac{-2 \,\big|\, 3195.9 - 3275 \text{ kJ} \,\big|\, 1000 \text{ m}^2/\text{s}^2}{\big|\ \text{kg} \,\big|\, \text{kJ/kg}}\right]^{1/2} = 397.7 \text{ m/s}$$

OK!

Next question is $\dot{m}$

$$\dot{m} = \rho V A = \frac{VA}{v}$$

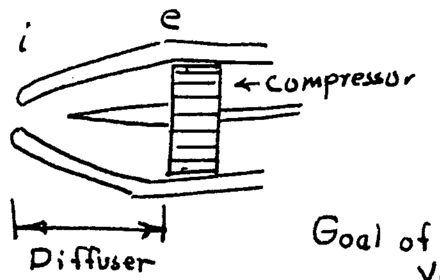
$$A = \frac{\pi d^2}{4} = \frac{\pi}{4}(0.015\text{m})^2 = 1.77 \times 10^{-4} \text{ m}^2$$

$v_e = 2.917$ m³/kg from steam tables at exit.

$$\dot{m} = \frac{397.7 \text{ m}}{\text{s}} \Big| \frac{1.77 \times 10^{-4} \text{ m}^2}{} \Big| \frac{\text{kg}}{2.917 \text{ m}^3} \Big| \frac{60 \text{ s}}{\text{min}} = 1.45 \text{ kg/min}$$

Also OK

- Main Application of diffusers is in jet engines:




Goal of the diffuser is to recover the incoming Velocity to preheat & pressurize gas.

Example for jet aircraft. Outside conditions are $V_i = 500$ mph $= 224$ m/s

$T_i = 27°C$

Treat engine as stationary: $\dot{m} = 2.5$ kg/s

Heat loss from diffuser $= 18$ kW.

⇒ Find $V_e$ ⇒ TC @ e = 42°C

Start with 1st Law, including KE term.

$$\dot{Q} - \cancel{\dot{W}}^{\,0} = \dot{m}(h_e - h_i) + \dot{m}\left[\frac{V_e^2 - V_i^2}{2}\right]$$

$$-18\ \frac{kJ}{s} = \left(2.5\ \frac{kg}{s}\right)(315.27 - 300.19) + \left(2.5\ \frac{kg}{s}\right)\left[\frac{V_e^2 - (224\ m/s)^2}{2}\ \frac{kJ/kg}{1000\ m^2/s^2}\right]$$

$$\boxed{V_e = 74.9\ m/s}$$

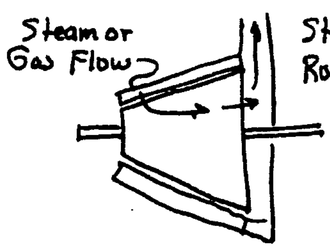
- HW - #75 gave problems.
- Quiz: Ideal gas part Ch. 3., Selection of proper first law form ch. 4.
- Recitation: Some examples on areas that gave trouble
- Wed. Exam
- Fri. No class.
- 4-13 Hint - Don't use first law: undisclosed work/heat flow

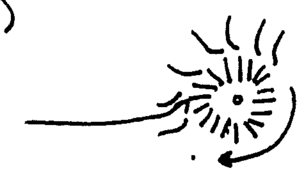


$\boxed{\text{April 18}}$

$\boxed{\text{Turbines, Fans, Compressors, Pumps, Mixers, Heat Exch}}$

Turbines: Extract work from a high-pressure flowing fluid.



- Inside vanes are straight because curved vanes have problems with centrifical fource.

Two major applications of turbines:

① Steam turbines in power plants: Steam is brought to high T, P in boiler.

② Gas turbines: Combustion of fuel under pressure is the source of the working fluid.

What does first law looks like around a turbine?

$$\dot{Q} - \dot{W} = \cancel{\sum \dot{m}_e h_e} - \sum \dot{m}_i h_i + \cancel{\frac{d}{dt}(mu)_{cv}} + \cancel{\frac{d}{dt}(KE)}$$ (neglecting KE & PE).

Steady flow: Does it pass the snapshot test?

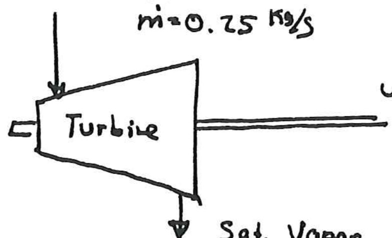
$$\dot{Q} - \dot{W} = \sum \dot{m}_e (h_e + KE_e + PE_e) - \sum \dot{m}_i (h_i + KE_i + PE_i) + \frac{d}{dt}(mu)_{cv}$$

Steady Flow: Does it pass the snapshot test?

Will work 3 examples: Most will fall into one of three categories:
→ Non-ideal fluids (e.g. steam).
→ Ideal Gas: Variable $C_p$, $C_v$
→ Ideal Gas: Constant $C_p$, $C_v$.

$\boxed{\text{Commercial Refrig. Plant} - \text{Expand comp. ref. to get cold T.}}$

R-12 0.7 MPa
70°C
$\dot{m} = 0.25$ Kg/s




$\dot{W} = ?$

Exit Volumetric Flow Rate.

Sat. Vapor
−20°C

First Step: First Law: $\cancel{\dot{Q}}^{0} - \dot{W} = \sum \dot{m}_e (h_e + \cancel{KE_e}^{0} + \cancel{PE_e}^{0}) - \sum \dot{m}_i (h_i + \cancel{KE_i}^{0} + \cancel{PE_i}^{0})$

$$-\dot{W} = \dot{m}(h_e - h_i)$$

inlet: 0.7 MPa, 70°C $\xrightarrow{\text{A-9 Superheat}}$ $h_i = 229.1$ KJ/Kg. $= h_g$

exit: Sat Vapor, −20°C → $h_e = 178.74$ KJ/Kg.
$v_e = v_g = 0.10885$ m³/Kg

$$-\dot{W} = \frac{0.25\ \text{Kg}}{\text{s}} \left| \frac{178.74 - 229.1\ \text{KJ}}{\text{Kg}} \right. \Rightarrow \boxed{\dot{W} = 12.6\ \text{KW}}$$

$$\text{Volumetric Flow Rate} = \dot{m} v_e = \frac{0.25\ \text{Kg}}{\text{s}} \left| \frac{0.10885\ \text{m}^3}{\text{Kg}} \right. = \underline{0.0272\ \text{m}^3/\text{s}}$$

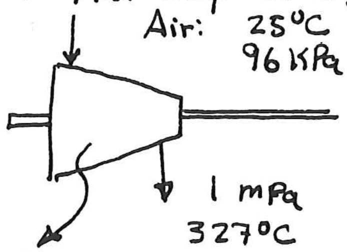
---

April 29

Previous example was for non-ideal ~~materials~~ fluid.

