

Overview power plant design

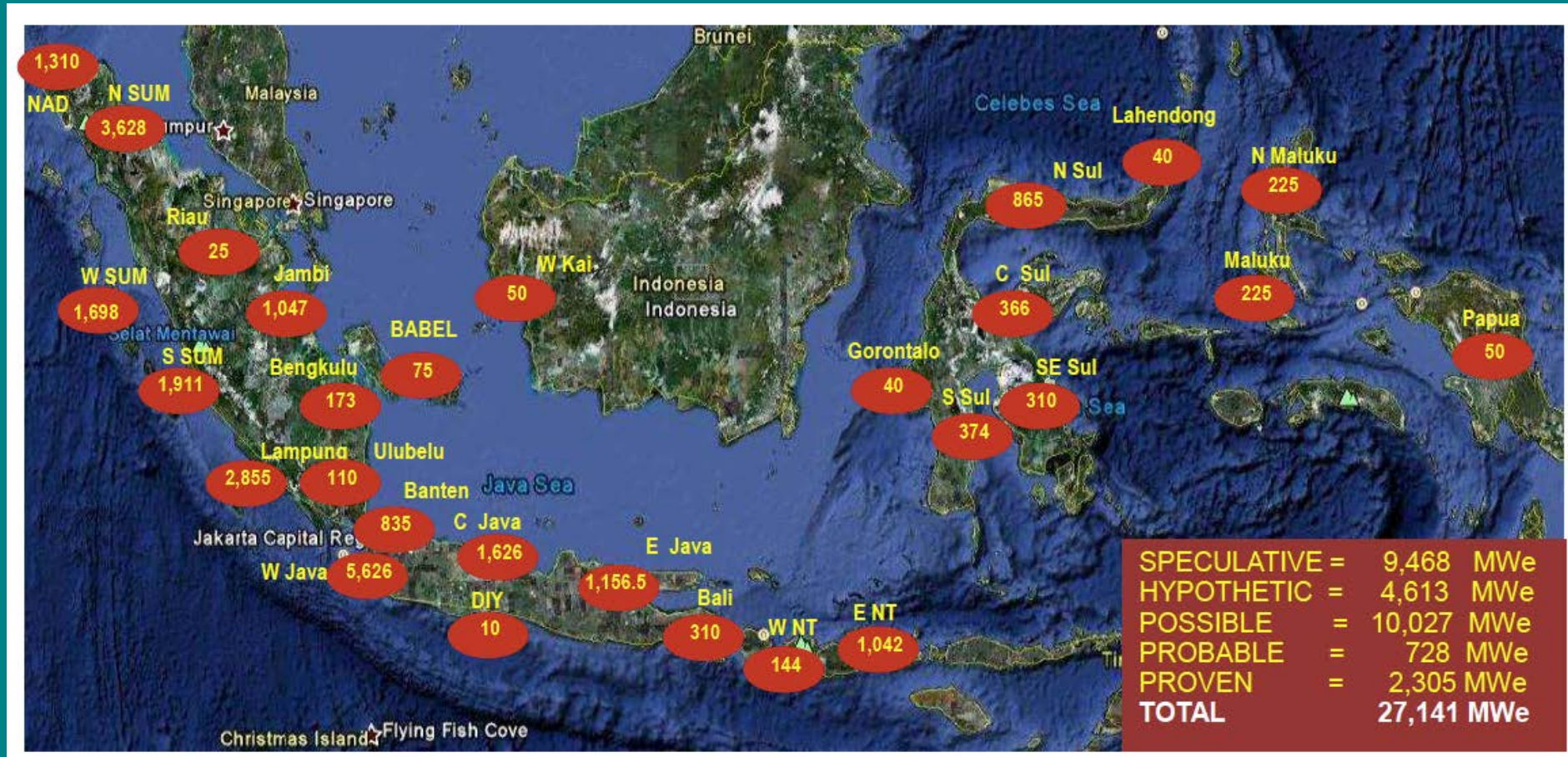
Workshop for inspectors – Method and Techniques in Geothermal Power Plant inspection

