Thermal Fluids Lab EML4304

First Cycle of Experiments

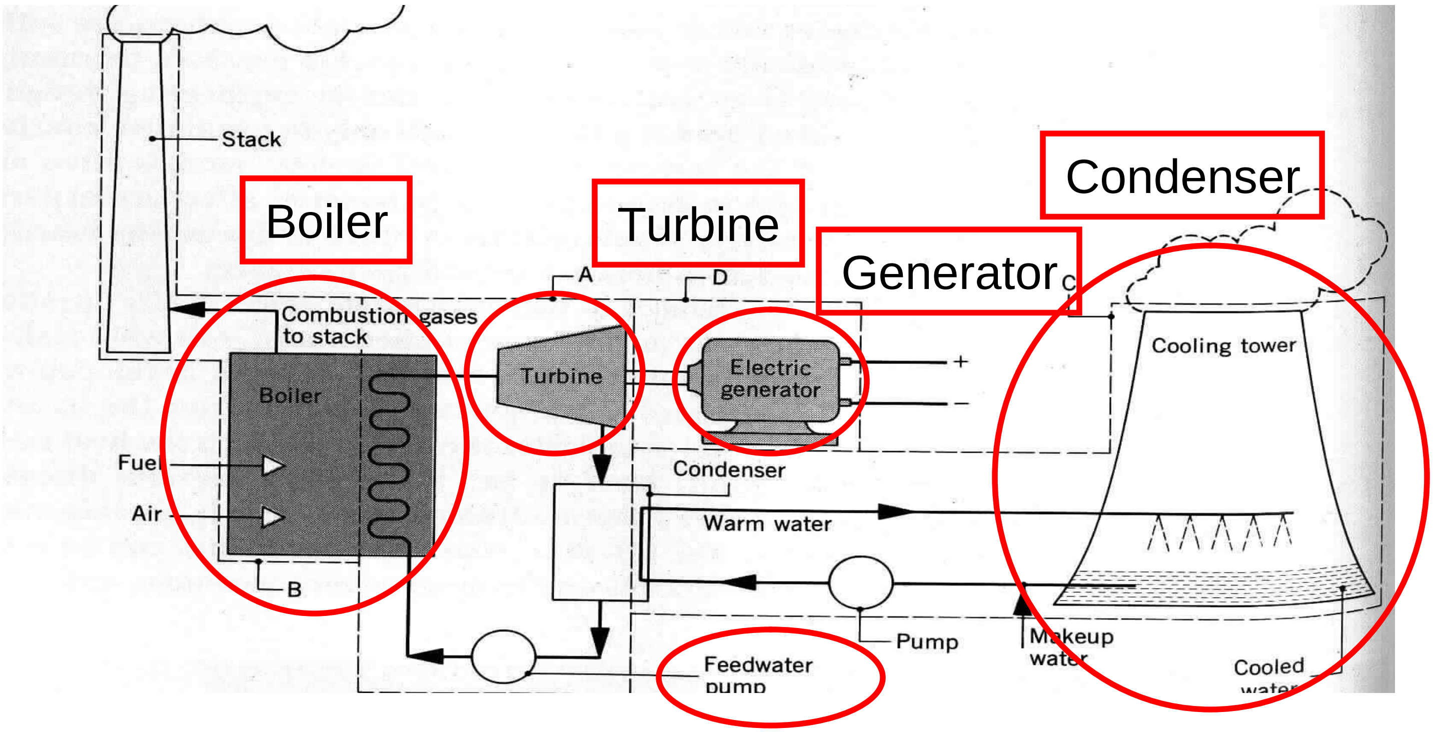
1. Properties of thermal radiation

2. Rankine cycler (Experiment on Rankine Cycle)

3. Extended surface heat transfer

4. Temperature sensors & their calibration

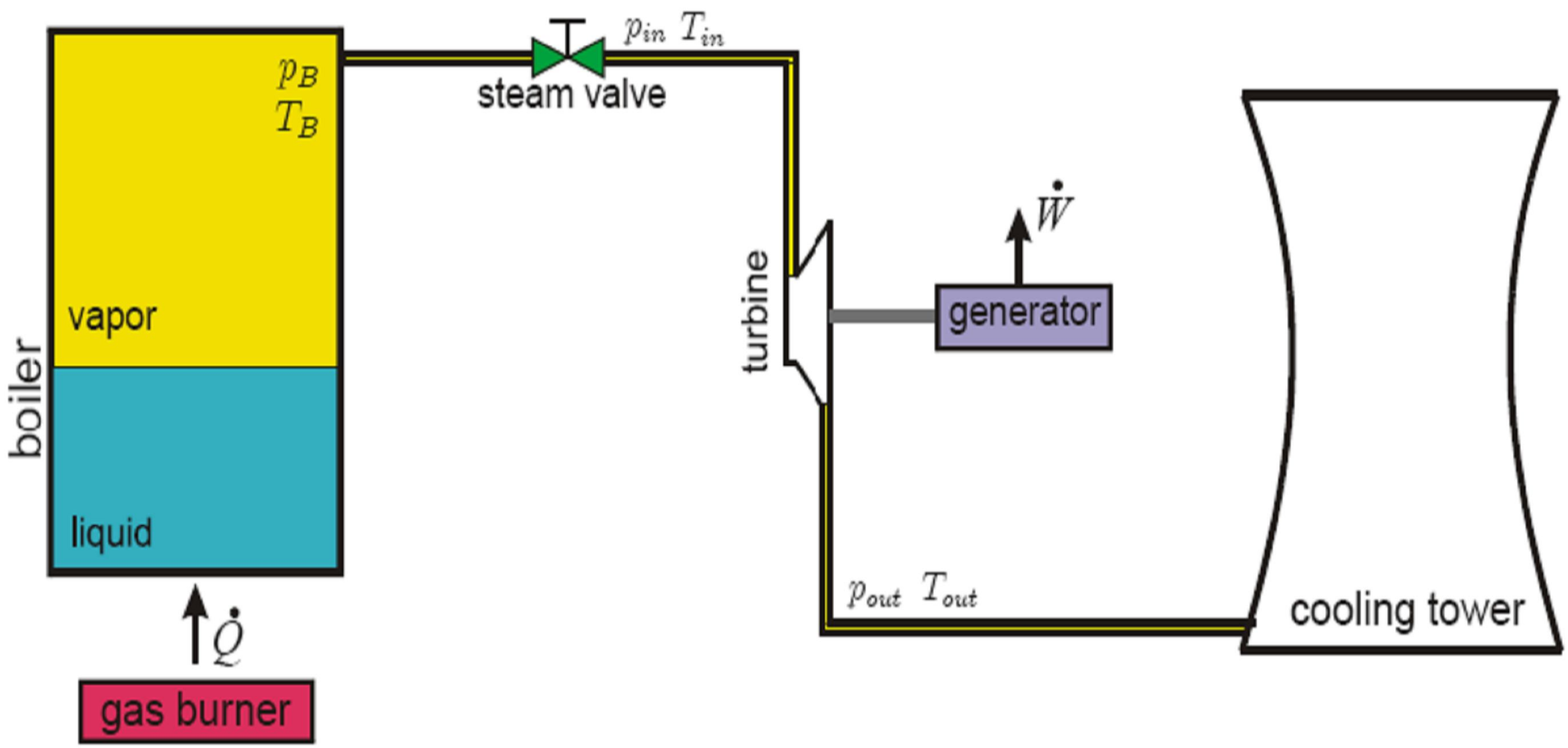
Expt.2 Experiments on Rankine Cycle Steam Power system