⇒ Now ideal gas:
⇒ First step in a gas turbine system is to compress ambient air

Air: 25°C
96 KPa
V = negligible.



$\dot{W} = 300$ KW

1 MPa
327°C
120 m/s

⇒ Find $\dot{m}_{air}$

Heat loss to surroundings = 1500 KJ/min.

$$\dot{Q} - \dot{W} = \sum \dot{m}_e (h_e + KE_e) - \sum \dot{m}_i (h_i + KE_i)$$

$$\dot{Q} - \dot{W} = \dot{m}(h_e - h_i) + \dot{m}\left[\frac{V_e^2}{2}\right]$$

$$\dot{Q} = \frac{1500 \text{ kJ}}{\text{min}} \left| \frac{\text{min}}{60 \text{ sec}} \right. = -25 \text{ kJ/s} \quad (\text{sign?})$$

$$\dot{W} = -300 \text{ kJ/s} \quad (\text{sign?})$$

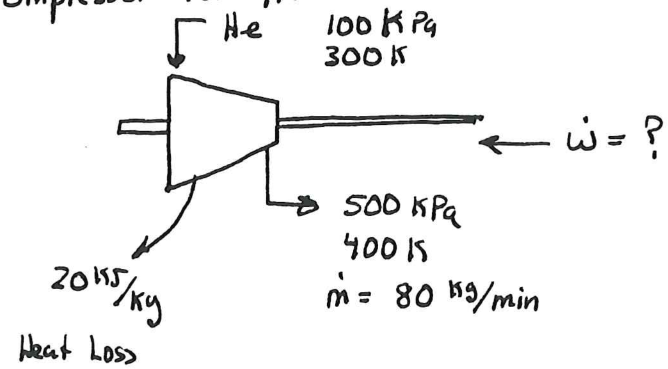
| | T (K) | A-17 | h (kJ/kg) |
|---|---|---|---|
| i | 298 | $\longrightarrow$ | 298.2 |
| e | 600 | $\longrightarrow$ | 607.02 |

$$-25 \frac{\text{kJ}}{\text{s}} - \left(-300 \frac{\text{kJ}}{\text{s}}\right) = \dot{m}\left[\underbrace{(607.02 - 298.2)}_{\text{kJ/kg}} + \frac{(120 \text{ m/s})^2}{2} \left| \frac{\text{kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right. \right]$$

$$\boxed{\dot{m} = 0.87 \text{ kg/s}}$$

---

Compressor for Helium:




First Law $\quad \dot{Q} - \dot{W} = \dot{m}(h_e - h_i)$

$$\dot{Q} = \frac{80 \text{ kg}}{\text{min}} \left| \frac{\text{min}}{60 \text{ s}} \right| \frac{20 \text{ kJ}}{\text{kg}} = -26.67 \text{ kJ/s}$$

No He tables
Why?

$$\dot{m}(h_e - h_i) \overset{?}{=} \dot{m}\int_{T_i}^{T_e} C_p\, dT = \dot{m}\, \underset{\text{Const.}}{C_p}\, (T_e - T_i) = \frac{5.20 \text{ kJ}}{\text{kg-K}} \left| 400 - 300 \text{K} \right| \frac{80 \text{ kg}}{\text{min}} \left| \frac{\text{min}}{60 \text{ s}} \right.$$

Don't need these

$$= 692.8 \text{ kJ/kg}.$$

No helium tables

from Table A-15: $\frac{C_p}{R} = 2.5$ for all monatomic (inert) gases
He, Ar, Kr, Ne, etc.

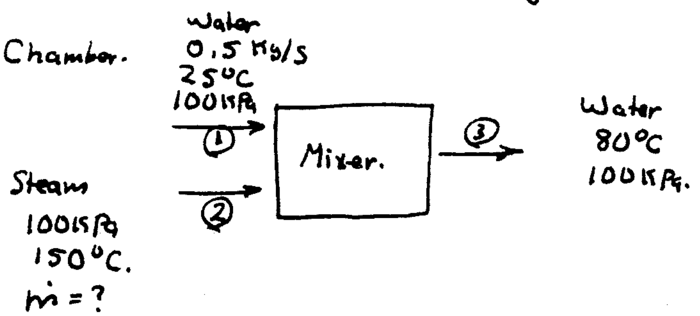
$$C_p = 2.5R = \frac{2.5 \,|\, 8.314 \text{ kJ} \,|\, \text{Kmole}}{\cancel{\text{kg}}\text{-K} \,|\, 4 \text{ kg}}$$
Kmole

$$C_p = 5.20 \frac{\text{kJ}}{\text{kg-K}}$$

$$\dot{W} = \dot{Q} - \dot{m}(h_e - h_i) = -26.67 - 692.8 \frac{\text{kJ}}{\text{kg}} = \boxed{-719.5 \text{ kW}}$$

# Another Steady Flow Example

Mixing Chamber.




Swimming Pool Heater with live steam available.

How much do you need?

$$\cancel{\dot{Q}}^{0} - \cancel{\dot{W}}^{0} = \sum \dot{m}_e \left[ h_e + \cancel{KE_e}^{0} + \cancel{PE_e}^{0} \right] - \sum \dot{m}_i \left[ h_i + \cancel{KE_i}^{0} + \cancel{PE_i}^{0} \right] + \cancel{\frac{d}{dt}\left[ mu \right]_{cv}}^{0}$$

$$\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$$

How many knowns?
~~How many unknowns~~?

2 - Unknowns, 1 equ.

What to do?

Conservation of mass: ~~$\sum \dot{m}_e - \sum \dot{m}_i$~~

$$\sum \dot{m}_i - \sum \dot{m}_e = \cancel{\frac{dm_{cv}}{dt}}^{0} \quad \text{0, steady state.}$$

$$\Rightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

Substitute into above: $(\dot{m}_1 + \dot{m}_2) h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$

Find terms:

② Steam 100 kPa, 150°C $\xrightarrow{\text{Superheat}}$ $h_2 = 2776.4 \ \mathrm{kJ/kg}$.

① Water 25°C, 100 kPa $\xrightarrow{\text{Compressed Liquid}}$ ? Sat. Liquid @ 25°C $\Rightarrow h_1 = 104.88 \ \mathrm{kJ/kg}$.

③ Water 80°C, 100 kPa $\xrightarrow{\text{Comp. Liquid}}$ $h_3 = 334.86 \ \mathrm{kJ/kg}$.

