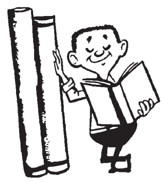
First Law of Thermodynamics



Reading	Problems
3-2 → 3-7	3-40, 3-54, 3-105
5-1 → 5-2	5-8, 5-25, 5-29, 5-37, 5-40, 5-42, 5-63, 5-74, 5-84, 5-109
6-1 → 6-5	6-44, 6-51, 6-60, 6-80, 6-94, 6-124, 6-168, 6-173

Control Mass (Closed System)

In this section we will examine the case of a control surface that is closed to mass flow, so that no mass can escape or enter the defined control region.

Conservation of Mass

Conservation of Mass, which states that mass cannot be created or destroyed, is implicitly satisfied by the definition of a control mass.

Conservation of Energy

The first law of thermodynamics states "Energy cannot be created or destroyed it can only change forms".

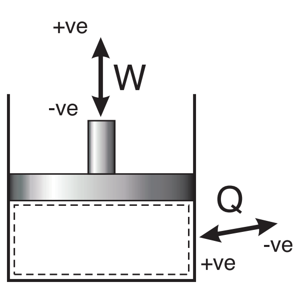
$$\boxed{\text{energy entering}} - \boxed{\text{energy leaving}} = \boxed{\text{change of energy within the system}}$$

Sign Convention

Cengel Approach

Heat Transfer: heat transfer to a system is positive and heat transfer from a system is negative.

Work Transfer: work done by a system is positive and work done on a system is negative.

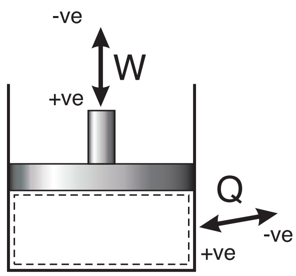


For instance: moving boundary work is defined as:

$$W_b = \int_1^2 P \, dV$$

During a compression process, work is done on the system and the change in volume goes negative, i.e. $dV < 0$. In this case the boundary work will also be negative.

Culham Approach

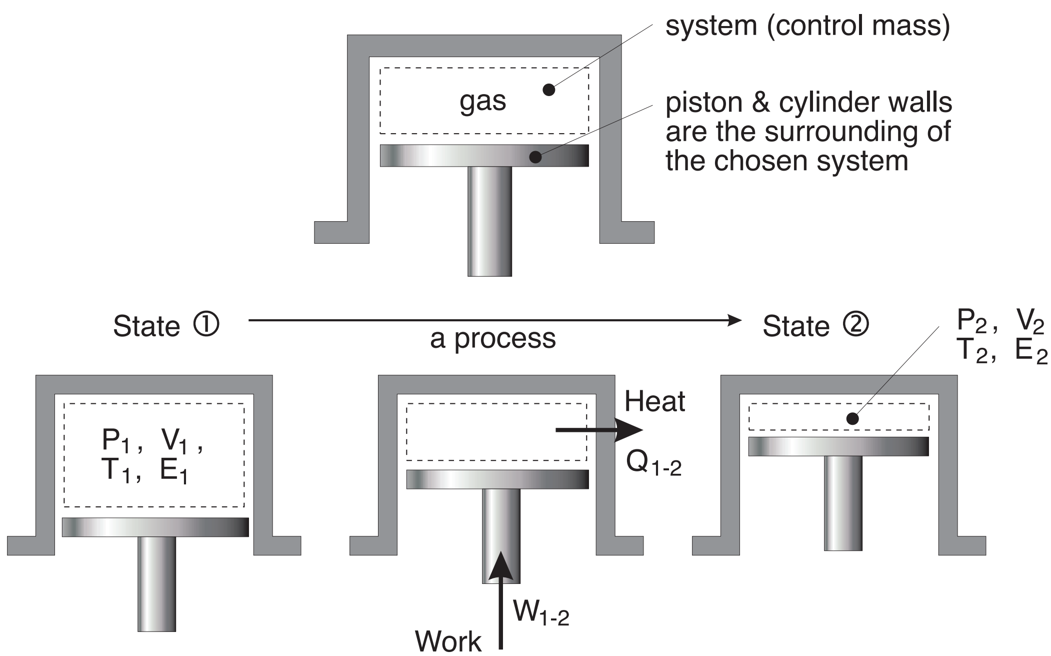


Using my sign convention, the boundary work is defined as:

$$W_b = -\int_1^2 P\,dV$$

During a compression process, the change in volume is still negative but because of the negative sign on the right side of the boundary work equation, the boundary work directed into the system is considered positive. Any form of energy that adds to the system is considered positive.