Simple Steam Vapor Power Plant

- **Expt. 2 models the working of a Rankine cycle steam power system**

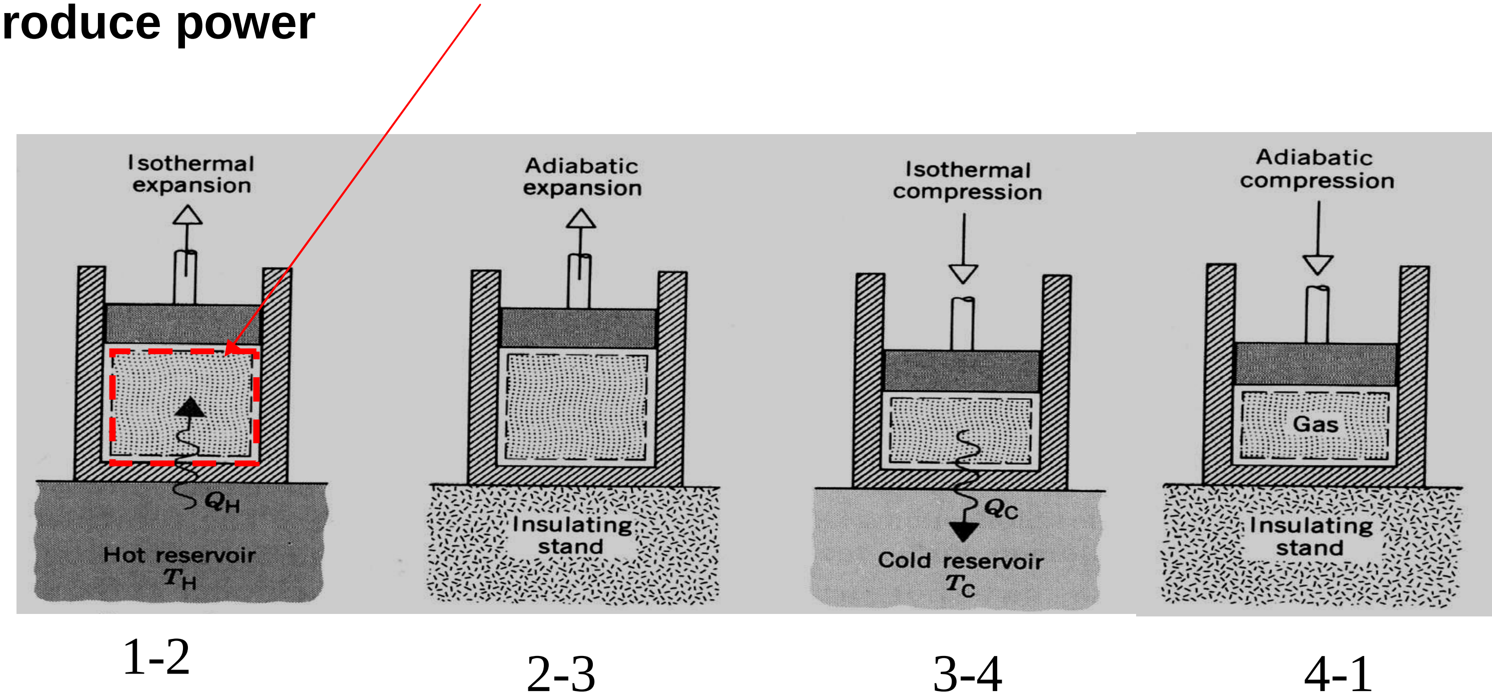
Rankine Cycle Experimental model



- **Turbine Technologies *Rankine Cycler* is a simplified model of a Rankine cycle steam power system**

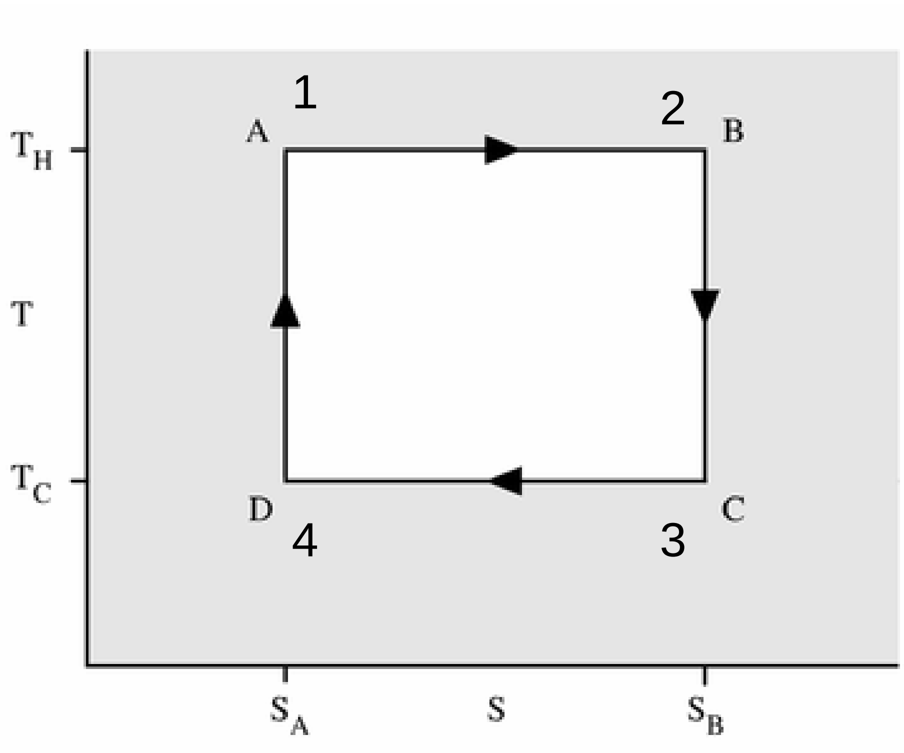
Review on power cycles -The Carnot Cycle

•In a power cycle a <u>working fluid</u> under go a thermodynamic cycle and produce power

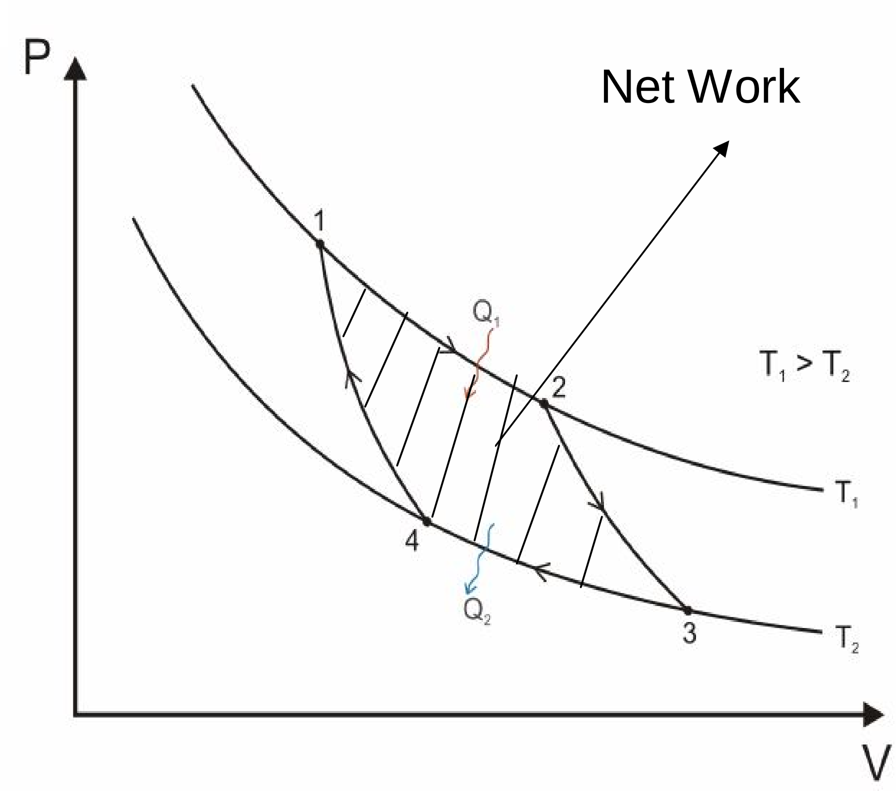


- Reversible isothermal expansion (1-2,A-B, T_H= constant)
- Reversible adiabatic expansion (2-3,B-C, Q = 0, $T_H \rightarrow T_C$)
- Reversible isothermal compression (3-4, C-D, T_L=constant)
- Reversible adiabatic compression (4-1,D-A, Q=0, $T_L \rightarrow T_C$)

Carnot Cycle T-s and p-v diagrams



T-s diagram



P-V diagram

Carnot Principles/ Corollaries

- The efficiency of an irreversible, i.e. a **real, heat engine,** **is always less than the efficiency of a reversible one operating between the same two reservoirs**.

Thermal Efficiency $_{irre}$ < Thermal Efficiency $_{rev}$

- The efficiencies of all reversible heat engines operating between the same two thermal reservoirs are the same.

(Thermal Efficiency $_{rev}$)A = (Thermal Efficiency $_{rev}$)**B**

$$\eta_{thermal} = \frac{W_{net}}{Q_H} = 1 - \frac{Q_L}{Q_H} = f(T_L, T_H)$$

$$We \ \ can \ \ show \ \ that \ \ \eta_{thermal} = 1 - \frac{T_L}{T_H}$$

$$\underline{This \ \ is \ \ carnot \ \ efficiency}$$

Power Cycles- Classification

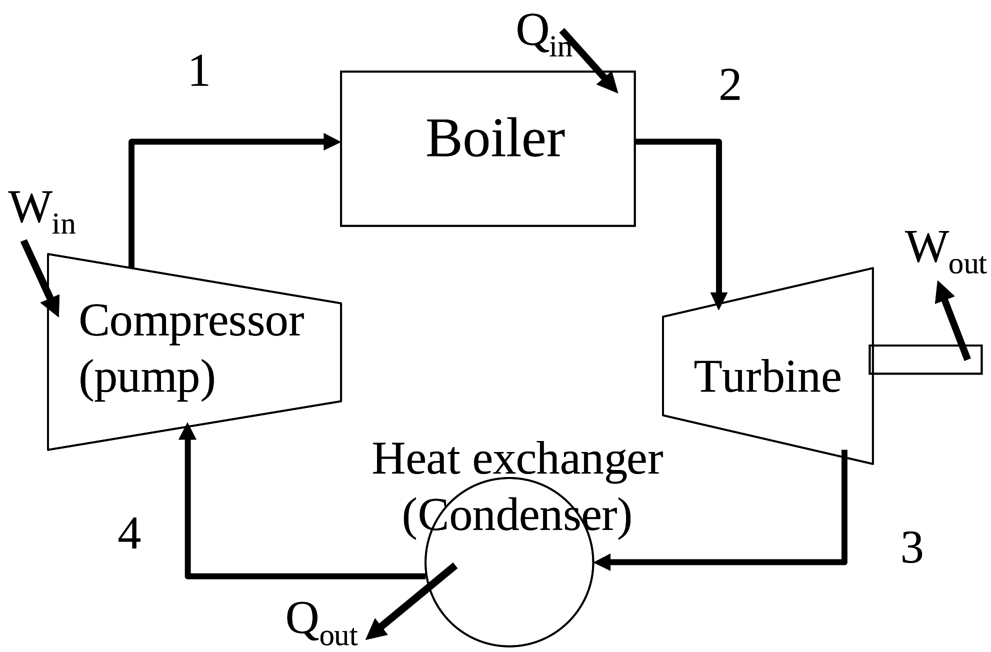
Vapor cycles – Working fluid in liquid and vapor phases in different portions of the cycle.