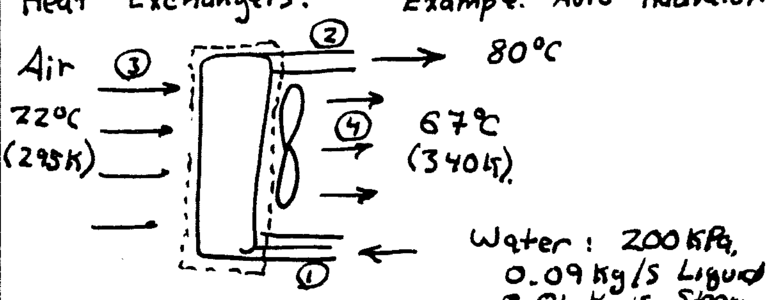
Reassemble.

$$\left(0.5 \tfrac{kg}{s} + \dot{m}_2\right)\left(334.86 \tfrac{kJ}{kg}\right) = \left(0.5 \tfrac{kg}{s}\right)\left(104.88 \tfrac{kJ}{kg}\right) + \dot{m}_2 \left(2776.4 \tfrac{kJ}{kg}\right)$$

$$\boxed{\dot{m}_2 = 0.0471 \ \mathrm{kg/s}}$$

April 19

Heat Exchangers: Example: Auto Radiator.




Find air flow (fan size).

Put down $1^{st}$ Law:

$$\cancel{\dot{Q}}^{0} - \cancel{\dot{W}}^{0} = \sum \dot{m}_e (h_e + \cancel{KE_e}^{0} + \cancel{PE_e}^{0}) - \sum \dot{m}_i (h_i + \cancel{KE_i}^{0} + \cancel{PE_i}^{0}) + \cancel{\frac{d}{dt}(mu)_{cv}}^{0}$$

Before we start working on terms, we need to identify a CV.
– Choice less clear here.

~~⇒ Note t~~

→ Time steady? After ~~the~~ car has warmed up.

→ W ?

→ Q (remember, although its a heat exchanger, ~~nothing~~ no heat crosses bdy – this is all you care about).

$$\sum \dot{m}_e h_e = \sum \dot{m}_i h_i$$

Lets number diagram.

$$\dot{m}_2 h_2 + \dot{m}_4 h_4 = \dot{m}_1 h_1 + \dot{m}_3 h_3$$

Look at $\dot{m}$'s ⇒ $\dot{m}_1 = \dot{m}_2$, $\dot{m}_3 = \dot{m}_4$

$\cancel{\dot{m}_1 (h_2 - h_1) =}$

$\cancel{\dot{m}_2 h_2 - \dot{m}_1 h_1 = \dot{m}_3 h_3 -}$

$$\dot{m}_4 h_4 - \dot{m}_3 h_3 = \dot{m}_1 h_1 - \dot{m}_2 h_2$$

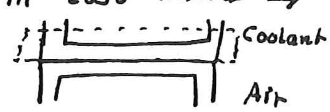
$$\dot{m}_a (h_4 - h_3) = \dot{m}_{cool} (h_1 - h_2) \Rightarrow \dot{m}_{air} = \dot{m}_{cool} \left[\frac{h_1 - h_2}{h_4 - h_3}\right]$$

$h_{fg}$ → Used often enough in Table ⇒ Listed

| | $h_i$ |
|---|---|
| $h_1 = h_f + x(h_g - h_f)$ @ 200 kPa $= 504.70 + 0.1(2201.9) =$ | 724.89 |
| $h_2 \cong h_f$ @ 80°C (comp. liquid) $=$ | 334.91 |
| $h_3 =$ Air @ 295 K | 295.17 |
| $h_4 =$ Air @ 340 K | 340.42 |

$$\dot{m}_a = \cancel{\dot{m}_{cool}\left[\frac{h_1 - h_2}{}\right]} = \left[0.1 \frac{kg}{s}\right]\left[\frac{724.89 - 334.91}{340.42 - 295.17}\right] = \boxed{0.86 \frac{kg}{s}}$$

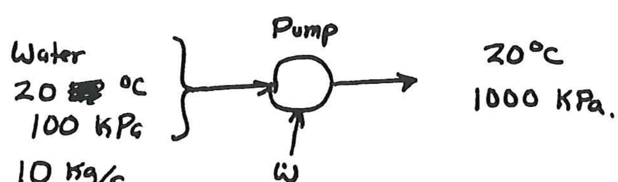
⇒ Note that we could have analyzed this in two halves ⇒ C




$Q \neq 0$.

May 1

## Pumps on Incompressible Fluids:




• For incompressible liquid:

$$T_i \cong T_e$$

(i.e., put pressure on liquid, no change in T).

First Law:

$$-\dot{W} = \dot{m}(h_e - h_i)$$

$$= \dot{m}(u_e + P_e v_e - u_i - P_i v_i)$$

Since $T_i = T_e$ ⇒ $u_i = u_e$, $v_i = v_e \cong v_f$ @ 20°C.

$\Rightarrow$ For incompressible liquids: $\boxed{-\dot{W} \cong \dot{m}\, v_f\, (P_e - P_i)}$

$$-\dot{W} = \frac{10\ \text{kg}}{\text{s}} \cdot \frac{0.0010018\ \text{m}^3}{\text{kg}} \cdot (1000-100\ \text{kPa}) \Rightarrow \boxed{\dot{W} = 9.02\ \text{kW}}$$

---

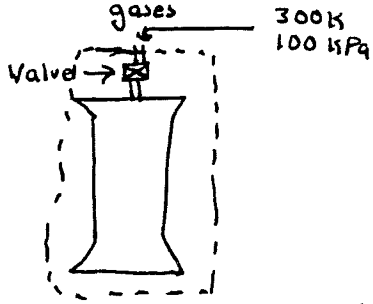
Unsteady Flow Problems:

$\Rightarrow$ These are problems that fail the "snap shot" test... some property changes with time.

$\Rightarrow$ Work mostly with the form of the first law that describes fixed endstates:

$$Q - W = \sum m_e (h_e + KE_e + PE_e) - \sum m_i (h_i + KE_i + PE_i) + (m_2 u_2 - m_1 u_1)_{cv}$$

Example: In lab we have an 11 liter glass tank we use for making calibration gases




Operation
① Draw to vacuum
② Open valve and refill with room air. (+ a small amount of cal. gas that you want to dilute).

What will tank ~~pressure~~ T be after filling?
common sense says 300K, but it ain't so.

First Law: Neglect KE, PE

Not really, but will assume

$$\cancel{Q}^{\,0} - \cancel{W}^{\,0} = \cancel{\sum m_e h_e}^{\,0} - \sum m_i h_i - (m_2 u_2 - \cancel{m_1 u_1}^{\,0})_{cv}$$

$$m_i h_i = m_2 u_2$$

Draw CV so that ① properties are constant crossing boundary
② V is low so can justify neglecting KE.

$m_i h_i = m_2 u_2$ $\Rightarrow$ what about $m_i, m_2$ $\Rightarrow$ $m_i = m_2$
$\Rightarrow$ Can get this from conservation of mass, or common sense.