Example: A Gas Compressor



Performing a 1st law energy balance:

$$\left\{\begin{array}{c} Initial \\ Energy \\ E_1 \end{array}\right\} \begin{array}{c} + \\ - \end{array} \left\{\begin{array}{c} Energy\ gain\ W_{1-2} \\ Energy\ loss\ Q_{1-2} \end{array}\right\} = \left\{\begin{array}{c} Final \\ Energy \\ E_2 \end{array}\right\}$$

$$E_1 + W_{1-2} - Q_{1-2} = E_2 \qquad \Rightarrow \qquad \Delta E = Q - W$$

A first law balance for a control mass can also be written in differential form as follows:

$$dE = \delta Q - \delta W$$

Note: d or Δ for a change in property and δ for a path function

The differential form of the energy balance can be written as a rate equation by dividing through by dt, a differential time, and then letting $dt \to 0$ in the limit to give

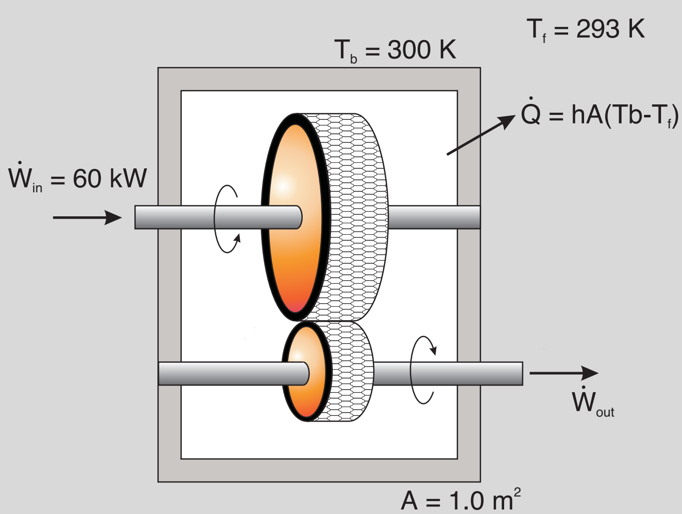
$$\frac{dE}{dt} = \frac{\delta Q}{dt} - \frac{\delta W}{dt} \quad \Rightarrow \quad \frac{dE}{dt} = \dot{Q} - \dot{W}$$

where

$$\begin{aligned} \frac{dE}{dt} &= \text{rate of energy increase within the system,} \quad \equiv \frac{dU}{dt} + \frac{d\,KE}{dt} + \frac{d\,PE}{dt} \\ \dot{Q} &= \text{rate of heat transfer} \\ \dot{W} &= \text{rate of work done,} \quad \equiv \text{power} \end{aligned}$$

- most closed systems encountered in practice are stationary i.e. the velocity and the elevation of the center of gravity of the system remain constant during the process
- for stationary systems we can assume that $\dfrac{d\,KE}{dt} = 0$ and $\dfrac{d\,PE}{dt} = 0$

Example 3-1: During steady-state operation, a gearbox receives $\dot{W}_{in} = 60\ kW$ through the input shaft and delivers power through the output shaft. For the gearbox as the system, the rate of energy transfer by heat is given by Newton's Law of Cooling as $\dot{W} = hA(T_b - T_f)$. where h, the heat transfer coefficient, is constant ($h = 0.171\ kW/m^2 \cdot K$) and the outer surface area of the gearbox is $A = 1.0\ m^2$. The temperature of the outer surface of the gearbox is $T_b = 300\ K$ and the ambient temperature surrounding the gearbox is $T_\infty = 293\ K$. Evaluate the rate of heat transfer, $\dot{Q}$ and the power delivered through the output shaft, $\dot{W}_{out}$.