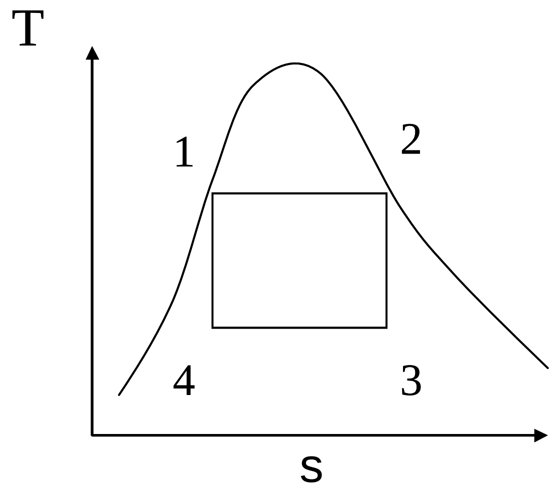
Gas cycles – Working fluid in gas phase in all portions of the cycle.

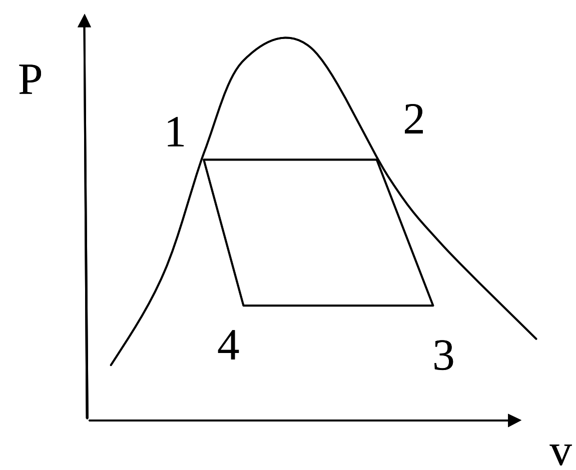
Closed cycles – The same working fluid is re-circulated through the entire cycle, I.e. the fluid undergoes a thermodynamic cycle. E.g. Steam Vapor Power Plants, the refrigerant in heat pumps and A/C's

Open cycles – The working fluid is replaced by new fluid at the end of each cycle, e.g. I.C. engines

A typical vapor Cycle







Ideal cycle Vs Real cycle

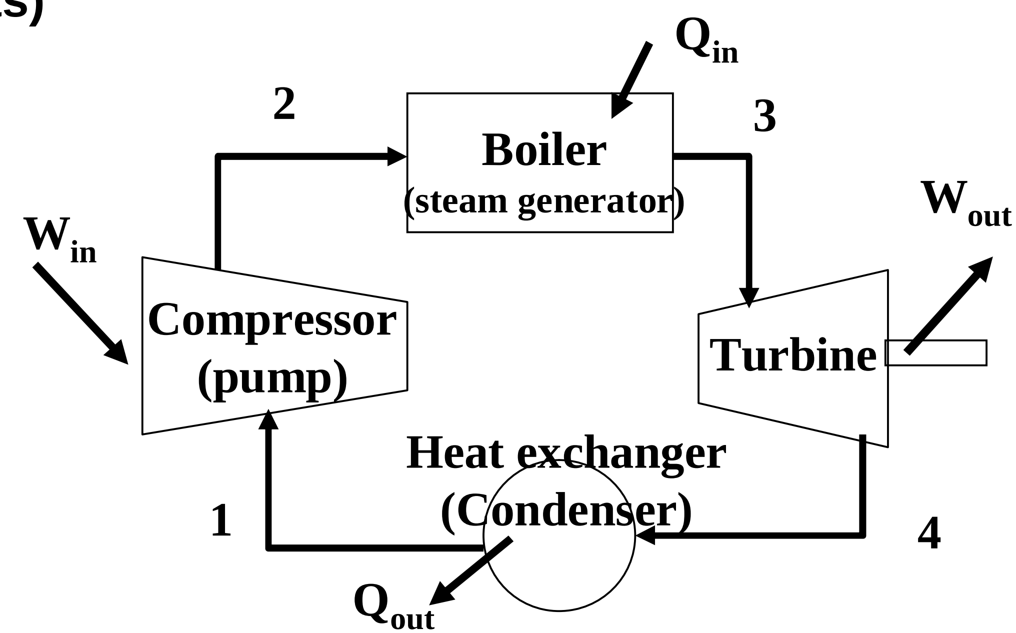
- **Most real devices operate on cycles which are usually very complex.**
- **We analyze such real devices by making *simplifying assumptions*, which lead to *idealized cycles***

- **Some common simplifying assumptions:**
- **All compression and expansion processes are reversible (quasi-equilibrium)**
- **Friction is negligible, i.e. no pressure losses in pipes, heat exchangers, etc.**
- **Perfect insulation, i.e. no heat losses in pipes or other components. (Note: this does not mean that there is no heat transfer transfer between the working fluid and thermal reservoirs)**
- **Changes in Kinetic energy and Potential energy usually neglected.**

- **What is the use of studying such idealized cycles ?**
- **They allow us to study the influence of major parameters on the behavior of real cycles.**
- **E.g. Increasing TH or decreasing TL will increase the efficiency of idealized and real cycles.**

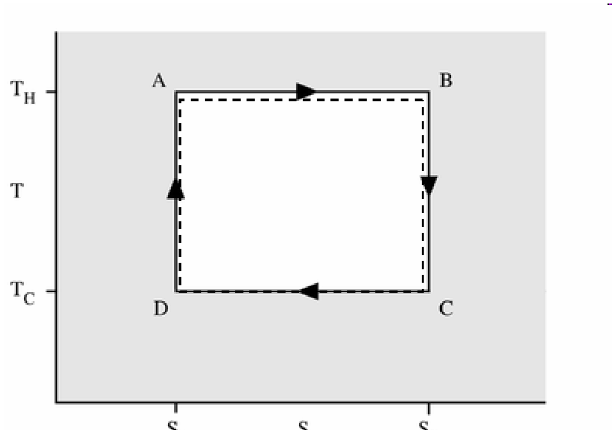
Rankine Cycle

- There are many practical issues using Carnot Cycle for power generation
  - Max. temperature limitation (Critical Temp, 374°C for water)
  - Isentropic process are not feasible
- A modified cycle can take care of those issues-Rankine Cycle
- All fluid exiting the turbine is condensed into liquid before reaching pump
- super heating of vapor will Increase thermal efficiency- reduce corrosion and/or erosion of turbine blades (due to the hitting of water droplets)