$h_i = u_2$ at 300K, $\xrightarrow{A-17}$ $h_i = 300.19$ kJ/kg

If $u_2 = 300.19$ kJ/kg $\xrightarrow{A-17}$ $T_2 = 419.31$ K $= 146°C$.

In reality, the heat transfer effect is significant, so you don't see this much T-rise, but you see some... will give you an error if you don't realize this happens.

April 20

Example: Recharging an air conditioner.


$V = \cancel{0.1\ m^3}$ ~~0.001~~ 0.1 $m^3$ 100 (+ fillers)

$P = 800\ KPa$

Vol = 20% of total.

- If tank is insulated, then tank would cool as liquid boils off.
  ⇒ Eventually, you would get nothing more into your A/C.
- If you want to charge vapor, you put your can of R-12 in warm water to keep T & P up.

⇒ Find heat needed to keep vapor pressure constant to the point where the last drop of R-12 liquid has evaporated.

⇒ Draw CV so that you know the properties crossing boundary are constant, if possible.

$$Q - \cancel{W}^{0} = \sum \dot{m}_e h_e - \cancel{\sum \dot{m}_i h_i}^{0} + (m_2 u_2 - m_1 u_1)_{cv}$$

$$m_e h_e + (m_2 u_2 - m_1 u_1)_{cv}$$

Terms: $m_1 = m_f + m_g = \dfrac{V_f}{v_f} + \dfrac{V_g}{v_g} = \dfrac{0.02\,m^3}{0.0007802\,m^3/Kg} + \dfrac{0.08\,m^3}{0.02188\,m^3/Kg}$
$\quad\quad 25.634 \quad\quad 3.656$

$= 29.29\ Kg.$

$$x_1 = \frac{m_g}{m_f + m_g} = \frac{3.656\ Kg}{29.29\ Kg} = 0.0125$$

$$u_1 = u_f + x_1(u_g - u_f) = 66.68 + 0.125\left[183.13 - 66.68\right] = 81.24\ KJ/Kg.$$

$$m_2 = \frac{V_T}{v_g} = \frac{0.1}{0.02188\ m^3/Kg} = 4.57\ Kg$$

$$u_2 = u_g = 183.13\ KJ/Kg$$

$$m_e = m_1 - m_2 = 29.29 - 4.57 = 24.72\ Kg$$

$$h_e = h_g = 200.63\ KJ/Kg$$

$$\Rightarrow Q = (24.72\ Kg)(200.63\ KJ/Kg) + (4.57\ Kg)(183.13\ KJ/Kg) - (29.29\ Kg)(81.24\ KJ/Kg)$$

$$\boxed{Q = 3417\ KJ}$$

Question: If I turn the can upside down to drain the liquid off instead of the vapor, would my answer change?

$$Q = m_e h_e + (m_2 u_2 - m_1 u_1)_{cv}$$

$h_e = 67.3\ KJ/Kg$

$\boxed{Q = 121.0\ KJ}$

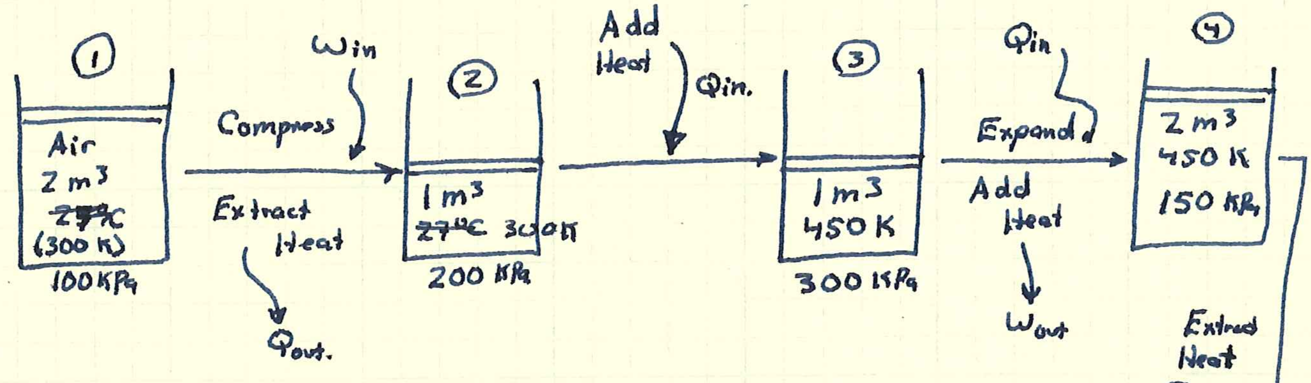
Why you do it this way.

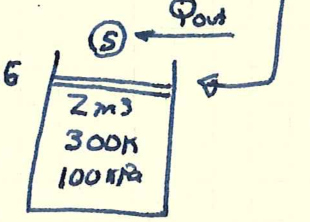
Summary
h vs u.
Steady State vs. Non-steady.
Flow vs. Fixed end?

# Chapter 5: Heat Engines – Thermo Cycles.

May 3

Thought Experiment. Have geothermal field ~ 200°C steam } Go into power production business.
Also have river ~ 5°C water.




| | | Q | W |
|---|---|---|---|
| 1–2 | $P_2 = P_1\left[\frac{V_1}{V_2}\right] = 100\text{ KPa}\left[\frac{2}{1}\right] = 200\text{ KPa}$ | −138.6 | −138.6 |
| 2–3 | $P_3 = P_2\left[\frac{T_3}{T_2}\right] = 200\text{ KPa}\left[\frac{450}{300}\right] = 300\text{ KPa}$ | +251.8 | 0 |
| 3–4 | $P_4 = P_3\left[\frac{V_3}{V_4}\right] = 300\text{ KPa}\left[\frac{1}{2}\right] = 150\text{ KPa}$ | +207.9 | +207.9 |
| 4–5 | $P_5 = P_4\left[\frac{T_5}{T_4}\right] = 150\text{ KPa}\left[\frac{300}{450}\right] = 100\text{ KPa}$ | −251.8 | 0 |

Back to original state ① Cycle Complete.

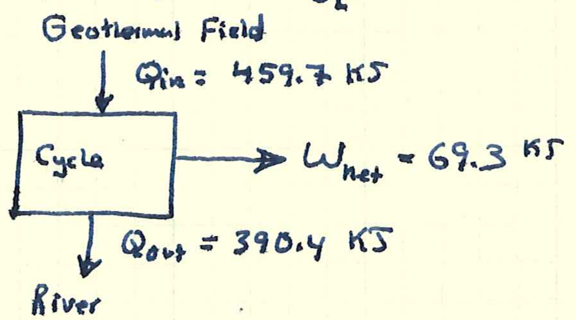
Now get work and heat values.