Theo van der Meer

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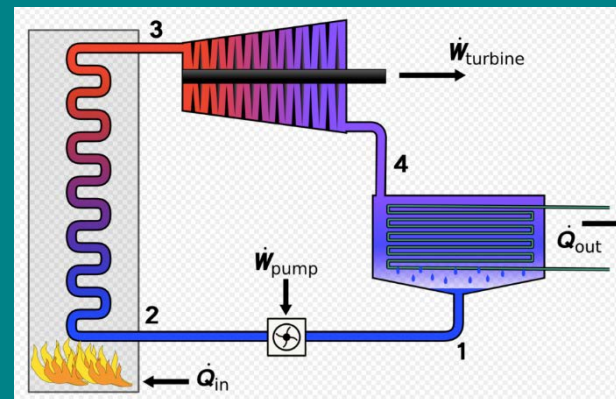
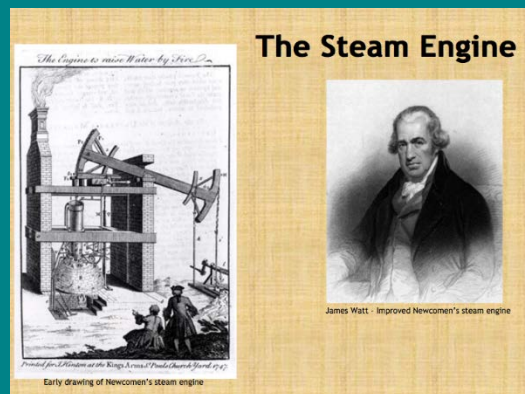
- List of Geothermal Power Plants in Indonesia
- Basic thermodynamics, 1st, 2nd law, efficiencies, exergy,
- The Rankine cycle
- Organic Rankine Cycle
- Dry, flash and binary cycles

List of Geothermal Power Plant in Indonesia

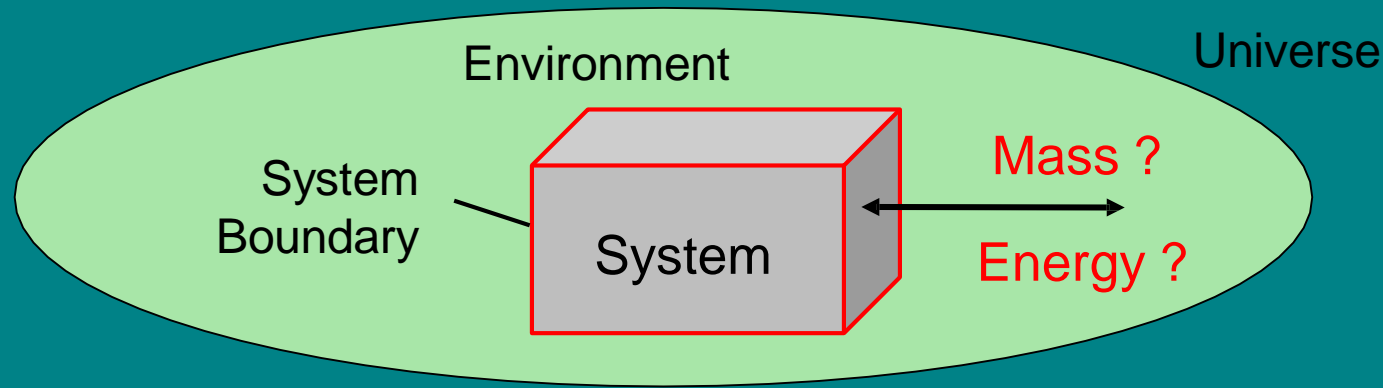


Thermodynamics – what is it?

- Source in Thermodynamics, a branch of physics and chemistry studying the effects of changes in temperature, pressure and volume on physical systems at a macroscopic scale
- Thermodynamics from the Greek: *therme* - 'heat' and *dunamis* - 'power'
- **Thermodynamics = science on using heat and power**



Systems and its boundaries

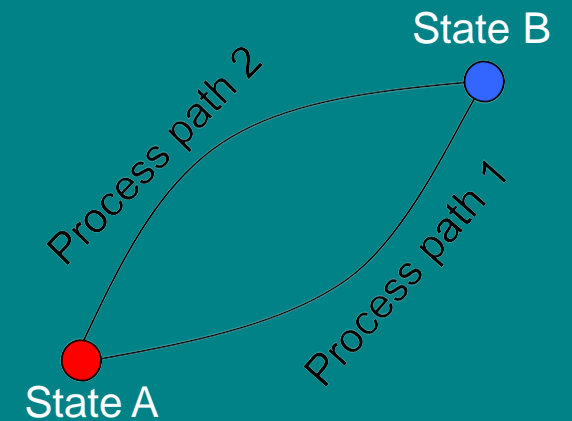


Based on the transport of mass and energy across the system boundary (rigid deformable or moveable) following system can be distinguished

- Open (Mass and energy can cross the boundary)
- Closed (Only energy can cross the boundary)
- Isolated (No mass or energy can cross the boundary)

