Thermodynamics Midterm 2 Review

Sigma Gamma Tau

Section 1: Dom, Hannah, John

Energy Balance of Control Volumes:

- The net mass transfer into the control surface is equivalent to the net mass increase of the control volume.
- For steady flow, mass flow rate is constant.
- For diffusers: Pressure increases and velocity decreases
- For nozzles: Pressure decreases and velocity increases
- For both diffusers and nozzles, the change in work rate, change in heat rate, and change in potential energy are zero.
- For a system like a mixing chamber with multiple mass flows in and only one flow out, if the system is steady: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Useful Equations:

- $\dot{m} = \rho V A = \rho \dot{V} = \frac{\Delta m}{\Delta t}$
    - $\dot{m}$: Mass flow rate
    - ρ: Density
    - V: Velocity
    - A: Area
    - $\dot{V}$: Volumetric flow rate
- For a C.V.: $m_{in} - m_{out} = \Delta m = \frac{\Delta Vol}{\nu}$
    - Subsequently: $\dot{m}_{in} - \dot{m}_{out} = \frac{dm}{dt}$
    - Note: this holds for systems with multiple inlets and exits
- Work due to a flow: $W = p\nu$
- Total energy of a fluid: $\theta = e + p\nu$
    - θ: Total specific fluid energy
    - e: Total specific energy
    - p: Pressure

- ν: Specific volume

- $h = u + p\nu$
  - h: enthalpy
- $\dot{E}_{mass} = \dot{m}\theta$
  - For slow fluids: $\dot{E}_{mass} \simeq \dot{m}h$
  - Use this in combination with energy balance
- h = CpT
- u = CvT

Heat Exchanger:

- 2 moving fluids that do not mix
- Q(heat) moves from how to cold
- Typically work is 0
- Create 2 control volumes. One of all inlets and exits, and one of the fluid in the tank only.
- Evaluate energy balance from both c.v.

Useful Equations:

- $\dot{m}_1 = \dot{m}_2$ and $\dot{m}_3 = \dot{m}_4$

Unsteady Flow:

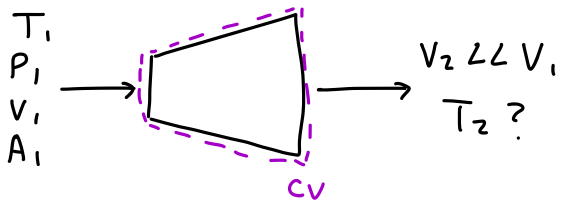
- There is a Δm in the system.

Useful Equations:

- $m_{in} - m_{out} = \Delta m$
- Now: $\Delta E_{sys} = m_2 u_2 - m_1 u_1$
  - Takes the form $\sum m\theta$

EXAMPLE 1: 5-4

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (a) the mass flow rate of the air and (b) the temperature of the air leaving the diffuser.



$\dot{m}$?

$$SS \Rightarrow \Delta m_{cv} = 0 \quad \Delta E_{cv} = 0$$

$$\dot{m}_1 = \dot{m}_2$$

a) $\dot{m} = \rho A V$

$$v_1 = \frac{RT_1}{P_1} = \frac{(287)(283)}{(80 \times 10^3)} = 1.015 \ \frac{m^3}{kg}$$

$$\dot{m} = \frac{1}{v} V A = \frac{1}{1.015}(200)(0.4) = \boxed{78.8 \ \frac{kg}{s}}$$

b) $\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_g}^{\,0} = \cancel{\frac{d\dot{E}_{st}}{dt}}^{\,0}$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\cancel{\dot{m}_1}\left(h_1 + \frac{V_1^2}{2}\right) = \cancel{\dot{m}_2}\left(h_2 + \frac{V_2^2}{2}\right)$$