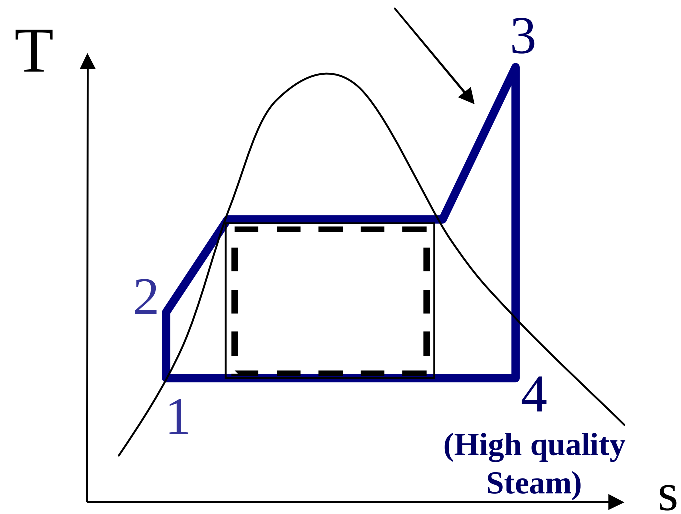
A typical vapor cycle

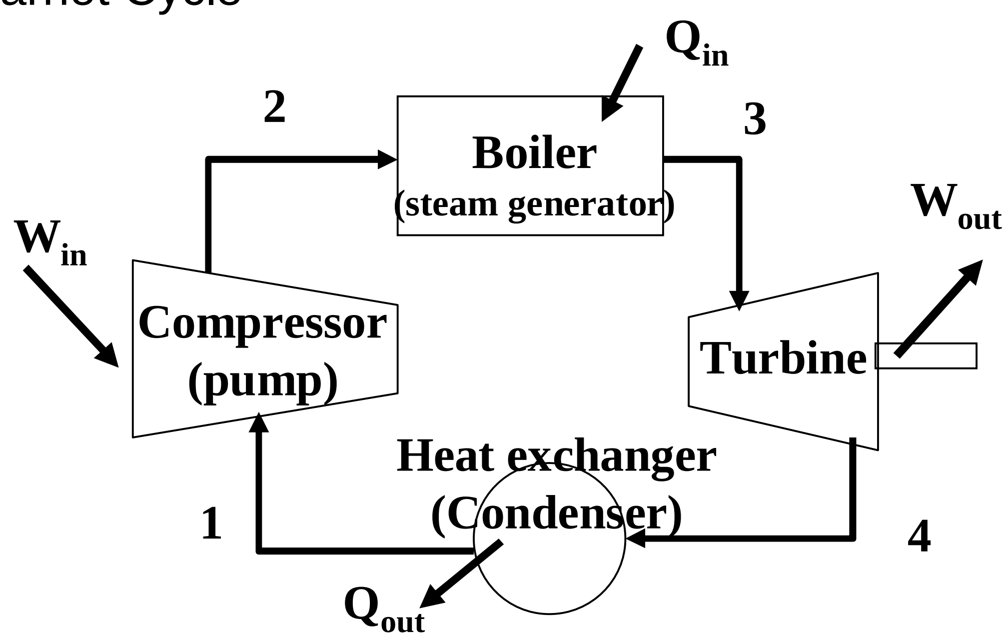
Carnot Cycle



Carnot Cycle

Rankine Cycle



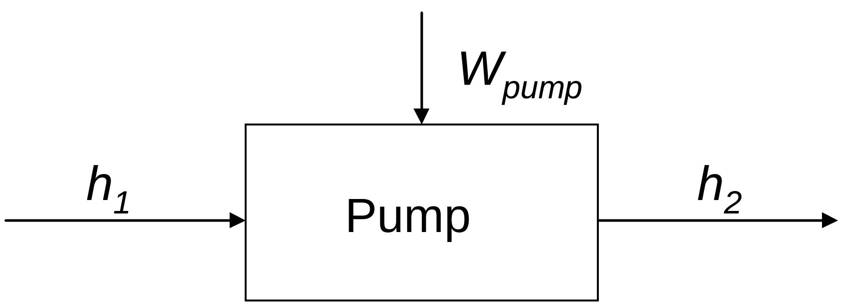


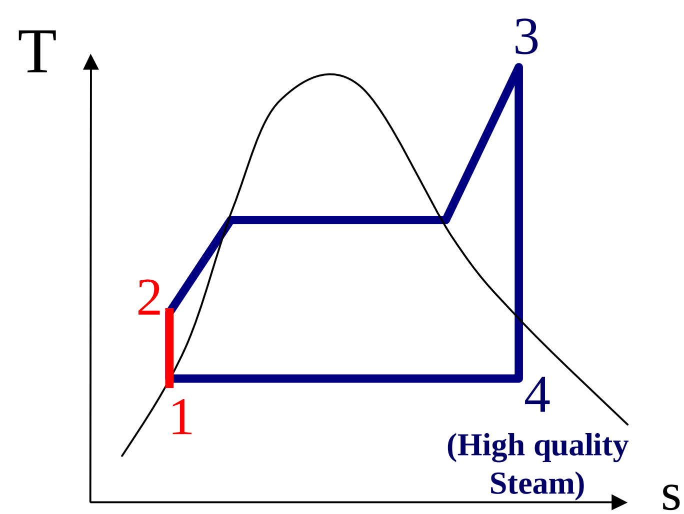
Rankine Cycle-Energy Analysis (Assume ideal processes)

- **Assumptions: steady flow process, no internal energy generation, neglect KE and PE changes for all four devices**

Steady flow energy equation for Pump

$$First\ \ Law\ \ \Rightarrow (q_{in} - q_{out}) - (W_{in} - W_{out}) + (h_{in} - h_{out}) = 0$$





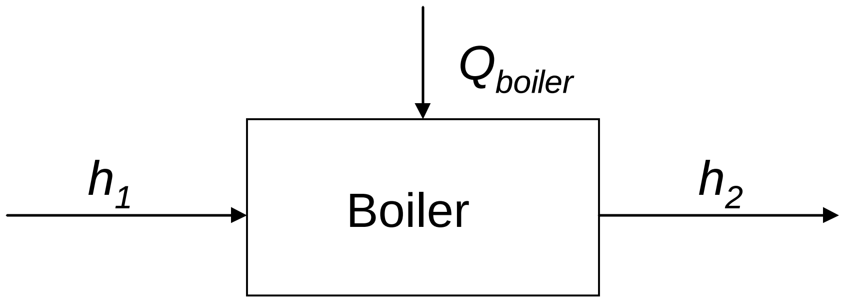
- 1-2: ***Pump*** *(q=0)*

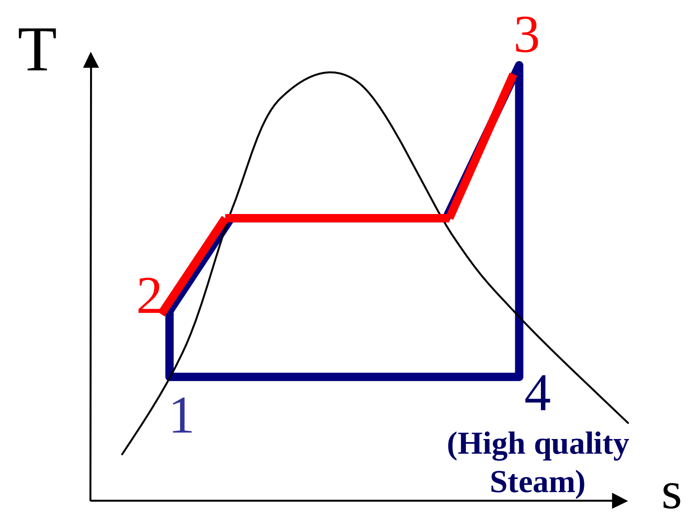
⇨ $W_{pump} = h_2 - h_1 = v(P_2 - P_1)$

h=u+pv dh=du+pdv+vdp

Steady flow energy Equation for Boiler

$$First\ \ Law\ \ \Rightarrow (q_{in} - q_{out}) - (W_{in} - W_{out}) + (h_{in} - h_{out}) = 0$$





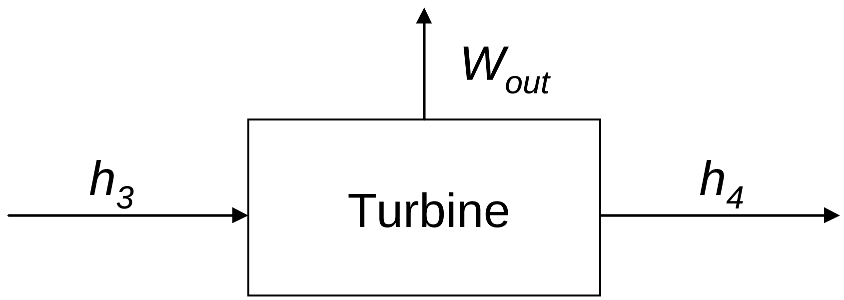
- 2-3: ***Boiler*** *(W=0)*

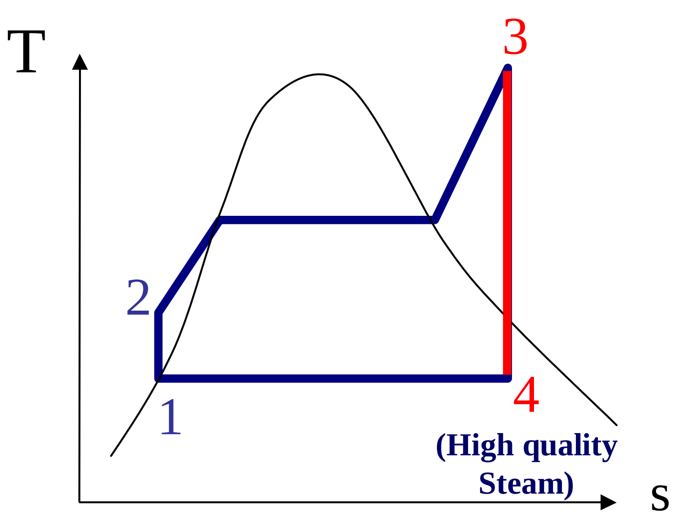
⇨ $Q_{boiler} = h_3 - h_2$

Energy input to the boiler (by fuel) in case of Rankine Cycler** = **(**m^o_{fuel}. HV_{fuel}**)

Steady flow energy Equation for Turbine

$$First\ \ Law\ \ \Rightarrow (q_{in} - q_{out}) - (W_{in} - W_{out}) + (h_{in} - h_{out}) = 0$$



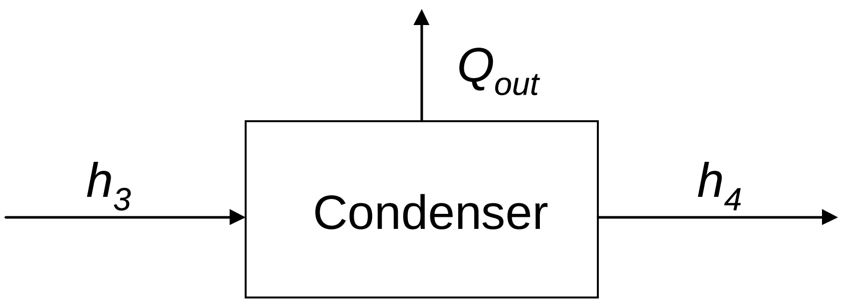


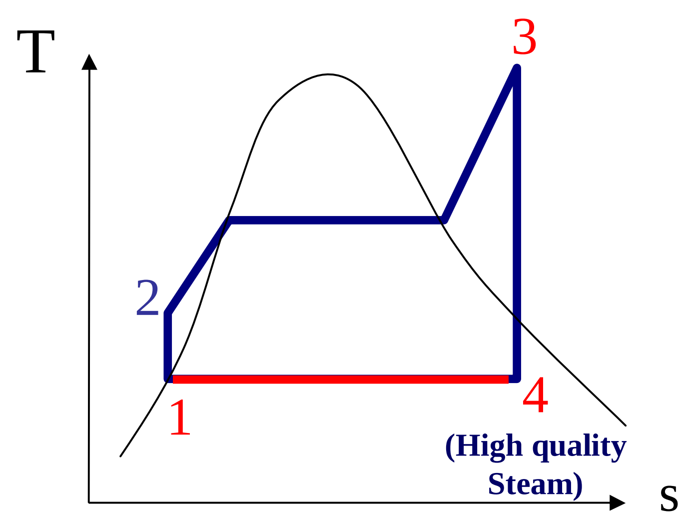
- 3-4: ***Turbine*** *(q=0)*

⇨ $W_{out} = h_3 - h_4$

$$First\ \ Law\ \Rightarrow (q_{in} - q_{out}) - (W_{in} - W_{out}) + (h_{in} - h_{out}) = 0$$