Process

- If the value of even one of the properties changes, the system will change to a different state, this change is called a **process**.
- Several commonly studied thermodynamic processes are:
 - Isothermal: constant temperature ($\Delta T=0$)
 - Isobaric: constant pressure ($\Delta P=0$)
 - Isometric or isochoric: constant volume ($\Delta v=0$)
 - Isentropic: constant entropy ($\Delta s=0$)
 - Isenthalpic: constant enthalpy ($\Delta h=0$)
 - Adiabatic: no heat transfer ($q=0$)



Total energy, work, heat, energy transfer

- The **total energy** of a system consists of the sum of all forms of energy:
- $E = U + KE + PE + \dots$ [J] or per unit mass: $e = E/m = u + ke + pe + \dots$ [J/kg]
- The energy of a system can change by **transferring energy** across the boundary by:
 - Work (W [J] or w [J/kg])
 - Heat (Q [J] or q [J/kg])
 - Mass (only in open systems, see next slide)
- **Work:** energy transferred as a force acts on the system through a distance, e.g. compression work: $\delta w = F ds = P dv$
- **Heat:** energy crossing the system boundary because of a temperature difference between the system and the surroundings, spontaneously the energy always goes from high to low temperature

Energy change, power, mass and volume flow rates

- The energy change of a system is:

$$\Delta E = E_{in} - E_{out} \text{ [J] or } \Delta e = e_{in} - e_{out} \text{ [J/kg]}$$

- Power determines how quickly a change in energy takes place

$$P = \dot{E} = \frac{\Delta E}{\Delta t} = \frac{dE}{dt} \text{ [J/s = W]}$$

- Note that power (the rate of energy change) is denoted by \dot{E} , analogously:

- Power as the rate of doing work: \dot{W} [J/s = W]

- Power as the rate of heat transfer: \dot{Q} [J/s = W]

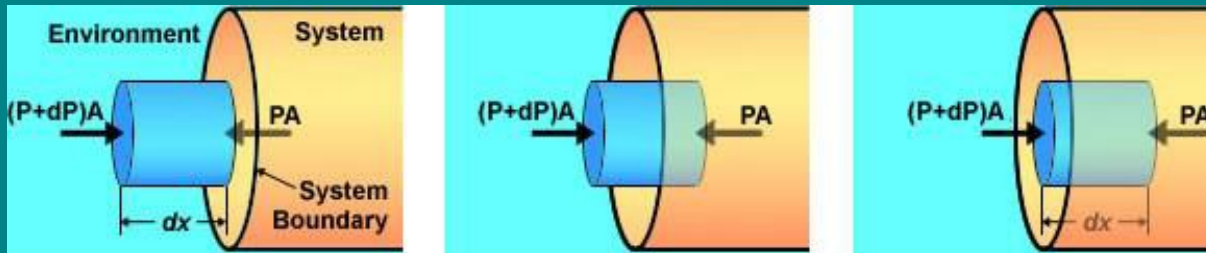
- In open systems mass can flow in and out the system and carry energy

- Mass flow rate, \dot{m} [kg/s] the amount of mass flowing through a cross section per unit time

- Volume flow rate, \dot{V} [m³/s] the volume flowing through a cross section per unit time, both are related by: $\dot{m} = \rho \dot{V}$

Energy transfer by mass transport, flow work, enthalpy

- **Flow Work (Pv):** the work required to push mass across the system boundary into the open system or in other words, the work required to make space for the next part of the flow (important in open systems)



$$\delta W_{flow} = \mathbf{F} \cdot d\mathbf{x} = P A dx = P d(Ax) = P dV = P d(vm) = P v dm \rightarrow [J]$$

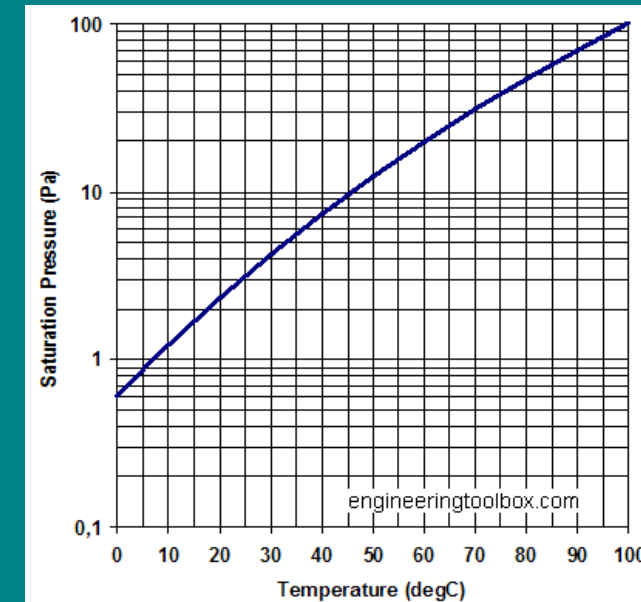
- Energy (due to mass) inside system boundary $dE_{in,mass} = (u + ke + pe) dm$
- Energy crossing system boundary with mass transfer (energy inherent to mass + flow work)
 $dE_{in,mass} = (u + Pv + ke + pe) dm = (h + ke + pe) dm$
- *Enthalpy* by definition: $h = u + Pv$ (Units: like energy [J/kg])