$$h_2 = h_1 - \frac{\cancel{V_2^2} - V_1^2}{2}$$

$$h\Big|_{T=283\,K} = 283.14\ \frac{kJ}{k} \leftarrow \text{Table A-17}$$

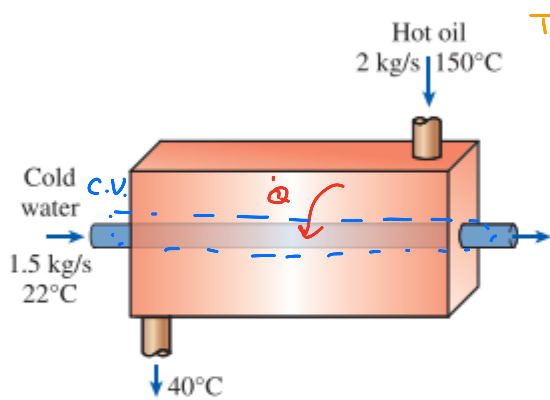
$$h_2 = 283.14 + \frac{200^2}{2}\left(\frac{1}{1000}\right) = 303.14\ \frac{kJ}{kg}$$

Table A-17 $\boxed{T\Big|_{h=303.14} = 303\ K}$

EXAMPLE 2: 5-78

A thin-walled double-pipe counter-flow heat exchanger is used to cool oil (c_p = 2.20 kJ/kg·°C) from 150 to 40°C at a rate of 2 kg/s by water (c_p = 4.18 kJ/kg·°C) that enters at 22°C at a rate of 1.5 kg/s. Determine the rate of heat transfer in the heat exchanger and the exit temperature of water.

$\dot{Q} = ?$



$T_{1\,oil} = 150°C$

$\dot{m}_{oil} = 2\ kg/s$

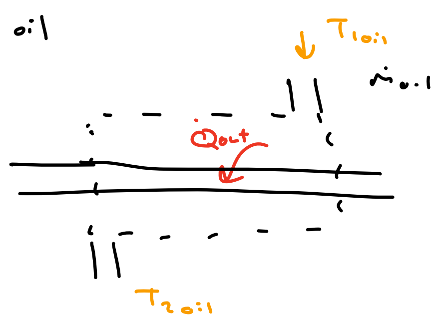
$T_{2w} = ?$

FIGURE P5–78

Assumptions:

- Steady-state : $\Delta m_{sys} = 0$, $\Delta \dot{E}_{sys} = 0$
- K.E./P.E. negligible

a) C.V. : hot oil



$h = c_p T$

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_g} = \cancel{\dot{E}_{st}} \qquad \dot{Q} + \dot{W}$$

$$\dot{E}_{in} = \dot{E}_{out} \Rightarrow \dot{m}_{oil}\left(h_1 + \cancel{\frac{V_1^2}{2}} + \cancel{gz_1}\right) = \dot{Q}_{out} + \dot{m}_{oil}(h_2)$$

$$\dot{m}_{oil} h_1 = \dot{Q}_{out} + \dot{m}_{oil} h_2$$

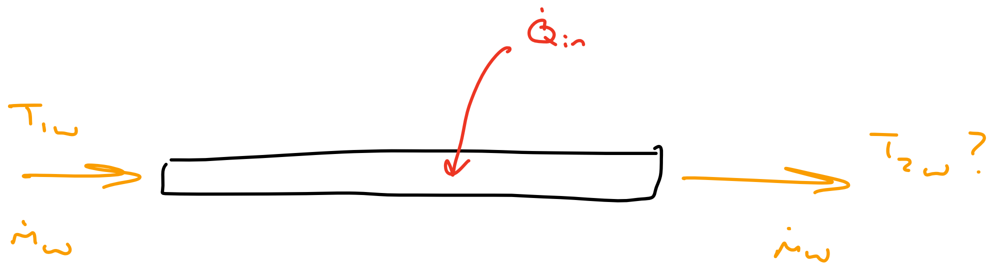
$$\dot{m}_{oil}\, c_{p_{oil}}\, T_{1_{oil}} = \dot{Q}_{out} + \dot{m}_{oil}\, c_{p_{oil}}\, T_{2_{oil}}$$

$$\dot{Q}_{out} = \dot{m}_{oil}\, c_{p_{oil}} \left(T_{1_{oil}} - T_{2_{oil}}\right)$$

$$\dot{Q}_{out} = (2\ kg/s)(2.2\ kJ/kg\cdot°C)(150°C - 40°C)$$

$$\boxed{\dot{Q}_{out} = 484\ kW}$$

b) T_{2_w}?