Forms of Energy Transfer

Work Versus Heat

- Work is macroscopically organized energy transfer.
- Heat is microscopically disorganized energy transfer.

more on this when we discuss entropy

Heat Energy

- heat is defined as a form of energy that is transferred solely due to a temperature difference (without mass transfer)
- heat transfer is a directional (or vector) quantity with magnitude, direction and point of action
- modes of heat transfer:
  - **conduction:** diffusion of heat in a stationary medium (Chapters 10, 11 & 12)
  - **convection:** it is common to include convective heat transfer in traditional heat transfer analysis. However, it is considered mass transfer in thermodynamics. (Chapters 13 & 14)
  - **radiation**: heat transfer by photons or electromagnetic waves (Chapter 15)

Work Energy

- work is a form of energy in transit. One should not attribute work to a system.
- work (like heat) is a "path function" (magnitude depends on the process path)
- work transfer mechanisms in general, are a force acting over a distance

Mechanical Work

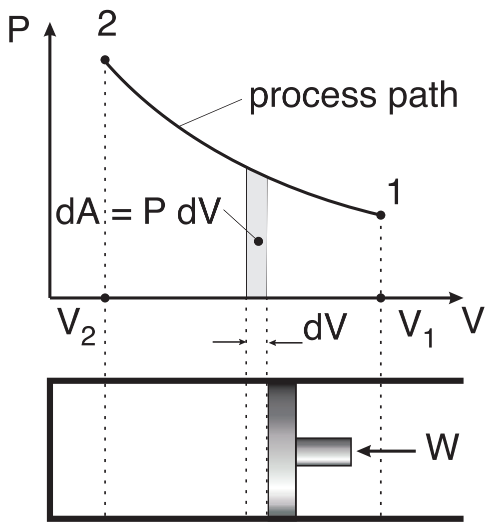
$$W_{12} = \int_1^2 F\, ds$$

- if there is no driving or resisting force in the process (e.g. expansion in a vacuum) or the boundaries of the system do not move or deform, $W_{12} = 0$.

Moving Boundary Work

$$W_{12} = -\int_1^2 F\, ds = -\int_1^2 P \cdot A\, ds = -\int_1^2 P\, dV$$

- a decrease in the volume, $dV \rightarrow -ve$ results in work addition ($+ve$) on the system



- consider compression in a piston/cylinder, where A is the piston cross sectional area (frictionless)
- the area under the process curve on a $P - V$ diagram is proportional to $\int_1^2 P\, dV$
- the work is:
  - $+ve$ for compression
  - $-ve$ for expansion
- sometimes called $P\, dV$ work or compression /expansion work

- *polytropic processes:* where $PV^n = C$
- examples of polytropic processes include:

Isobaric process: if $n = 0$ then $P = C$ and we have a constant pressure process

Isothermal process: if $n = 1$ then from the ideal gas equation $PV = RT$ and PV is only a function of temperature

Isometric process: if $n \rightarrow \infty$ then $P^{1/n}V = C^{1/n}$ and we have a constant volume process

Isentropic process: if $n = k = C_p/C_v$ then we have an isentropic process. (tabulated values for k are given in Table A-2) If we combine