Saturated temperature and pressure

- During a phase change process, the temperature and pressure of a pure substance are dependent properties:

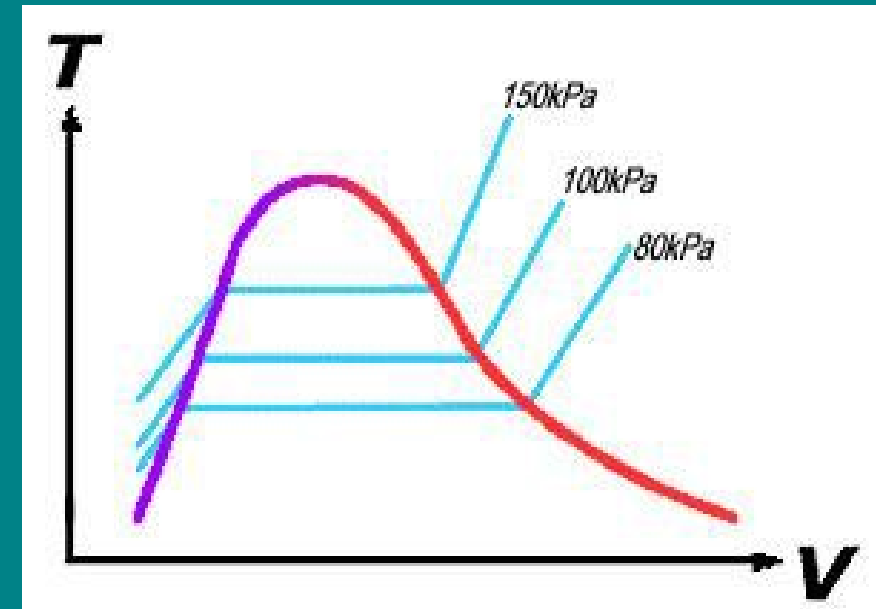
$$P_{sat} = f(T_{sat}) \text{ or } T_{sat} = f(P_{sat})$$

- At a given temperature the phase change takes place at a fixed pressure - P_{sat}
- During the boiling process both the liquid and the vapor phase coexist in equilibrium, they are called **saturated liquid** and **saturated vapor**
- The mixture is called **saturated liquid- vapor mixture** or **two phase mixture**