$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_s} = \cancel{\dot{E}_{st}} \Rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_w (h_{1_w}) + \dot{Q}_{in} = \dot{m}_w (h_{2_w})$$

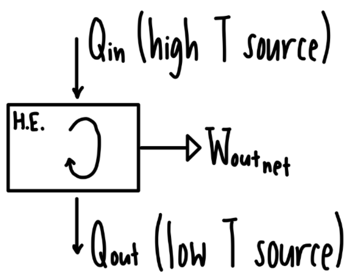
$$\frac{\dot{m}_w c_{p_w} T_{1_w} + \dot{Q}_{in} = \dot{m}_w c_{p_w} T_{2_w}}{\dot{m}_w c_{p_w}}$$

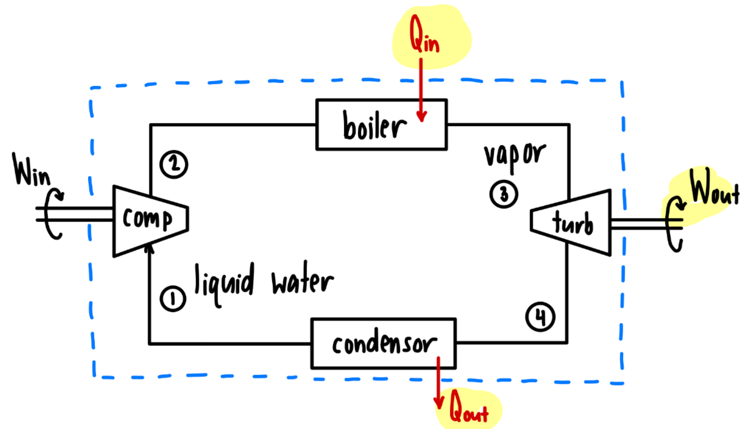
$$T_{2_w} = T_{1_w} + \frac{\dot{Q}_{in}}{\dot{m}_w c_{p_w}} = 22°C + \frac{484\ kW}{(1.5\ kg/s)(4.18\ kJ/kg\cdot°C)}$$

$$\boxed{T_{2_w} = 99.2°C}$$

HEAT ENGINE

- Heat Engine: Q_{in} from a high temperature source is used to produce usable W_{out} with excess Q_{out} dumped into a low temperature sink, shown in the cycle to the left. The cycle on the right includes a compressor that requires W_{in} but significantly improves efficiency.





- Energy Balance: $Q_{in} - Q_{out} = W_{out} - W_{in} = W_{out,\,net}$
  - Only for a steady system.
  - Q_{in} is the cost while Q_{out} is the waste.
- Thermal efficiency: measure of the performance of a heat engine (never greater than 1)
  - $\eta_{th} = \frac{W_{out,\,net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$
  - When operating between a high temperature and a low temperature reservoir
    - $\eta_{th} = \frac{W_{out,\,net}}{Q_H} = 1 - \frac{Q_L}{Q_H}$
    - $W_{out} > W_{in}$ must be achieved to obtain useful $W_{out,\,net}$
- Kelvin-Plank Statement $\left(2^{nd}\ Law\right)$: it is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.
  - For a complete cycle, any heat engine must have: high temperature source and low temperature sink.
  - Heat must be rejected as waste, such that no heat engine can achieve η_{th} =100%.