$$Pv^k = C \qquad \text{with} \qquad Pv = RT$$

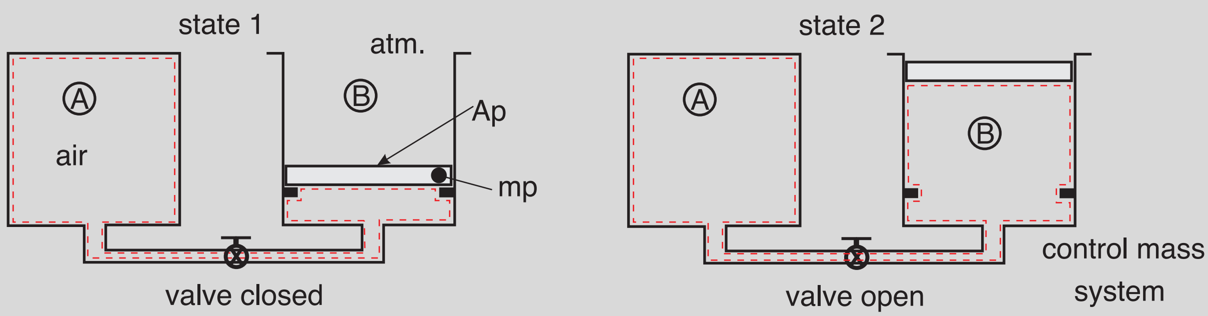
we get the isentropic equations, given as: $$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

Case 1: for an ideal gas with $n = 1$ $\rightarrow$ $$\boxed{W_{12} = -C \ln \frac{V_2}{V_1}}$$

Case 2: for $n \neq 1$ $\rightarrow$ $$\boxed{W_{12} = \frac{P_1V_1 - P_2V_2}{1-n}}$$ (in general)

$\rightarrow$ $$\boxed{W_{12} = \frac{mR(T_1 - T_2)}{1-n}}$$ (ideal gas)

Example 3-2: A pneumatic lift as shown in the figure below undergoes a quassi-equilibrium process when the valve is opened and air travels from tank A to tank B.



The initial conditions are given as follows and the final temperatures can be assumed to be the same as the initial temperatures.

$$
\begin{aligned}
P_{atm} &= 100\ kPa & 1\ Pa &= 1\ N/m^2 \\
m_p &= 500\ kg & A_p &= 0.0245\ m^2 \\
V_{A,1} &= 0.4\ m^3 & V_{B,1} &= 0.1\ m^3 \\
P_{A,1} &= 500\ kPa & P_{B,1} &= 100\ kPa \\
T_{A,1} &= 298\ K & T_{B,1} &= 298\ K = 25\ ^\circ C
\end{aligned}
$$

Find the final pressures $P_{A,2}$ and $P_{B,2}$ and the work, W_{12}, in going from state 1 to state 2.

Control Volume (Open System)

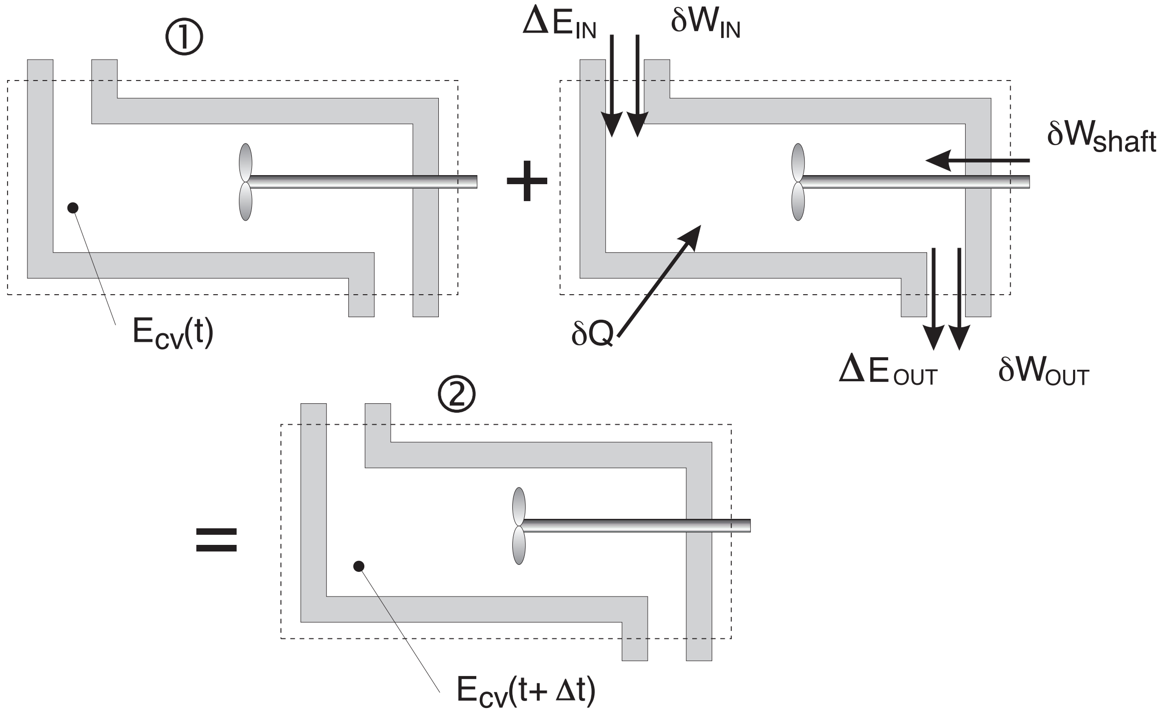
The major difference between a *Control Mass* and and *Control Volume* is that mass crosses the system boundary of a control volume.