1–2 $Q = W = P_1 V_1 \ln\frac{V_2}{V_1} = (100\text{ KPa})(2\text{ m}^3)\ln[0.5] = -138.6\text{ KJ}$

2–3 $Q = m(u_3 - u_2) = 2.32\text{ Kg}[322.62 - 214.07] = +251.8\text{ KJ}$

3–4 $Q = W = P_3 V_3 \ln\left[\frac{V_4}{V_3}\right] = [300\text{ KPa}][1\text{ m}^3]\ln\left[\frac{2}{1}\right] = +207.9\text{ KJ}$

4–5 $Q = m(u_5 - u_4) = 2.32\text{ Kg}[214.07 - 322.62] = -251.8\text{ KJ}$




If you draw CV around cycle:

$Q - W = \cancel{\Delta U}^{\,0}$ because you start and end at same place

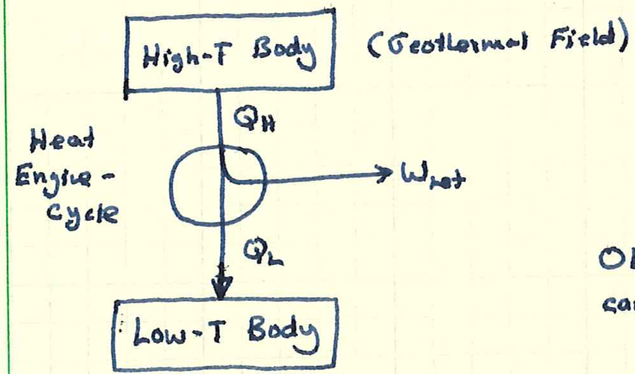
Convention for cycles: $Q_{in} = Q_{out} + W_{net}$

Efficiency: $\eta = \frac{\text{What you want}}{\text{What you pay for}} = \frac{W_{net}}{Q_{in}} = 15.1\% = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$

Note: This is just one kind of cycle...

Logical Questions
① ~~Can we~~ How can we get better $\eta$? → Next two chaps
② Can $\eta$ be 100%? No.

This leads to basic form of heat engine:

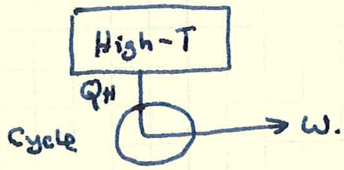



First Law: $Q_H = Q_L + W$

Observation is that only a part of $Q_H$ can be converted into $Q_L$

Formalized as Kelvin-Planck Statement of 2nd Law

Cannot have:

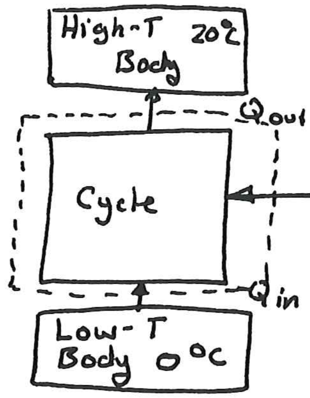



Postulate... Not provable.

~~Think about how to define an efficiency.~~

$$\eta = \frac{\text{What you want}}{\text{What you must pay for}} = \frac{W_{net}}{Q_{in}} = \frac{\overbrace{Q_{in}-Q_{out}}^{=W_{net}}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Refrigerator:

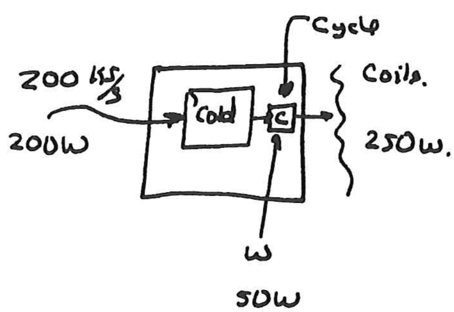



~~$Q = W_{net}$.~~

Numerically $Q_{in} + W_{net} = Q_{out}$.

$$\text{Efficiency} = \frac{\text{what you want}}{\text{What you must buy}} = \frac{Q_{in}}{W_{net}} = \frac{Q_{in}}{Q_{out}-Q_{in}} = COP_R \; (\cancel{\beta}) = \text{coefficient of performance.}$$

Typical $\beta = 4$ for good home unit. Heat leakage thru insulation is 200 kJ/s, find electric power needed. & heat rejected from coils on back.




~~$4 = Q_{in}$~~

$$COP_R \; \beta = \frac{Q_{in}}{W_{net}} \Rightarrow W_{net} = \frac{Q_{in}}{\beta} = \frac{200 \text{ kJ/s}}{4}$$

$$= 50 \text{ W.}$$

$$Q_{out} = Q_{in} + W = 250 \text{ W.}$$

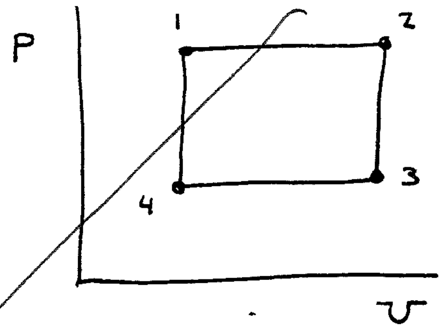
A couple of points:

⇒ Refrigerator is a true closed cycle: Refrigerant moves in a cycle so it always ends at same condition as it started. ⇒ $\Delta U = 0$.

⇒ Think of refrigerator as a heat pump.

⇒ Use work to pump heat against a temperature difference the same way you use a pump to push water uphill.

~~First Law~~




First Law:

(1-2) $Q - W = m(u_2 - u_1)$; but constant $P$: $Q = m(h_2 - h_1)$

$Q = (1\,kg)(821.45 - 400.98) = 420.97\ KJ$

(2-3) $Q - \cancel{W}^{0} = m(u_3 - u_2) = (1\,kg)(286.16 - 592.3) = -306.14\ KJ$

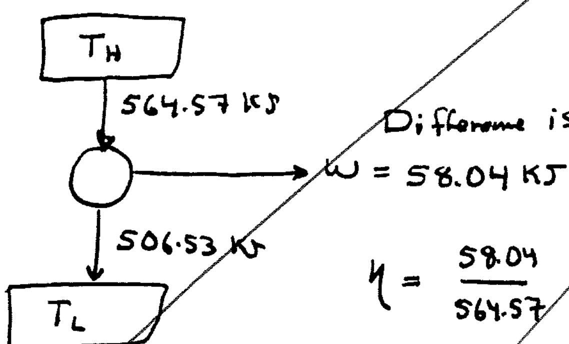
(3-4) $Q = m(h_4 - h_3) = (1\,kg)(199.97 - 400.49) = -200.59\ KJ$

(4-1) $Q - \cancel{W}^{0} = m(u_1 - u_4) = (1\,kg)(286.16 - 142.56) = 143.6\ KJ$

For cycle: $Q_{in} = 420.97 + 143.6 = 564.57\ KJ$

$Q_{out} = 306.14 + 200.39 = 506.53\ KJ$

So our heat engine looks like




$\eta = \dfrac{58.04}{564.57} = 10.3\%$

⇒ Of course, this is a good review of the first law, but.