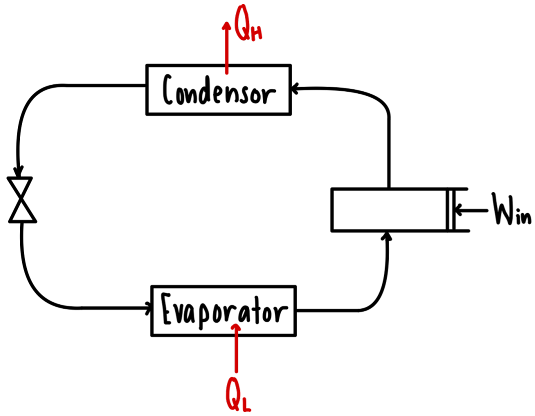
REFRIGERATOR AND HEAT PUMP

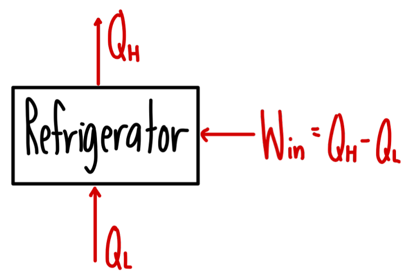
Refrigerator

- Refrigerators: W_{in} is input to the system to transfer heat from a low-temperature medium to a high-temperature medium.
  - Unlike a heat engine, W_{in} is now the required energy input to result in the desired outcome, not a high-temperature heat source.
- Coefficient of Performance (COP_R): measure of performance of a refrigerator
  - $COP_R = \frac{desired\ output}{required\ input} = \frac{Q_L}{W_{in,\,net}} = \frac{Q_L}{Q_H - Q_L} = \frac{Q_L}{Q_H/Q_L - 1}$
    - COP_R can be greater than one
    - W_{in} is required to maintain Q_L at a low-enough temperature.

Heat Pump

- Heat pump: also transfers heat from low-temperature medium to high-temperature medium
- Coefficient of Performance (COP_{HP}): measure of performance of a heat pump (can be greater than 1)
  - $COP_{HP} = \frac{desired\ output}{required\ input} = \frac{Q_H}{W_{in,\,net}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$
  - $COP_{HP} = COP_R + 1$
    - COP_{HP} can be greater than one
    - W_{in} is required to maintain Q_H at a high-enough temperature.





Clausius Statement

- For both refrigerators and heat pumps: Clausius Statement
  - ******************

EXAMPLE 1: 6-23

An automobile engine consumes fuel at a rate of 6.11 $\frac{cm^3}{s}$ and delivers 55 kW of power to the wheels. If fuel has a heating value of 44,000 $\frac{kJ}{kg}$ and a density of 0.8 $\frac{g}{cm^3}$, determine the thermal efficiency of this engine.

$$\dot{m} = \left(6.11 \frac{cm^3}{s}\right)\left(0.8 \frac{g}{cm^3}\right) = 4.888 \times 10^{-3} \frac{kg}{s}$$

$$\underline{\dot{Q}_H} = \left(44000 \frac{kJ}{kg}\right)\left(4.888 \times 10^{-3} \frac{kg}{s}\right) = 215.07\, kW$$

$$\dot{W}_{out} = 55\, kW$$

$$\eta_{TH} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{55}{215.07} = 0.256 \rightarrow \eta_{TH} = 25.6\%$$

EXAMPLE 2: 6-42

An air conditioner removes heat steadily from a house at a rate of 750 kJ/min while drawing electric power at a rate of 6 kW. Determine (a) the COP of this air conditioner and (b) the rate of heat transfer to the outside air.

$$\dot{W}_{in} = 6\,kW$$

$$\dot{Q}_L = 750\ \frac{kJ}{min}\left(\frac{1}{60}\right) = 12.5\,kW$$

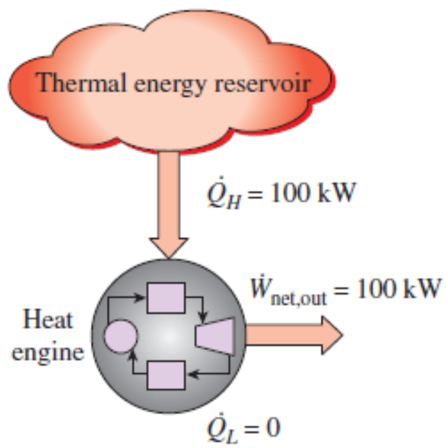
$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{12.5}{6} = 2.0833$$

$$\dot{W}_{in} = \dot{Q}_H - \dot{Q}_L \rightarrow \dot{Q}_H = \dot{W}_{in} + \dot{Q}_L = 6\,kW + 12.5\,kW = 18.5\,kW$$

Section 3:

Kelvin-Planck Statement (Heat Engine)

- No heat engine can convert all the heat it receives to useful work. It requires a low-temperature sink.