CONSERVATION OF MASS:

Unlike a control mass approach, the control volume approach does <u>not</u> implicitly satisfy conservation of mass, therefore we must make sure that mass is neither created nor destroyed in our process.

$$
\left\{ \begin{array}{c} rate\ of\ increase\ of \\ mass\ within\ the\ CV \end{array} \right\} = \left\{ \begin{array}{c} net\ rate\ of \\ mass\ flow\ IN \end{array} \right\} - \left\{ \begin{array}{c} net\ rate\ of \\ mass\ flow\ OUT \end{array} \right\}
$$

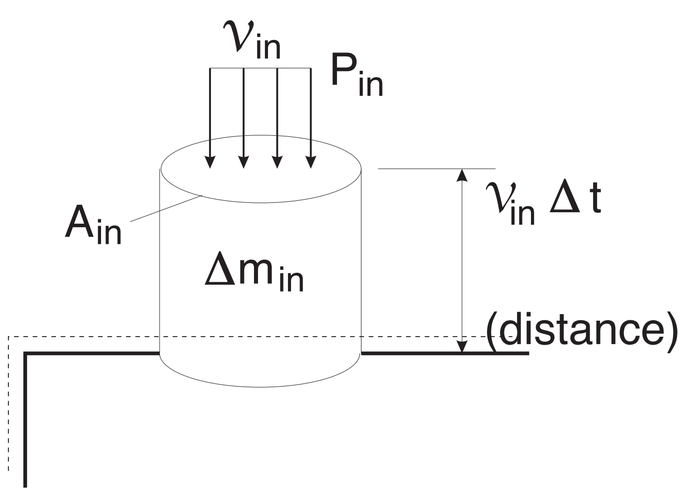
CONSERVATION OF ENERGY:



$$
\begin{aligned}
&E_{CV}(t) + \delta Q + \delta W_{shaft} + (\Delta E_{IN} - \Delta E_{OUT}) + \\
&\qquad (\delta W_{IN} - \delta W_{OUT}) \;=\; E_{CV}(t + \Delta t) \qquad (1)
\end{aligned}
$$

<u>**What is flow work?**</u>

This is the work required to pass the flow across the system boundaries.



$$
\begin{aligned}
\Delta m_{IN} &= \rho_{IN} \overbrace{A_{IN}\, \mathcal{V}_{IN}\, \Delta t}^{volume} \\
\delta W_{IN} &= F \cdot distance \\
&= \underbrace{P_{IN}\, A_{IN}}_{F} \cdot \underbrace{\mathcal{V}_{IN}\, \Delta t}_{\Delta s} \\
&= \frac{P_{IN}\, \Delta m_{IN}}{\rho_{IN}}
\end{aligned}
$$

since $\quad v = 1/\rho$

$$\delta W_{IN} = (P\ v\ \Delta m)_{IN} \quad \rightarrow \text{flow work} \tag{2}$$