⇒ For 2nd Law, the key point is that it was impossible to return to the original cycle condition without extracting heat.

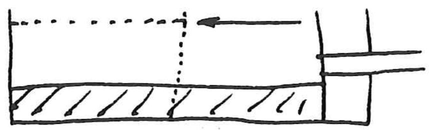
$\boxed{\text{Efficiency Lowy}}$

<u>Reversible Process</u>

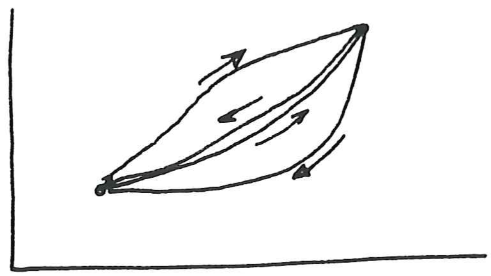
Formal Definition: You can undo the process, and there will be no changes on surroundings.

⇒ Specifically both Q and W will be recovered in their original quantities.

One example of this is a sliding trough:

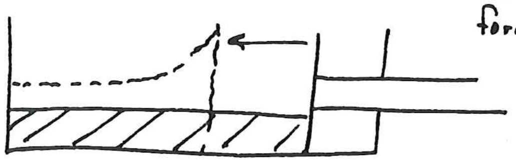


If I push it in slowly, the water level rises uniformly everywhere.




If I reverse slowly, it comes back along same line. ⇒ Get all work back.

If I push fast, what happens?
⇒ Water "Piles up". Since its deeper, we get a greater force.



~~If~~ If I also "undo" fast, will get lower force:

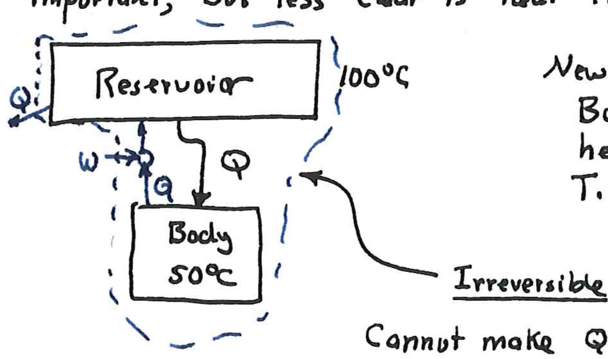
⇒ Net result is that I put more work in than I took out
⇒ Where did energy go? Into internal energy of $H_2O$
⇒ If I want to return $H_2O$ to original T, must extract Q.
⇒ Not reversible, because when I returned to original state some W → Q.

⇒ Friction does same thing Q → W.

⇒ More important, but less clear is heat transfer.

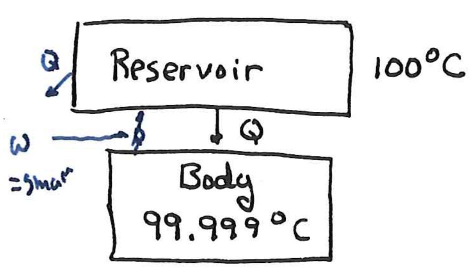
Reprise above, but add gas

May 6

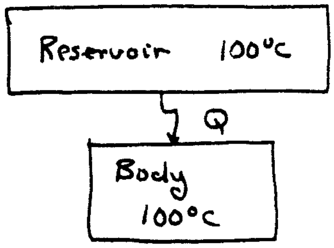



New Defn: Thermal Reservoir
Body thats so big you can take heat from it without changing T. e.g. - geothermal field. - river - atmosphere } can use as constant T source or sink for Q.

Cannot make Q go backwards without applying work... e.g. heat pump.




Almost Reversible Only a very small amount of W is needed to return the heat flow.




Reversible: No $\Delta T$... no work needed to reverse heat flow.

This is an idealization. A limit case.

➔ Like all reversible processes, you cannot get all the way there in real life

➔ But the closer you get the more reversible it is.

⇒ In real life, e.g. power plant, you sometimes go to great lengths to reduce the $\Delta T$ associated with heat transfer processes.

Globally why? Irreversibility tends to turn Work → Heat (e.g. friction)

But goal of heat engine: $Q \rightarrow W$.

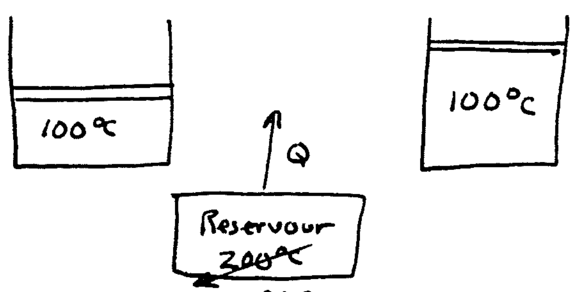
⇒ So the more revesibly you do things, the more Q you get.

This leads to a key point ⇒ The most work you can extract from a given Q will occur if you do ~~veryt~~ everything in the cycle revesibly.

→ Let's define a fully reversible cycle and see what happens.

→ Before we do... have one more concept to drive home.

→ Slow isothermal expansion.



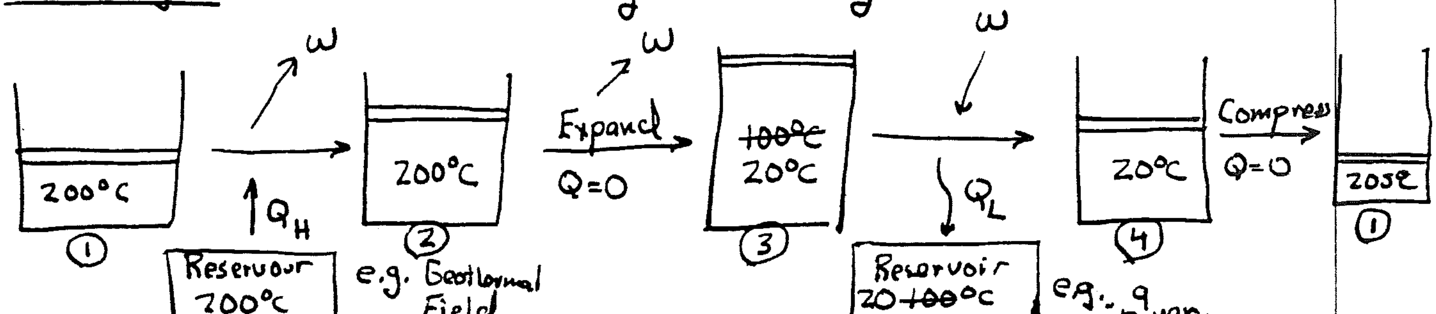

Cannot reverse because Q won't go from 100°C → 200°C

→ But if reservour is at 100°C

Now can reverse because heat flow can go from 100°C → 100°C

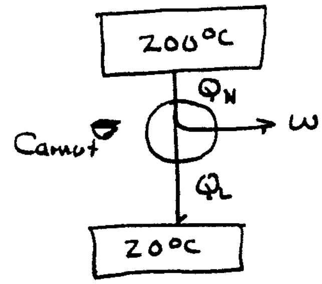
April 27

Carnot Cycle: Best known totally reversible cycle.