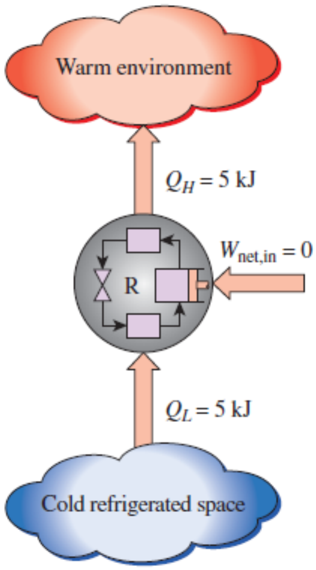


AN ENGINE THAT VIOLATES KP STATEMENT.

Why? Because it's an engine, it has to return to its initial state. To achieve that, you have to dump excess heat into a lower-temperature sink.

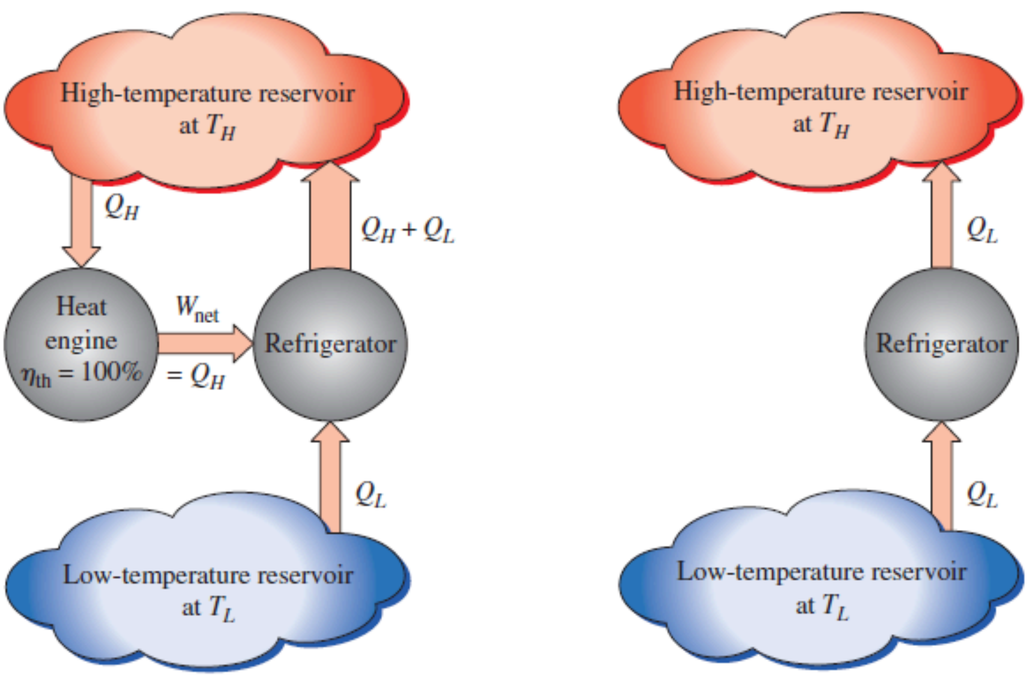
Clausius Statement (Heat Pump)

- "It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body."
- → Refrigerator or heat pump cannot operate unless *Win* is externally supplied (like with an external power source).



A REFRIGERATOR THAT VIOLATES THE CLAUSIUS STATEMENT.

Equivalence of the Two Statements



(*a*) A refrigerator that is powered by a 100 percent efficient heat engine

(*b*) The equivalent refrigerator

Violation of one leads to a violation of the other.

The Carnot Principles

- The above two statements are called the 2nd Law of Thermo.
- This leads to the Carno Principles:
    1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible heat engine operating on the same two reservoirs.
       ∵ Loss of energy occurs during the process.
    2. The efficiency of all reversible heat engines operating on the same two reservoirs is the same.
       ∵ The proportionality of heat input and output stays the same.

The Carnot Cycle

- Under a cycle, it must return to its initial state at the end of each cycle.
- A reversible process is ideal for maximizing cycle efficiency.
    - This cannot be achieved in practice, but they do provide the upper limits on real cycle performances.
- The Carnot cycle is the best-known reversible cycle.