Similarly

$$\delta W_{OUT} = (P\ v\ \Delta m)_{OUT} \tag{3}$$

Substituting Eqs. 2 and 3 into Eq. 1 gives the 1st law for a control volume

$$\begin{aligned} E_{CV}(t + \Delta t) - E_{CV}(t) &= \delta Q + \delta W_{shaft} + \Delta m_{IN}(e + Pv)_{IN} \\ &\quad - \Delta m_{OUT}(e + Pv)_{OUT} \end{aligned} \tag{4}$$

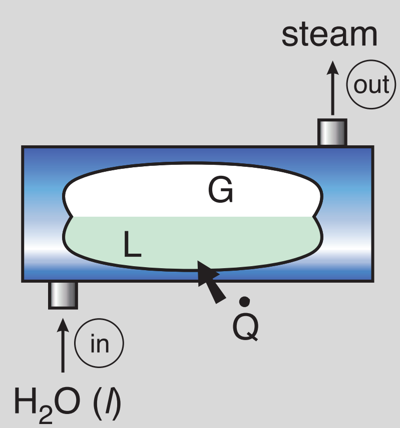
Equation 4 can also be written as a rate equation $\rightarrow$ divide through by Δt and take the limit as $\Delta t \rightarrow 0$

$$\frac{d}{dt} E_{CV} = \dot{Q} + \dot{W}_{shaft} + [\dot{m}(e + Pv)]_{IN} - [\dot{m}(e + Pv)]_{OUT}$$

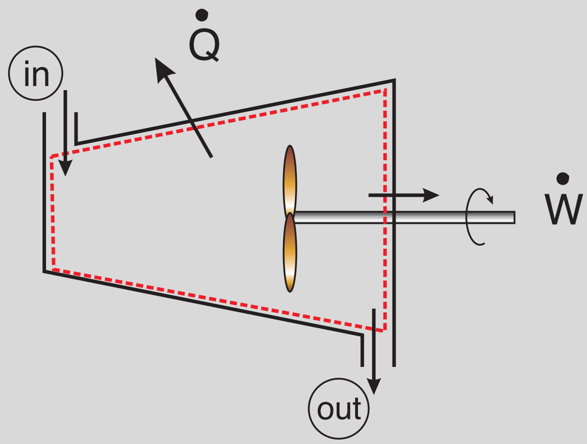
where:

$$\begin{aligned} e + Pv &= \underbrace{u + Pv} + \frac{(\mathcal{V})^2}{2} + gz \\ &= h(enthalpy) \ + \ KE \ + \ PE \end{aligned}$$

Example 3-3: Determine the heat flow rate, $\dot{Q}$, necessary to sustain a steady flow process where liquid water enters a boiler at $120\ °C$ and $10\ MPa$ and exits the boiler at $10\ MPa$ and a quality of 1 for a mass flow rate is $1\ kg/s$. The effects of potential and kinetic energy are assumed to be negligible.