This cycle is totally reversible
① Because speed is slow enough that gas inside stays uniform
② Neglect friction, leaks, heat loss
③ All heat transfer is isothermal.

➡ Think about our cycle like this:




First Law

$$Q_H = Q_L + W$$

$$\eta = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Two observations:

① Any irreversible heat engine operating between these same two temperature limits will have lower $\eta$ (i.e., less work out) than a reversible engine.
② All reversible engines will have same $\eta$.

Final Point: Note that the cycle doesn't depend on anything dealing with the reservoirs, except their temperatures.

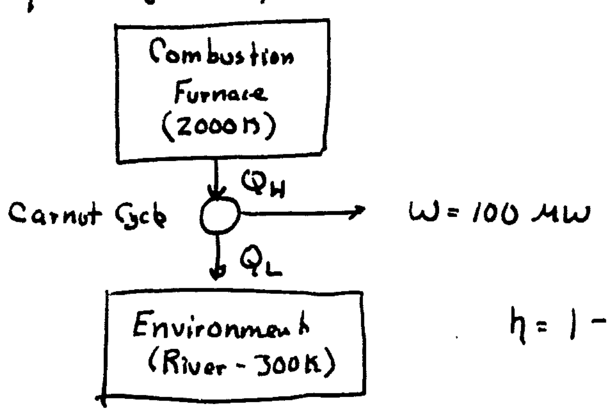
➡ Carnot efficiency only depends on reservoir temp.

From derivation in Section 5.5 (won't prove)

$$\left(\frac{Q_L}{Q_H}\right)_{reversible} = \frac{T_L}{T_H}$$

⇒ For Carnot & all reversible cycles $\boxed{\eta = 1 - \frac{T_L}{T_H}}$

A couple of exploratory examples:

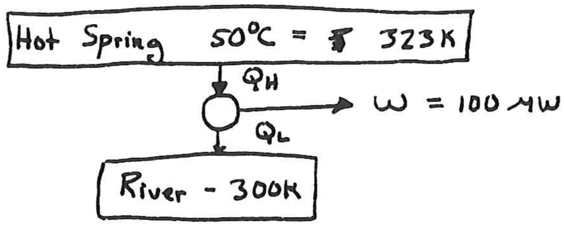



$$\eta = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{2000} = 0.85 = \frac{W}{Q_H}$$

$$\Rightarrow Q_H = 118 \text{ MW}$$

$$Q_L = 18 \text{ MW}$$

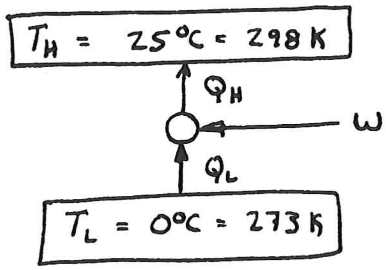
⇒ And this is the best you can do.
⇒ OK, this doesn't look too bad, but:




$$\eta = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{323} = 0.0712 = \frac{W}{Q_{in}}$$

$Q_H$ = 1404 MW
$Q_L$ = 1304 MW

Carnot Refrigeration
(throw cycle in reverse)




Still: $\frac{W}{Q_H} = 1 - \frac{T_L}{T_H}$

what you want

COP$_R$

But coefficient of performance $= \beta = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H - Q_L}{Q_L}} = \frac{1}{Q_H/Q_L - 1}$

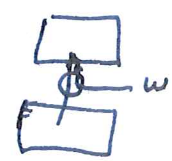
what you must pay for.

$$= \frac{1}{\frac{T_H}{T_L} - 1} = 10.92$$

- This means for every KW of work you put in, you move 10.92 KW from cold space.
- Also note that as $T_L \to T_H$, $\beta \to \infty$ ⇒ As the two reservoirs get closer together in T the heat transport between them gets more reversible because less work is required to move heat. ~ Also why heat pump craps out.

Summary of Main Points of Ch. 5. Three main points

1. $2^{nd}$ Law defines allowable directions for processes
   - A heat flow cannot be converted 100% to work.
   - Heat cannot flow from cold → hot without aid of work.




2. Reversibility
   - Can undo a process and recover your original values of Q, W.
   - Irreversible: On returning to original state, recover less W, more Q. ~~e.g. fr~~
     (a) Friction W → Q.
     (b) Heat Transfer across finite ΔT ⇒ Need W to return heat.

3. Carnot Engine & Principles.
   - All steps in cycle are reversible.
   - Maximum possible η between two fixed-T reservoirs.
     -- Most W for heat engine
     -- ~~Most~~ Least W for heat pump
   - All fully reversible cycles have same η.

April 29

# Chapter 6 - Entropy.

First: Entropy is nothing to fear... just a property like $u$, $h$, $v$. ⇒ Look up.

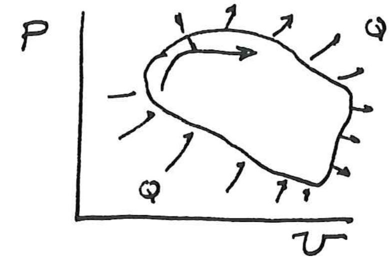
Starting point: Clausius Inequality:

May 8

$$\oint \left(\frac{\delta Q}{T}\right)_b \leq 0$$

~~This means that if I go~~

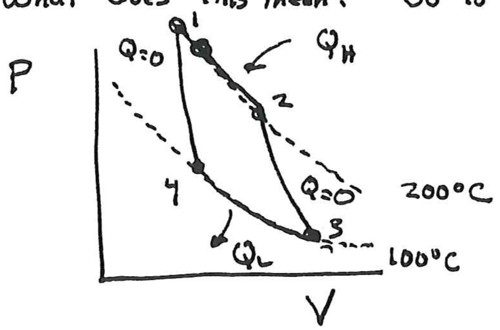
Look at cycle




Reverse Arrows!

If we integrate our way around the cycle, keeping track of local $T$, this will always be $\leq 0$.

What does this mean? Go to Carnot Cycle.