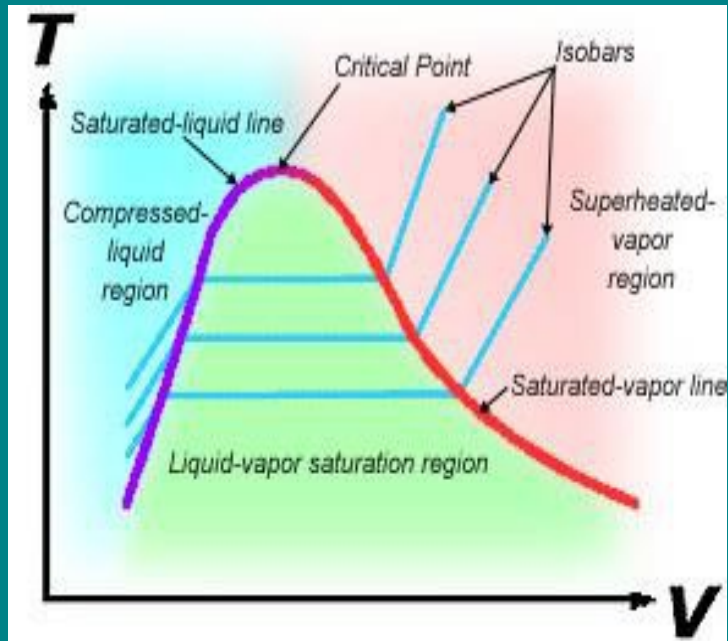


Compressed liquid and superheated vapor

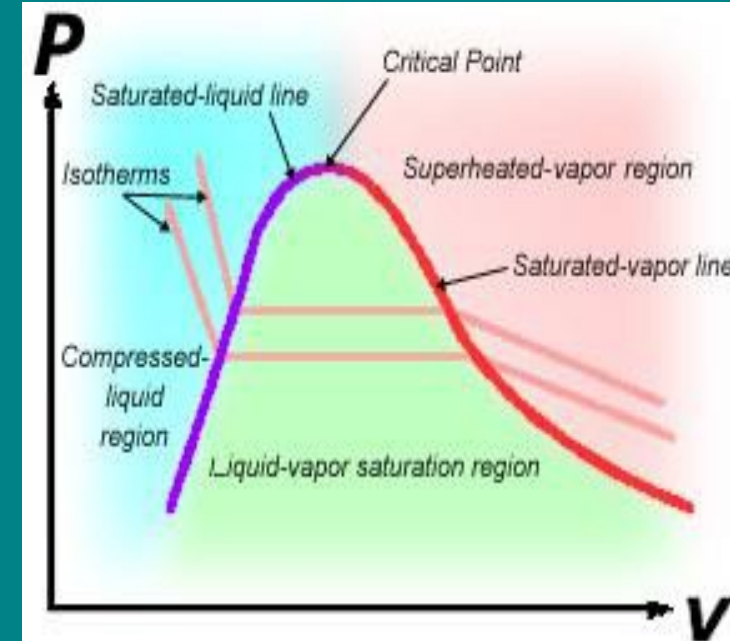
- A substance in the liquid phase that is not about to vaporize is called a **compressed or subcooled liquid**
- A substance in the gas phase that is not about to condense is called a **superheated vapor**
- The boundary between the compressed liquid phase and the mixture phase is called the **saturated liquid line**
- The boundary between the superheated vapor phase and the mixture phase is called the **saturated vapor line**



Phase change



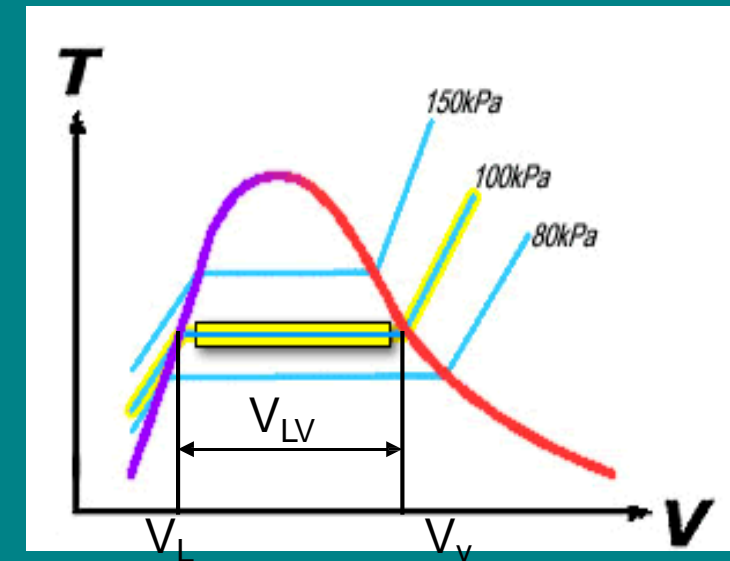
Note directions of isobars (constant pressure lines) horizontal inside the dome and rising slope outside



Note directions of isotherms (constant temperature lines) horizontal inside the dome and decreasing slope outside