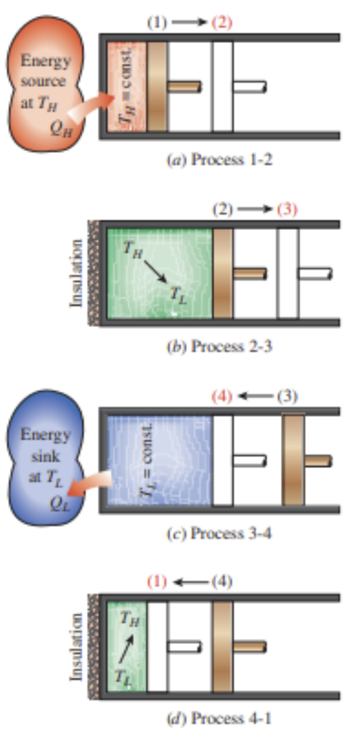


FIGURE 6–36
Execution of the Carnot cycle in a closed system.

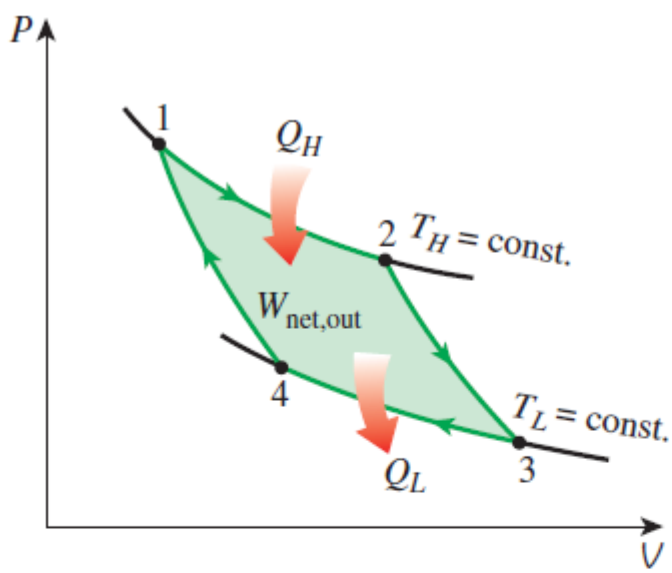
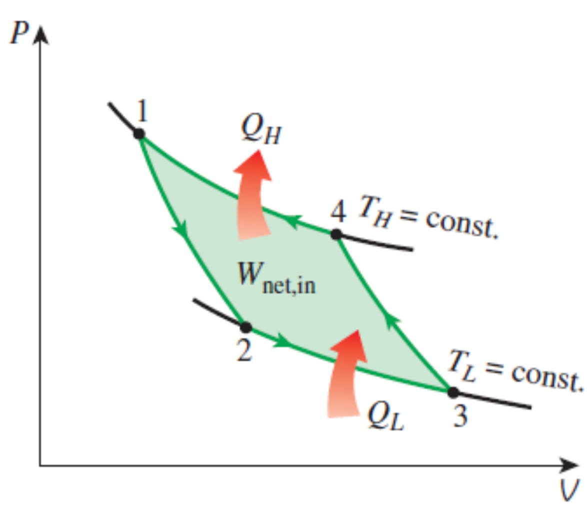


FIGURE 6–37
P-*V* diagram of the Carnot cycle.

- The four reversible processes of the Carnot cycle:
  - Reversible Isothermal Expansion, 1 to 2
    - $T_H = \ const.$
    - Gas is allowed to expand, which works on the surroundings.
    - Total heat transferred to the gas is Q_H .
  - Reversible Adiabatic Expansion, 2 to 3
    - $T_H \rightarrow T_L$
    - Temperature drops, the gas continues to expand, and work continues to be done on the piston.
  - Reversible Isothermal Compression, 3 to 4
    - $T_L = const.$
    - The piston is pushed in by an external force that works on the gas.
    - A heat of Q_L is rejected from the gas.
  - Reversible Adiabatic Compressionn, 4 to 1
    - $T_L \rightarrow T_H$
    - The temperature rises and the gas continues to be compressed.
    - Returns to initial state which completes the cycle.
- A heat engine needs two reservoirs to operate in a cycle at different temperatures.
- Carnot Refrigeration Cycle
  - The same cycle, except the directions of heat and work interactions are reversed.