Heat Transfer occurs only from $1 \to 2$, $3 \to 4$

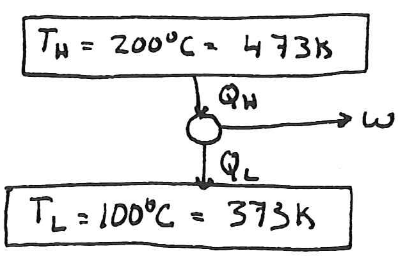
$$\oint \frac{\delta Q}{T} = \int_1^2 \frac{\delta Q_H}{T_H} + \int_3^4 \frac{\delta Q_L}{T_L}$$

But for Carnot cycle, $T_H$, $T_L$ are constants & pop out of the integral

$$\oint \frac{\delta Q}{T} = \frac{1}{T_H}\int_1^2 \delta Q_H + \frac{1}{T_L}\int_3^4 \delta Q_L = \frac{Q_H}{T_H} + \frac{Q_L}{T_L}$$

Lets calc. $Q_L$, $Q_H$ for Carnot & see where we end up.

Now back to Carnot Engine:




$$\eta = 1 - \frac{T_L}{T_H} = 1 - \frac{373}{473} = 0.211$$

If $W = 10\ kJ$, $Q_H = \frac{W}{\eta} = \frac{10}{0.211} = 47.39\ kJ$

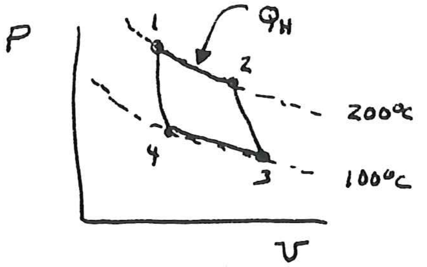
Also $Q_L = Q_H - W = 47.39 - 10 = 37.39\ kJ$

Plug In: $$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} + \frac{Q_L}{T_L} = \frac{47.39\ kJ}{473\ K} + \frac{(-37.39\ kJ)}{373\ K} = 0$$

This means:

| $\oint \frac{\delta Q}{T} = 0$ | $\oint \frac{\delta Q}{T} < 0$ | $\oint \frac{\delta Q}{T} > 0$ |
|---|---|---|
| Reversible Engine | Irreversible Cycle (Real) | Impossible (2nd Law violation... Perpetual motion |

Return to Carnot example:




~~If we start at 1, and we go to 2 on a reversible path~~

$$\oint \frac{\delta Q}{T} = \int_1^2 \left(\frac{\delta Q}{T}\right)_{rev} + \int_3^4 \left(\frac{\delta Q}{T}\right)_{rev.}$$

Define each of these as a property of the fluid used in the Carnot cycle:

$$\oint \frac{\delta Q}{T} = m\left[\Delta S_{1-2} + \Delta S_{3-4}\right]$$

S is entropy, and its a property of the working fluid.

Definition $\Delta S_{1-2} = \int_1^2 \left(\frac{\delta Q}{T}\right)_{reversible}$

Key point... ~~since~~ integral if I start at state 1, and end at state 2, the $\int_1^2 \left(\frac{\delta Q}{T}\right)_{rev}$ will always give the same value

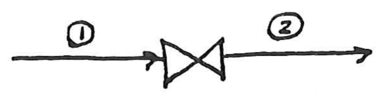
follow any reversible path

⇒ This is why we get to treat S as a property... because ~~it starts and ends at~~ ΔS between two points is not ~~a property of~~ affected by path, only of fluid & states @ 1 & 2.

⇒ Don't worry... learn to use it, then begin to think about what it means.

Example: Throttle Ideal Gas

200 kPa
300K




100 kPa
T = ? (300K)

No Temp. change, adiabatic ... Will there be a ΔS?

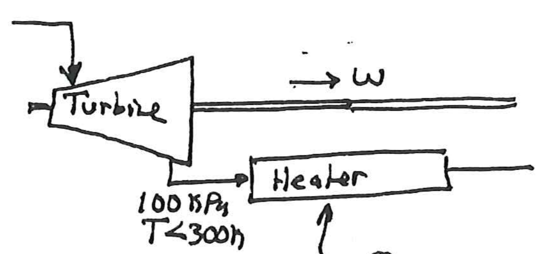
$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_{reversible}$$

→ Might think ΔS = 0, because Q = 0
→ But is a throttle reversible?
→ No... need work to return pumping.

⇒ Must construct a reversible path that connects 1 → 2.

One possible path:

200 kPa
300K




100 kPa
300K,

$$\boxed{\Delta S_{1-2} = \int_{Heater} \frac{\delta Q}{T}}$$

Key points of what we have just done...

① Defined entropy as $\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{reversible}}$.

② To find $\Delta S$ between any two points, you must construct a reversible means of going from ① → ②

⇒ Throttle valve was irreversible, so we had to construct a reversible ($\dot{\imath}$ $Q=0$) path connecting the two endpoints... this involved $Q$.

③ Using this $Q$, get $\Delta S$ ⇒ provides conceptual framework for evaluating entropy.

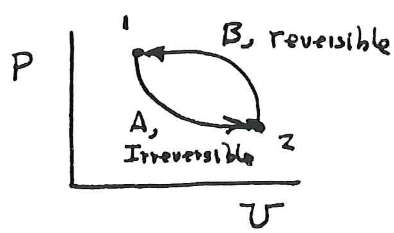
④ For All reversible paths between ① and ② $\int_1^2 \left(\frac{\delta Q}{T}\right)_{rev}$ = same

⇒ $\Delta S$ between ① and ② is independent of path
⇒ $\boxed{\text{Its a property because it depends only on endpoints}}$

May 10

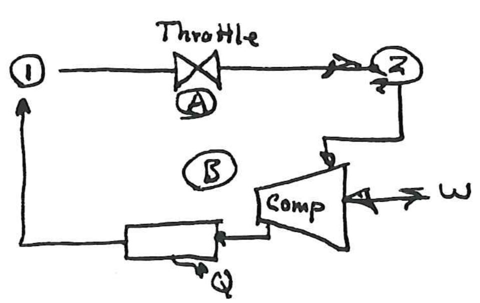
Increase in Entropy Principle.

Start with Clausius inequality $\oint \left(\frac{\delta Q}{T}\right)_{Irr} < 0$




Construct a cycle that starts and ends at 1
Leg A irreversible
Leg B reversible

e.g.




$\oint \left(\frac{\delta Q}{T}\right)_{\text{Irr. cycle}} =$

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_A + \underbrace{\int_2^1 \left(\frac{\delta Q}{T}\right)_B}_{\text{This is just definition of } S_1 - S_2} < 0$$

$S_1 - S_2 + \int_1^2 \left(\frac{\delta Q}{T}\right)_A < 0$ reverse signs.

$\Rightarrow \quad S_2 - S_1 - \int_1^2 \left(\frac{\delta Q}{T}\right)_A > 0$

But in terms of surroundings -

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_A = -\int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{surroundings}}$$