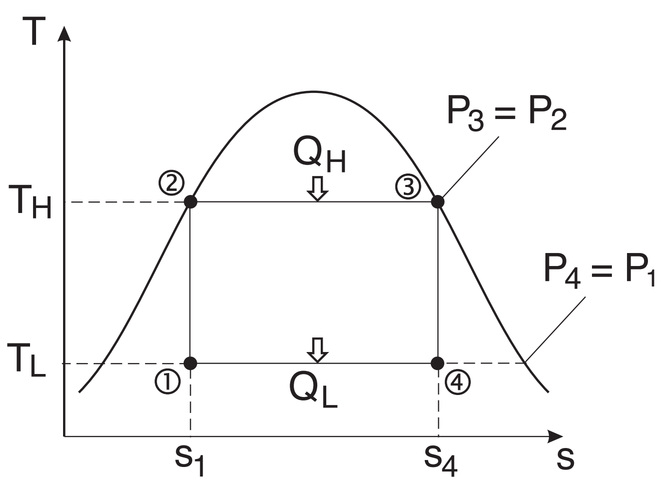


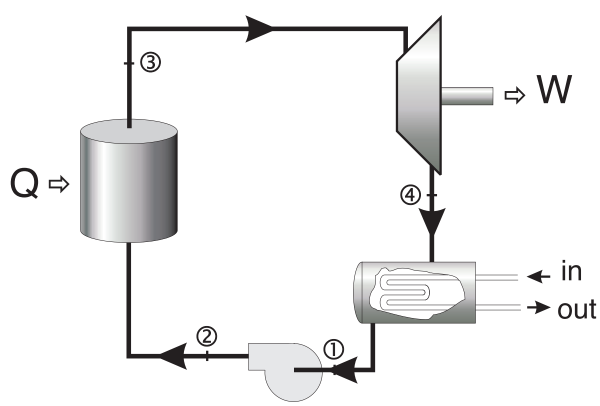
Example 3-4: Steam with a mass flow rate of $1.5\ kg/s$ enters a steady-flow turbine with a flow velocity of $50\ m/s$ at $2\ MPa$ and $350\ °C$ and leaves at $0.1\ MPa$, a quality of 1, and a velocity of $200\ m/s$. The rate of heat loss from the uninsulated turbine is $8.5\ kW$. The inlet and exit to the turbine are positioned $6\ m$ and $3\ m$ above the reference position, respectively. Determine the power output from the turbine.
Note: include the effects of kinetic and potential energy in the calculations.



The Carnot Cycle

If the heat engine is a reversible system where no entropy is generate internally, we refer to the cycle as the Carnot cycle.



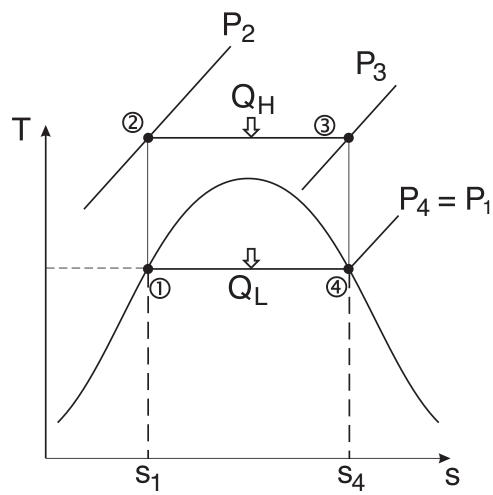


where the efficiency is given as:

$$\eta = 1 - \frac{T_L}{T_H} \quad \Leftarrow \quad \text{Carnot efficiency}$$

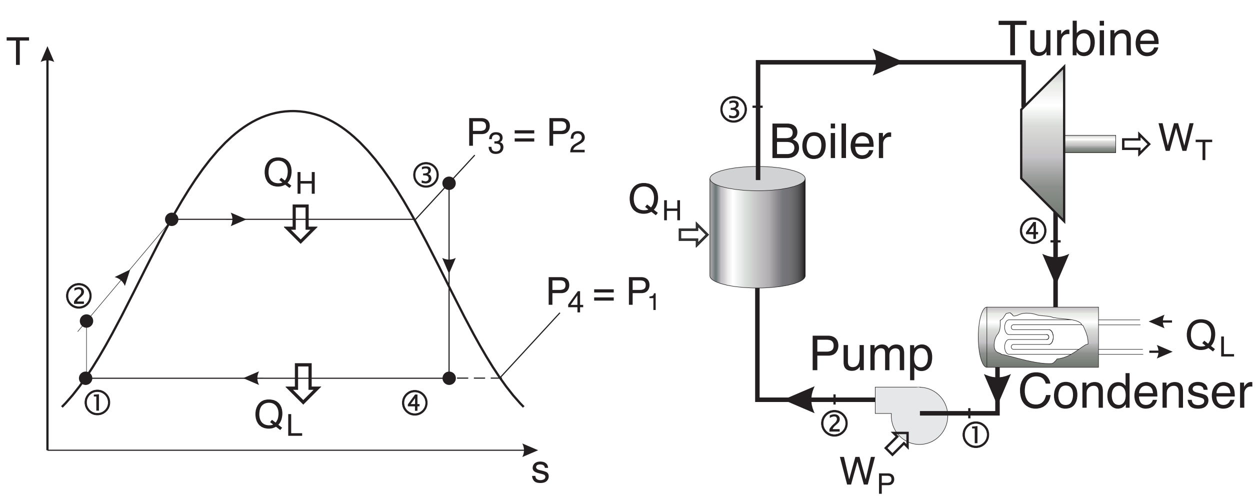
Practical Problems

- at state point 1 the steam is wet at T_L and it is difficult to pump water/steam (two phase) to state point 2
- can we devise a Carnot cycle to operate outside the wet vapor region