Condenser

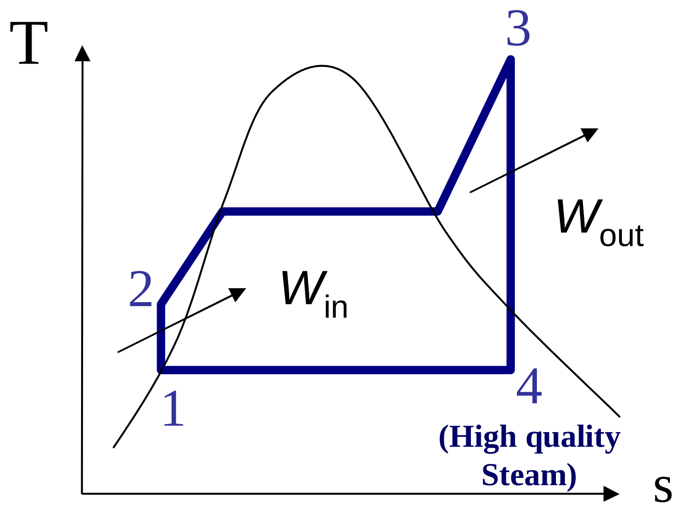




- 4-1: ***Condenser*** *(W=0)*

⇨ $Q_{out} = h_4 - h_1$

Thermal efficiency- Rankine Cycle



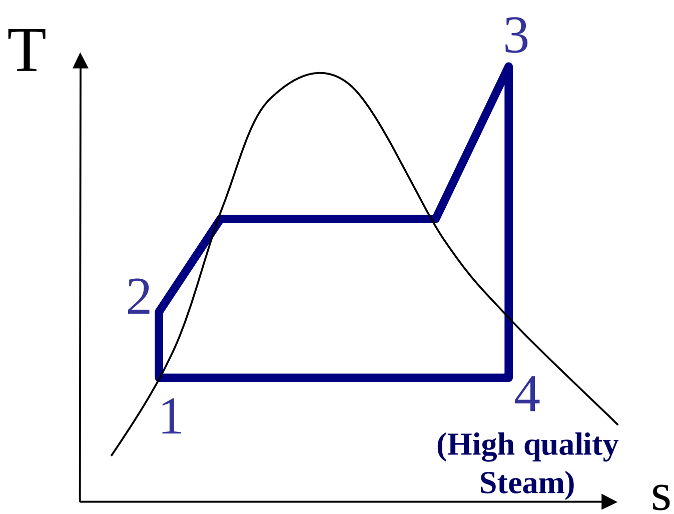
$$W_{net} = W_{out} - W_{in} = (h_3-h_4) - (h_2-h_1)$$

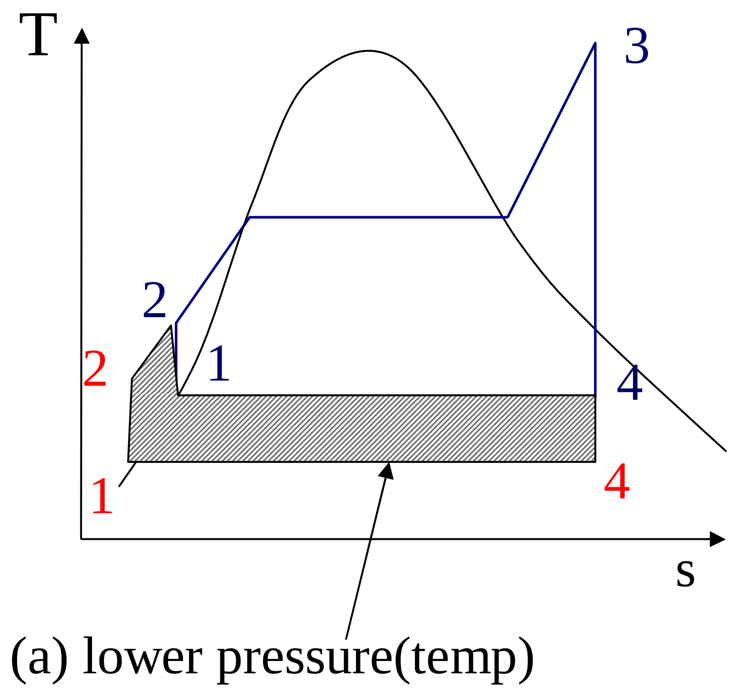
Thermal efficiency $\acute{\eta} = W_{net}/q_{in} = 1 - q_{out}/q_{in} = 1 - (h_4-h_1)/(h_3-h_2)$

Thermal Efficiency – How to enhance it?

Thermal efficiency can be improved by manipulating the temperatures and/or pressures in various components

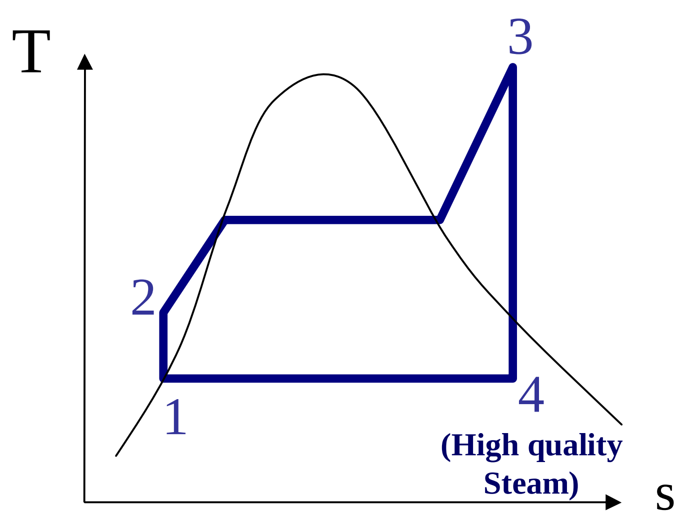
(a) Lowering the condensing pressure (*lowers T_L, but decreases quality, x_4* **)**

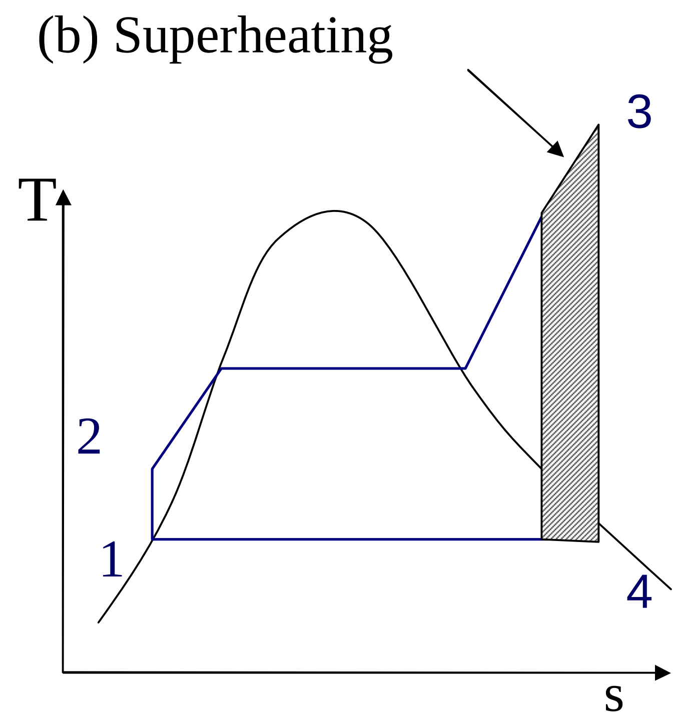




Thermal Efficiency – How to enhance it?

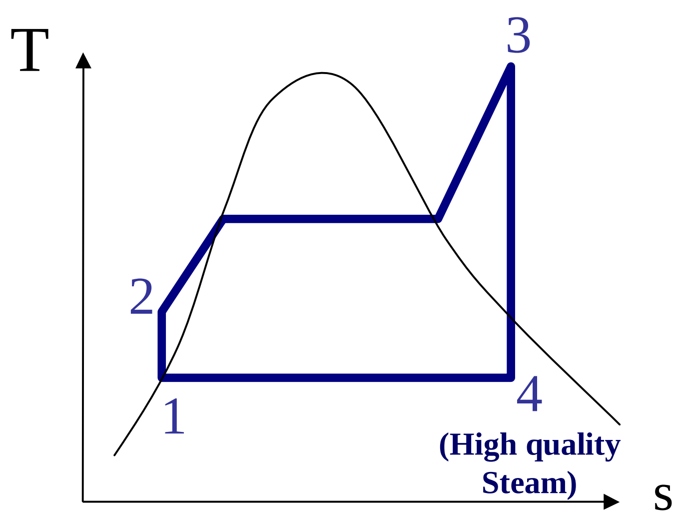
(b) Superheating the steam to a *higher temperature* (*increases T_H but requires higher temp materials*)

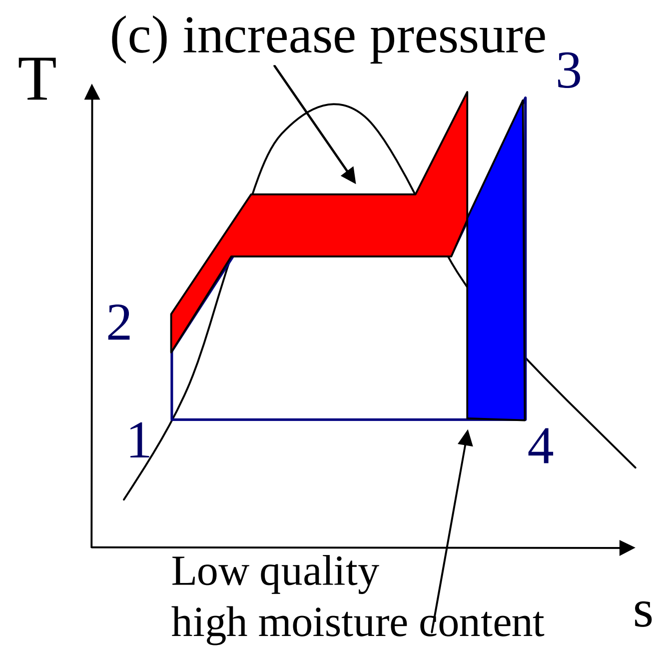




Thermal Efficiency – How to enhance it?