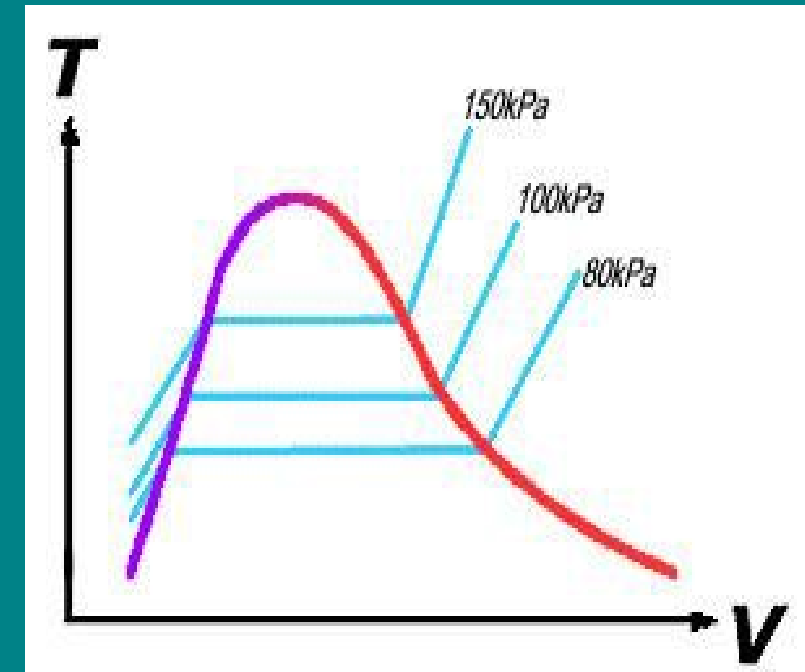
Finding the properties of a substance

- Saturated liquid (fluid) denoted by subscript L or F (e.g. v_L , h_L)
- Saturated vapor (gas) denoted by V or G (e.g. v_V , h_V)
- Under the dome in the **saturated liquid vapor** region **saturated mixture** is denoted by **SAT** (T_{SAT} and P_{SAT})
- P and T are dependent \rightarrow extra parameter, **x** mass fraction of vapor, is needed
 - $m = m_L + m_V$
 - $x = m_V / m$
 - $x = (v - v_L) / (v_{LV}) \rightarrow$ similar for u , h , s , etc.



Finding the properties of a substance

- $v, u, s, h \dots < v_L, u_L, s_L, h_L \dots \rightarrow$ compressed liquid
- $T < T_{SAT} \rightarrow$ compressed liquid
- $v > v_V \rightarrow$ superheated vapor
- $T > T_{SAT} \rightarrow$ superheated vapor
- $x = 1 \rightarrow$ saturated vapor
- $x = 0 \rightarrow$ saturated liquid
- $0 < x < 1 \rightarrow$ mixture
- $v_L < v < v_G \rightarrow$ mixture
- ...



Compressed liquid data approximation

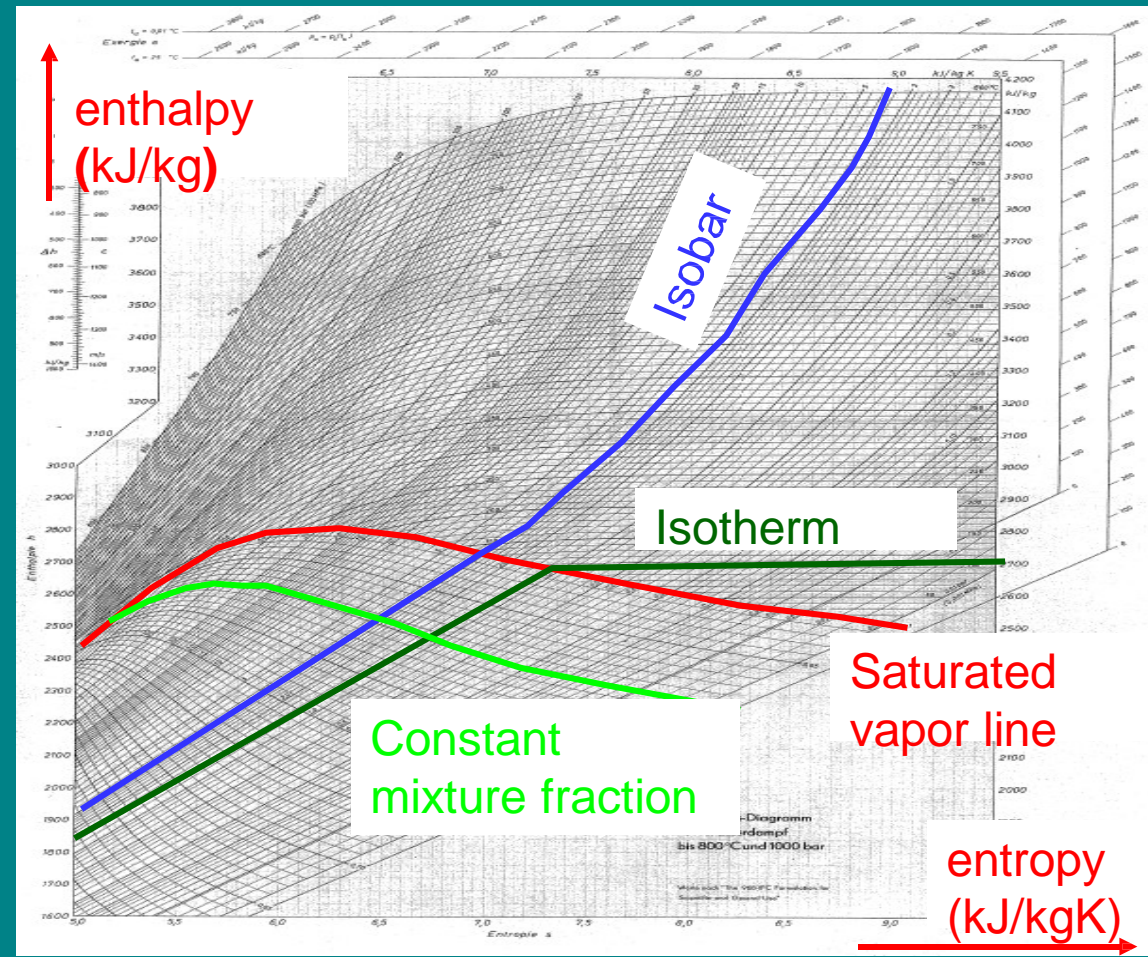
- $v_{CL}(T,P) \cong v_L(T)$
- $u_{CL}(T,P) \cong u_L(T)$
- $h_{CL}(T,P) \cong h_L(T) + v_L(T) [P - P_{SAT}(T)]$