  - between state points 2 and 3 the vapor must be isothermal and at different pressures - this is difficult to achieve
  - the high temperature and pressure at 2 and 3 present metallurgical limitations

The Ideal Rankine Cycle



- water is typically used as the working fluid because of its low cost and relatively large value of enthalpy of vaporization

Device	1st Law Balance			
Boiler	$h_2 + q_H = h_3$	$\Rightarrow$	$q_H = h_3 - h_2$	(in)
Turbine	$h_3 = h_4 + w_T$	$\Rightarrow$	$w_T = h_3 - h_4$	(out)
Condenser	$h_4 = h_1 + q_L$	$\Rightarrow$	$q_L = h_4 - h_1$	(out)
Pump	$h_1 + w_P = h_2$	$\Rightarrow$	$w_P = h_2 - h_1$	(in)

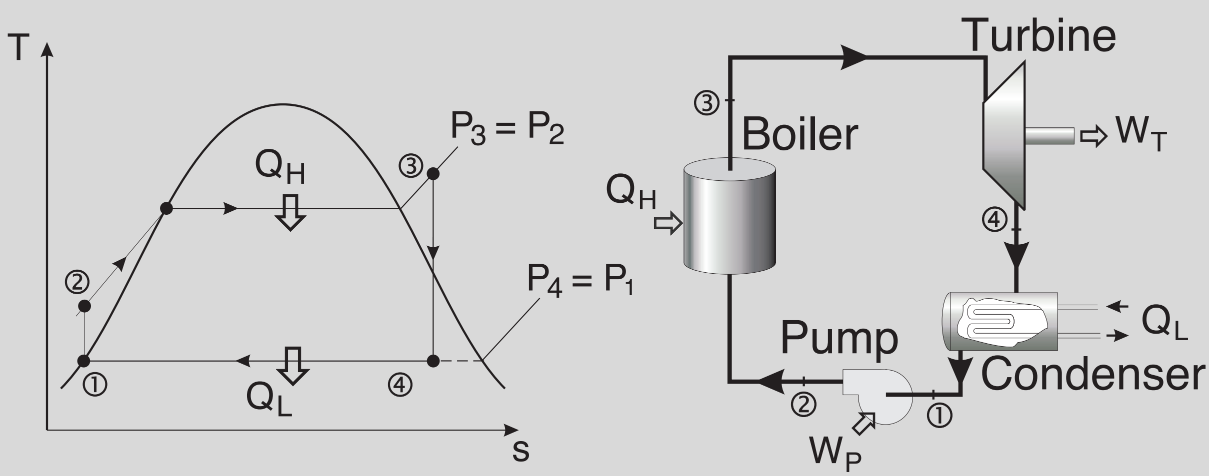
The net work output is given as

$$w_T - w_p = (h_3 - h_4) - (h_2 - h_1) = (h_3 - h_4) + (h_1 - h_2)$$

The Rankine efficiency is

$$\eta_R = \frac{net\ work\ output}{heat\ supplied\ to\ the\ boiler} = \frac{(h_3 - h_4) + (h_1 - h_2)}{(h_3 - h_2)}$$

Example 3-5: For the steam power plant shown below,



find: $\dot{Q}_H, \dot{Q}_L, \dot{W}_{net} = \dot{W}_T - \dot{W}_P$, and the overall cycle efficiency, η_R given the following conditions:

$P_1 = 10\ kPa$	$P_2 = 10\ MPa$
$P_3 = 10\ MPa$	$P_4 = 10\ kPa$
$T_1 = 40\ °C$	$T_3 = 530\ °C$
$T_2 = 110\ °C$	
$x_4 = 0.9$	$\dot{m} = 5\ kg/s$