(c) Increasing the boiler pressure (*increases T_H but requires higher temp/press materials*)

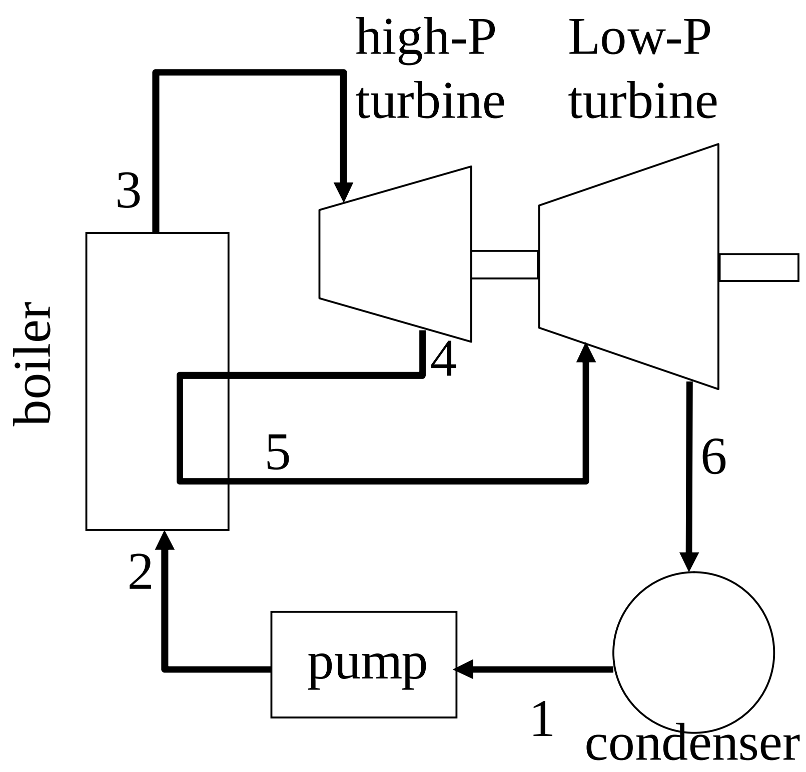


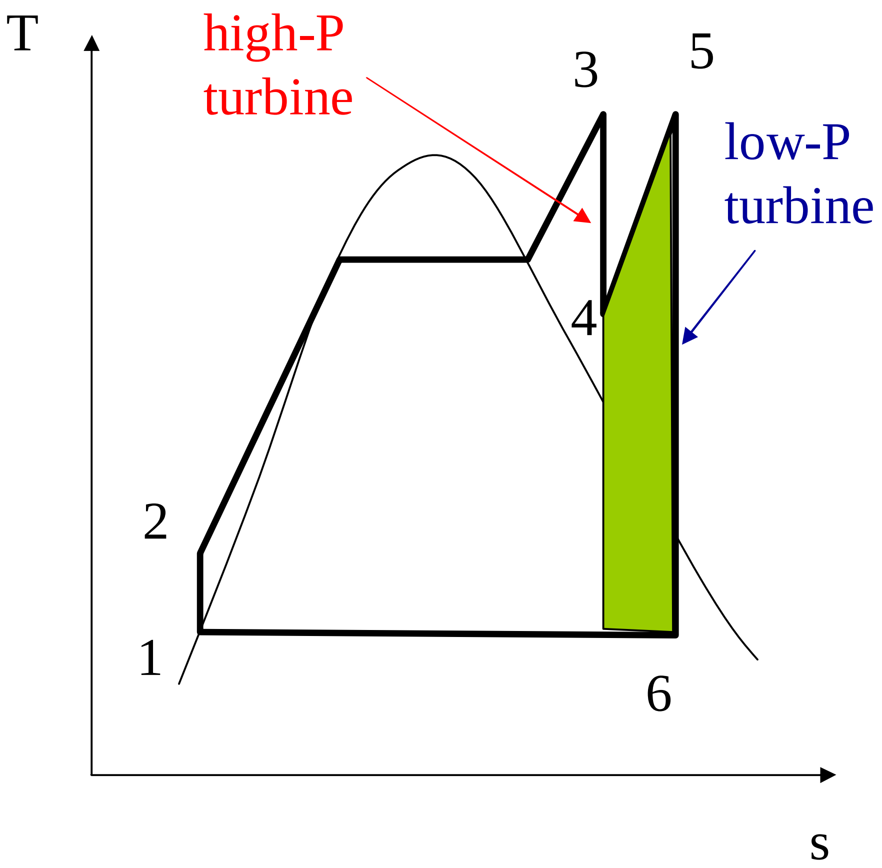


Red area = increase in W net
Blue area = decrease in W net

<u>Reheating</u>

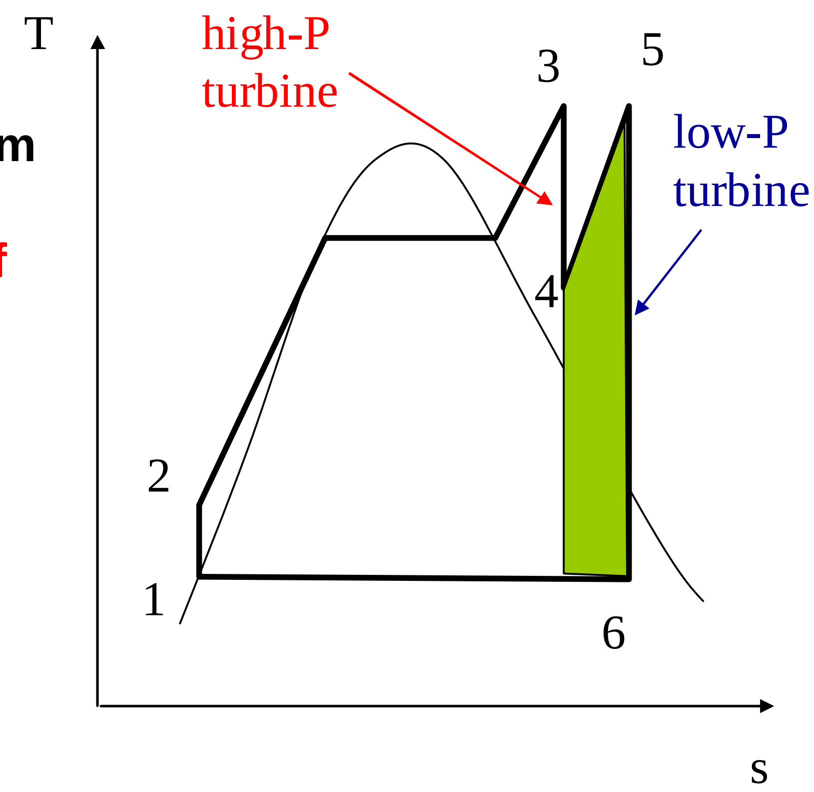
- **The optimal way of increasing the boiler pressure *without increasing the moisture content* in the exiting vapor is to *reheat* the vapor after it exits from a first-stage turbine and *redirect this reheated vapor into a second turbine*.**





Reheat Rankine Cycle

- Reheating allows one to increase the boiler pressure **without increasing the moisture content** in the vapor exiting from the turbine.
- By reheating, **the average temperature of the vapor entering the turbine is increased**, thus, it increases the thermal efficiency of the cycle. **Why?**
- Multistage reheating is possible but not practical. One major reason is because the vapor exiting will be superheated vapor at higher temperature, thus, decrease the thermal efficiency. ***Why***?