Known from the tables [m³/kg]:

- $v_{CL}(70^\circ\text{C}, 5000 \text{ kPa}) = 0.00102$
- $v_L(70^\circ\text{C}) = 0.00102$
- $v_L(5000 \text{ kPa}) = 0.00129$

- Recall $h = u + Pv \rightarrow h$ sensitive to P
- If $P \cong P_{SAT}(T)$
 - $\rightarrow h_L(T) \gg v_L(T) [P - P_{SAT}(T)]$
 - $\rightarrow h_{CL}(T,P) \cong h_L(T)$
- In conclusion: in order to find a property in the compressed liquid region (with too low pressure for the compressed liquid tables) use the value of the saturated liquid at the **right temperature**

Finding the properties of a liquid



Gases

- The ideal gas law
 - In chemistry mostly $PV = nR_uT$ is used
 - In thermodynamics mostly $Pv = RT$
- R_u is the **universal gas constant**, same for every gas → 8.314 kJ/(kmol K)
- R is the **specific gas constant**, unique for every gas, eg. $R_{\text{air}} = 0.287$ kJ/(kg K)
- Both are related by $R_u = RM$ where M is the molar mass ($M_{\text{air}} = 28.97$ kmol/kg)



<http://en.wikipedia.org/wiki/Gas>

Gases - internal energy, enthalpy

- Enthalpy and internal energy are the most important energies in thermodynamic systems
 - Internal energy is the energy associated with intermolecular motion, electronic and translational kinetic energy, for an ideal gas it only depends on the temperature of the substance $\rightarrow u = u(T) \neq u(P)$
 - Enthalpy, $h = u + Pv = u + RT$, for an ideal gas also only depends on temperature $\rightarrow h = h(T) \neq h(P)$
 - Internal energy and enthalpy are measured relative to a reference state
 - T , u and h are **dependent** properties for ideal gases
- Changes of u & h with respect to T are very important as thermodynamics deals with energy changes and differences