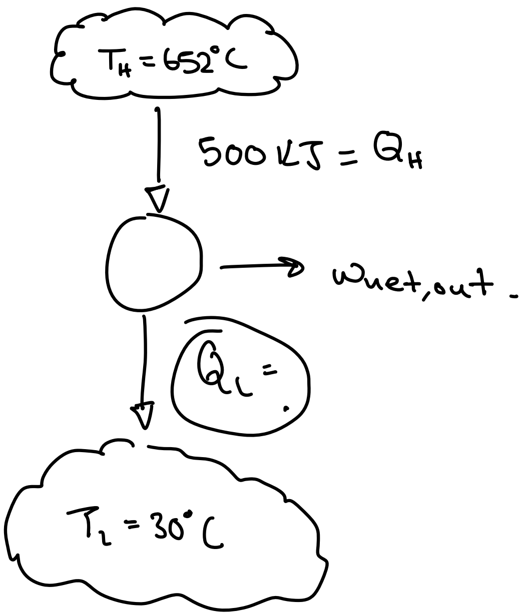


Practice Problem 1

- A Carnot heat engine receives 500 kJ of heat per cycle from a high-temperature source at ~~652°C~~ 652°C and rejects heat to a low-temperature sink at ~~30°C~~ 30°C. Determine
  - (a) the thermal efficiency of this Carnot engine and
  - (b) the amount of heat rejected to the sink per cycle.

• Celius + 273°

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



a) thermal efficiency.

$$\eta_{th,rev} = 1 - \left(\frac{T_L}{T_H}\right)$$

$$\eta_{th,rev} = 1 - \frac{(30+273)}{(652+273)} = 0.672$$

b.

$$Q_{L,rev} = \frac{T_L}{T_H} Q_{H,rev}$$

$$= \frac{(30+273)}{(652+273)}(500)$$

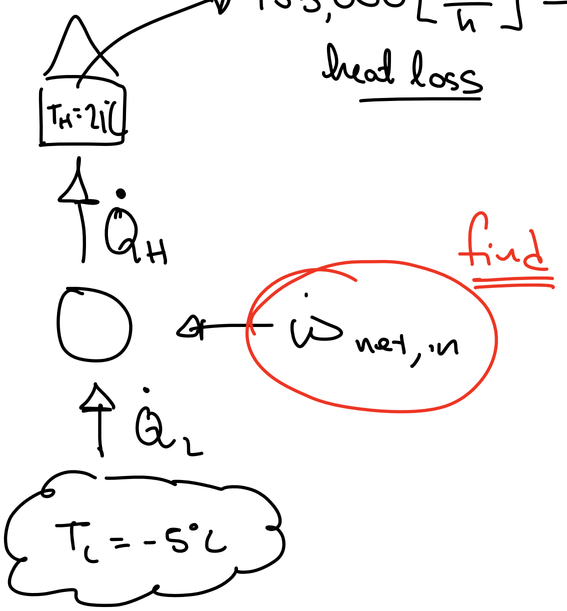
$$Q_{L,rev} = 164\ kJ$$

Practice Problem 2

- A heat pump is to be used to heat a house during the winter. The house is to be maintained at 21℃ at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to -5℃.
    - Determine the minimum power required to drive this heat pump.

Celsius to Kelvin

35.7



$135{,}000 \left[\frac{KJ}{h}\right] \rightarrow 135{,}000 \left[\frac{KJ}{\cancel{h}}\right] \cdot \frac{1 [\cancel{h}]}{3600 [s]} \Rightarrow \frac{KJ}{s} \Rightarrow KW$

heat loss

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}}$$

house maintained @ same temp

$\dot{Q}_H$ = heat loss = 37.5

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - \frac{(-5+273)}{(21+273)}}$$

$$COP_{HP,rev} = 11.3$$

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{37.5\ [kW]}{11.3} = 3.32 [kW]$$