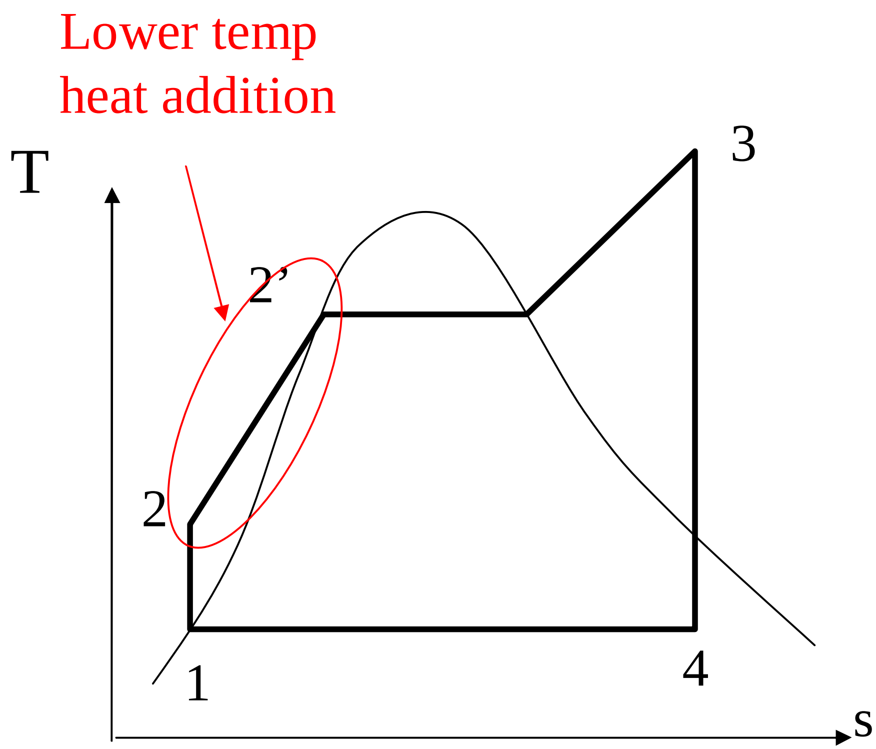


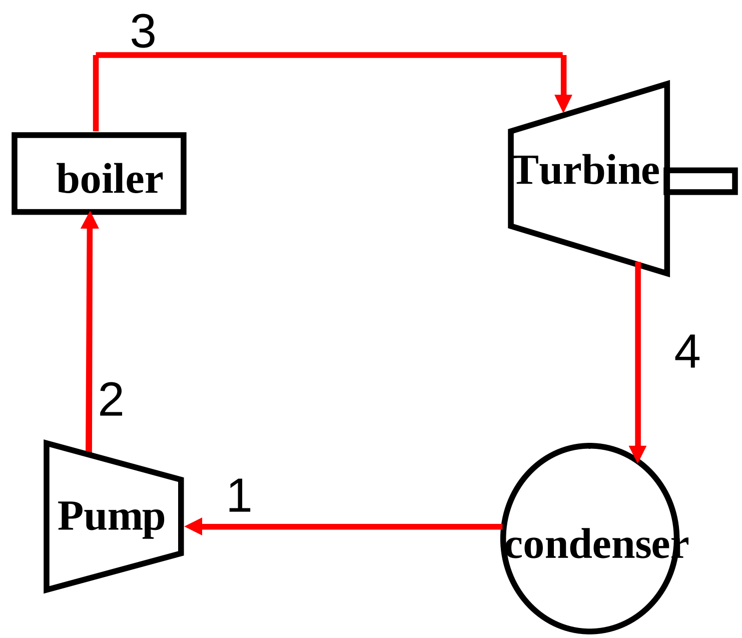
Energy analysis: Heat transfer and work output both change

$$q_{in} = q_{primary} + q_{reheat} = (h_3-h_2) + (h_5-h_4)$$

$$W_{out} = W_{turbine1} + W_{turbine2} = (h_3-h_4) + (h_5-h_6)$$

Regeneration

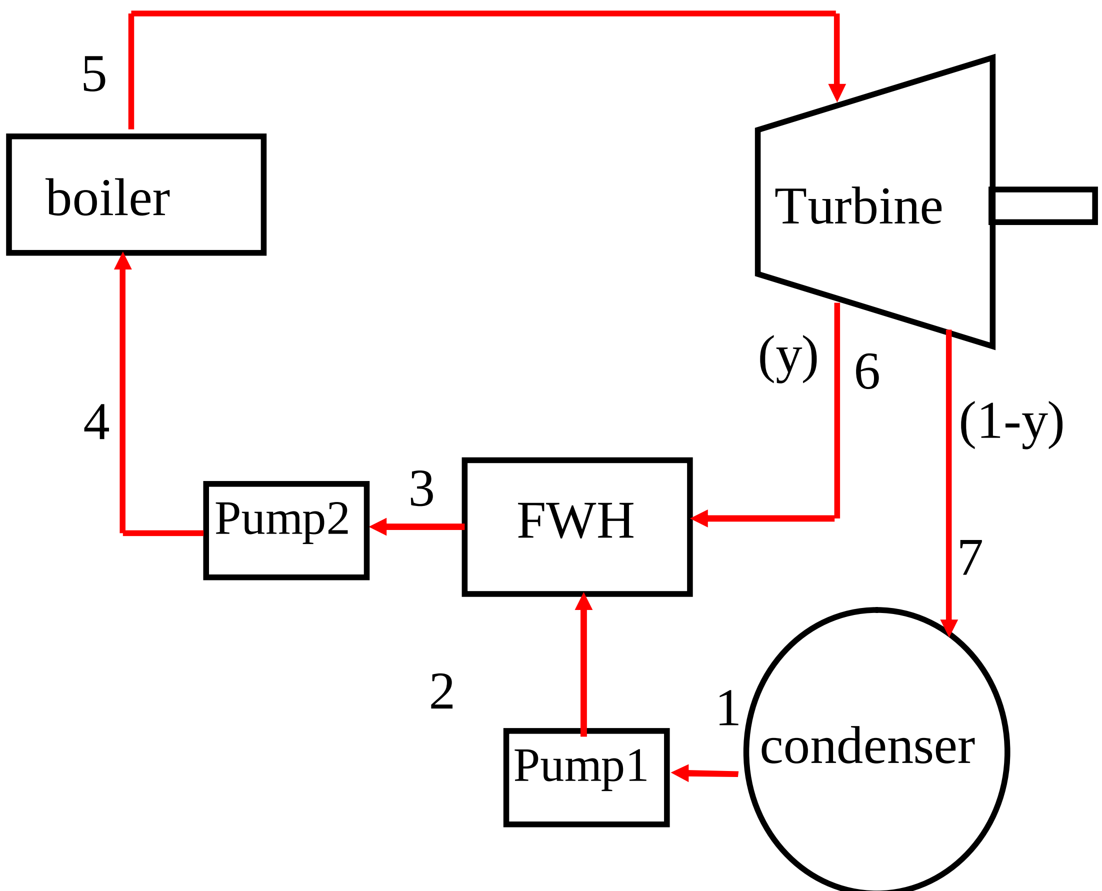




- **From 2-2', the average temperature is very low, therefore, the heat addition process is at a lower temperature and therefore, the thermal efficiency is lower. Why?**
- **Use a *regenerator* to heat the liquid (feed water) leaving the pump before sending it to the boiler. This increases the average temperature during heat addition in the boiler, hence it increases efficiency.**

Regenerative cycle

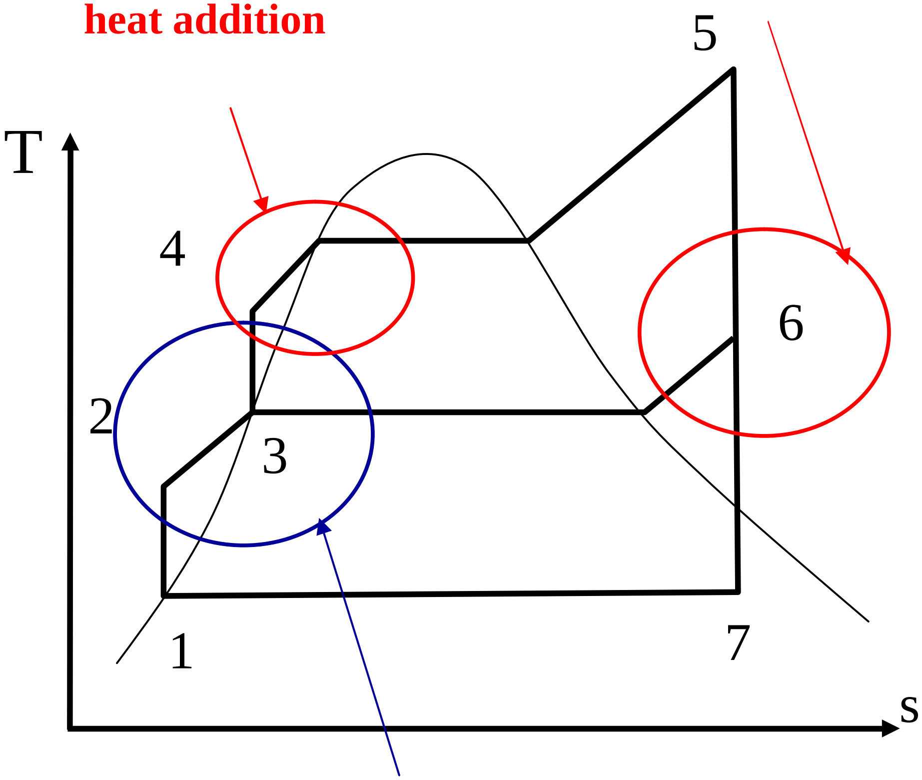
FWH- Feed water heater

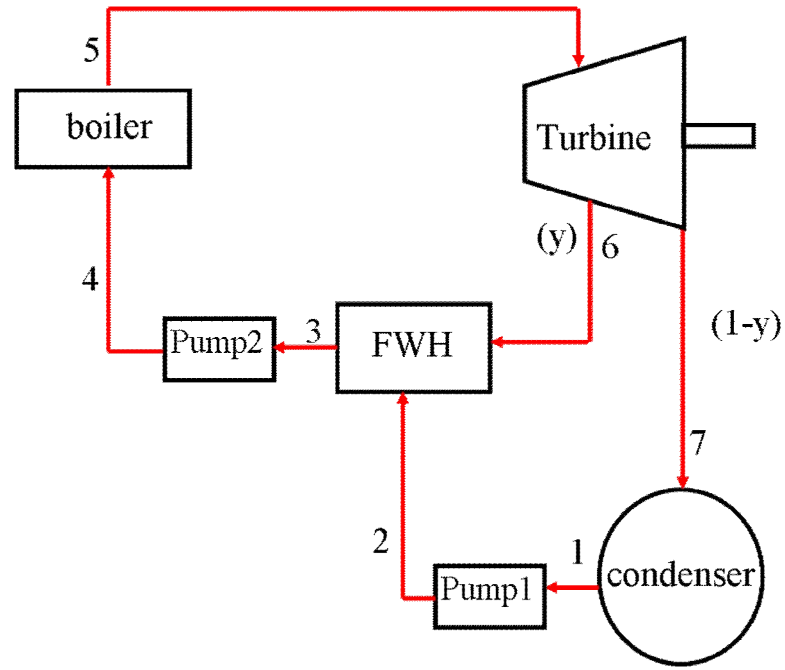


- **Improve efficiency by increasing feed water temperature before it enters the boiler.**
- **Two Options:**
  - **Open feed water : Mix steam with the feed water in a mixing chamber.**
  - **Closed feed water: No mixing.**

Extract steam @ 6
From turbine to provide
heat source in the
regenerator

higher temp
heat addition





Use regenerator to heat up the feed water

Regenerative Cycle - Analysis

- **Assume *y* percent of steam is extracted from the turbine and is directed into open feed water heater.**

- **Energy analysis:**

  $q_{in} = h_5 - h_4, \quad q_{out} = (1-y)(h_7 - h_1),$

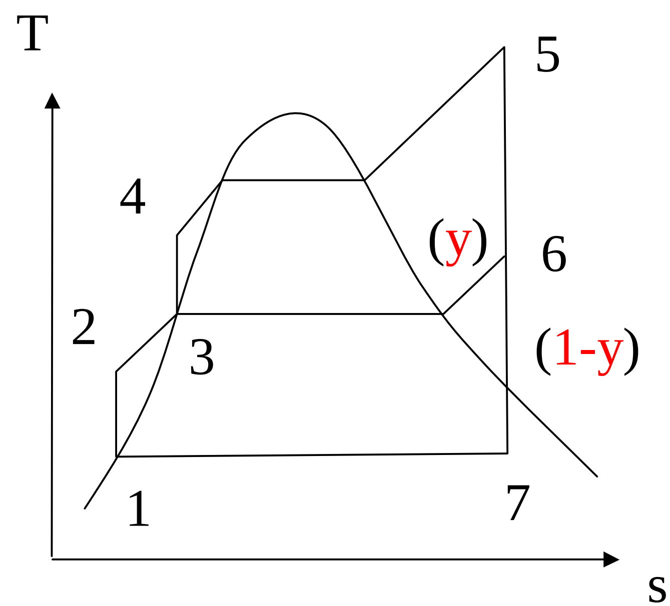
  $W_{turbine,\ out} = (h_5 - h_6) + (1-y)(h_6 - h_7)$

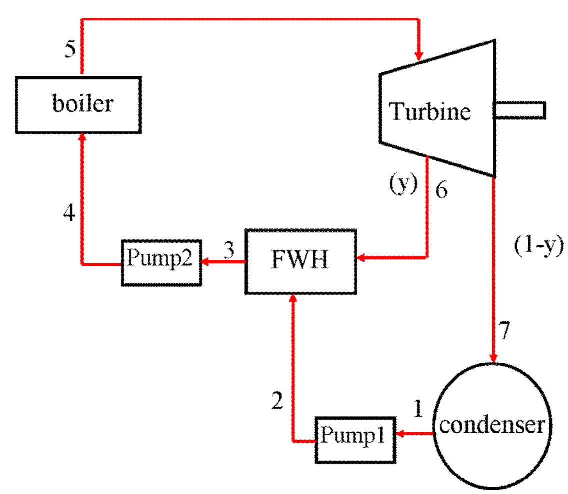
  $W_{pump,\ in} = (1-y)W_{pump1} + W_{pump2}$

  $= (1-y)(h_2 - h_1) + (h_4 - h_3)$

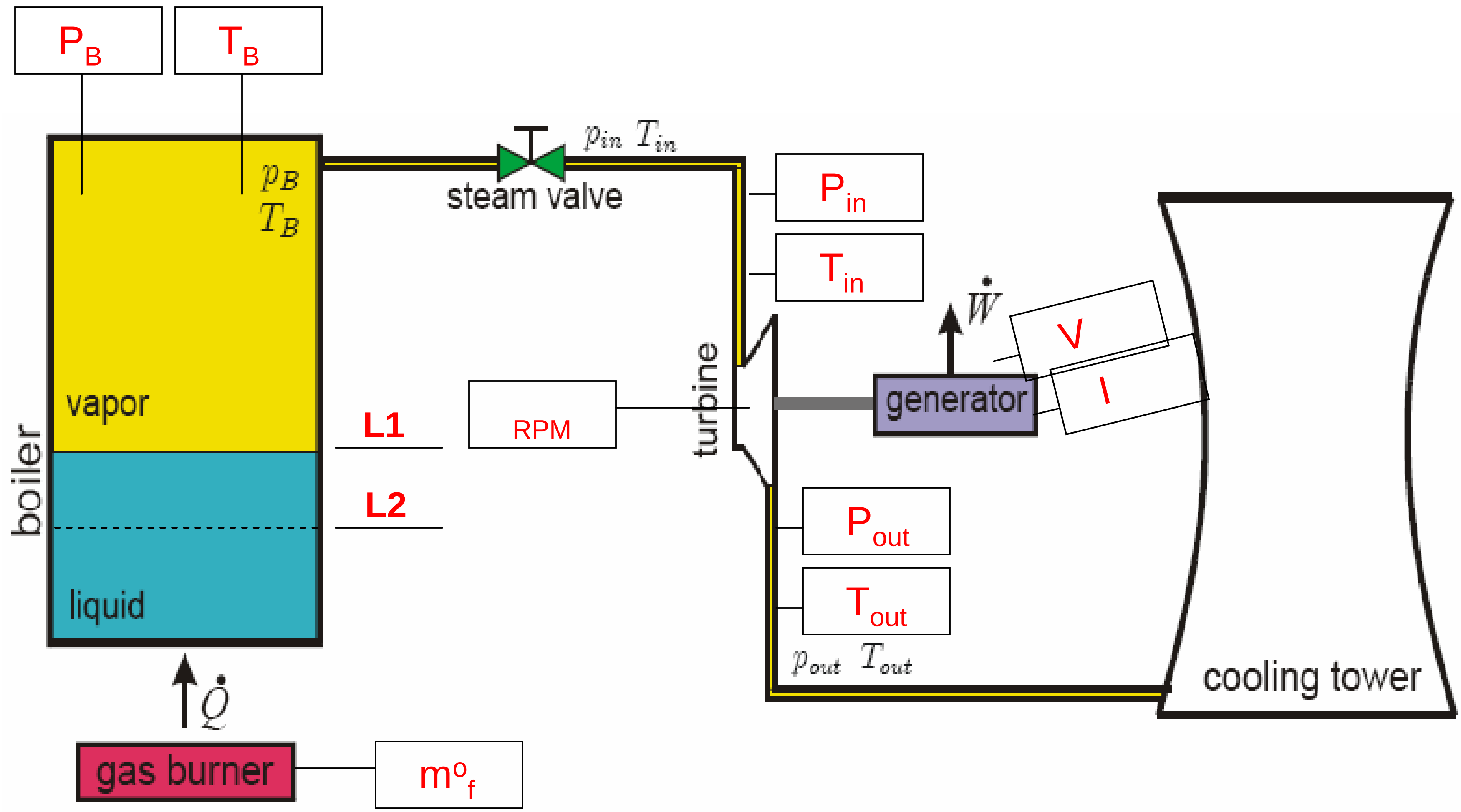
  $= (1-y)v_1(P_2 - P_1) + v_3(P_4 - P_3)$

- **In general, more feed water heaters result in higher cycle efficiencies.**





Rankine Cycle Experiment- Measurements



Measure 10 variables directly.
Also measure steam flow rate m^o_{steam} (by measuring the amount of water used)
And rate of condensation (by measuring the amount of water condensed.

Rankine Cycle – Questions to consider/answer

Plot the following parameters as a function of time:

Boiler Pressure, Boiler temperature, Turbine inlet and output temperature (on one same graph)
Turbine inlet and output pressure (on one same graph),
Generator current (load, Generator voltage
Turbine RPM, Fuel flow rate

On the plots above identify the beginning and the end of the steady state process

From the steady state run data plot identify the steady state system parameters for the analysis.
Record these into the data sheet provided.

Calculate the heat transferred from the boiler during the SS process based on the boiler temp & pressure.

Do **the same using the fuel rate**; compare the two and comment on the agreement and/or discrepancy.

Calculate the actual work produced by the turbine.

Using this, determine the efficiency of "Rankine Cycler" based on the total fuel consumed.

Calculate the overall efficiency based on the amount of steam produced. Discuss and compare this value with that of an actual steam power plant.

Find out the efficiency of condenser.

Find the overall efficiency of the Rankine Cycler steam turbine system. How does the performance of the turbine and the entire system change with applied load and boiler pressure