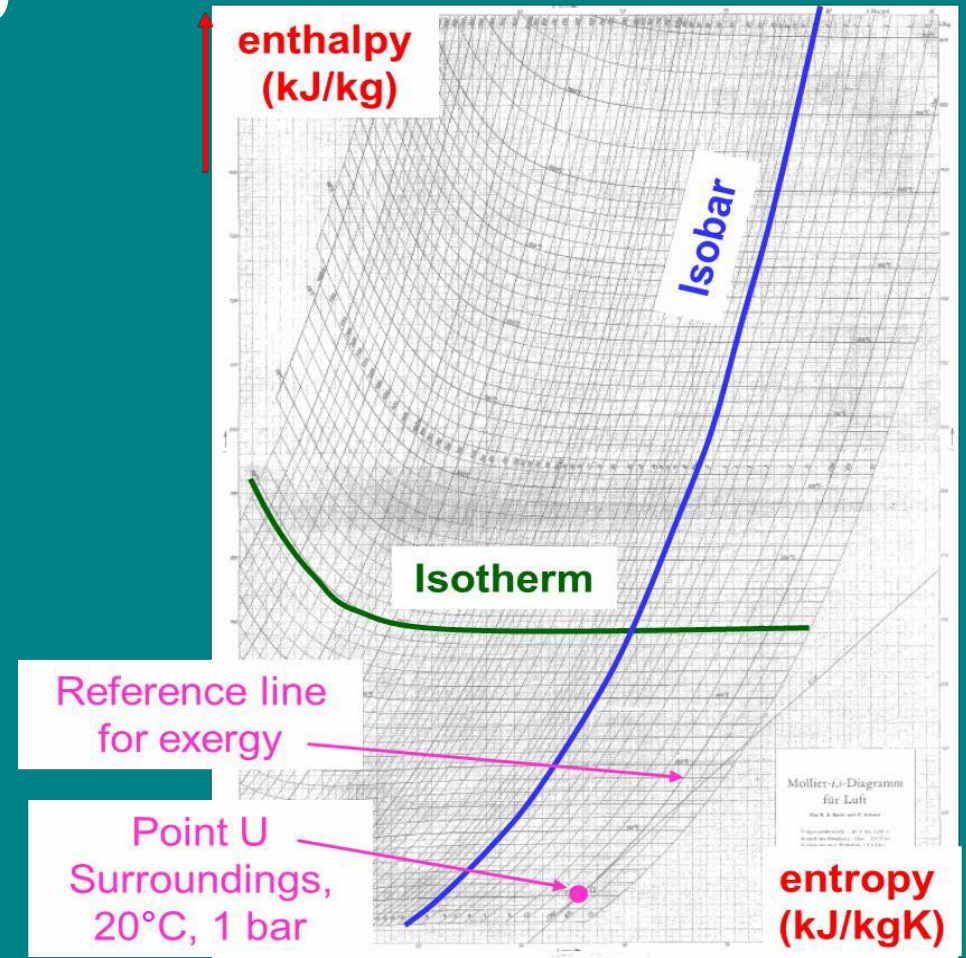
Gases – specific heat capacity

- The internal energy and the enthalpy are related by temperature via the **specific heat capacity**
→ the amount of heat needed to raise the temperature of 1 kg of a substance by one degree
- **Specific heat capacity (c)** depends on the substance and the process involved. For constant volume process (c_v) and for constant pressure process (c_p) is defined as:

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v \quad c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

- For an ideal gas: $\Delta u = \int_{T_1}^{T_2} c_v dT$ and $\Delta h = \int_{T_1}^{T_2} c_p dT$
- Note: In general the specific heat depends on temperature ($c_i = c_i(T)$)

Finding the properties of a gas



First law of thermodynamics

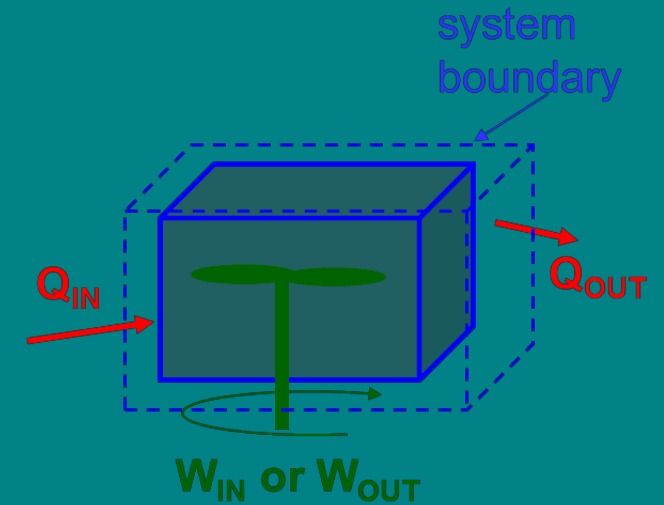
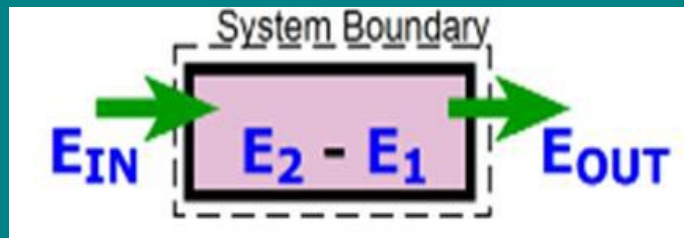
- The first law of thermodynamics → the conservation of energy principle, in general:

$$\Delta E = E_{in} - E_{out} \text{ [J]} \text{ or } \Delta e = e_{in} - e_{uit} \text{ [J/kg]} \text{ or } dE/dt = E_{in} - E_{out} \text{ [J/s = W]}$$

- For a **closed system** the energy can be changed by transferring/extracting **work (W)** or **heat (Q)** through system's boundary:

$$\Delta E = (Q_{IN} + W_{IN}) - (Q_{OUT} + W_{OUT}) = Q_{NET} + W_{NET} = \Delta U$$

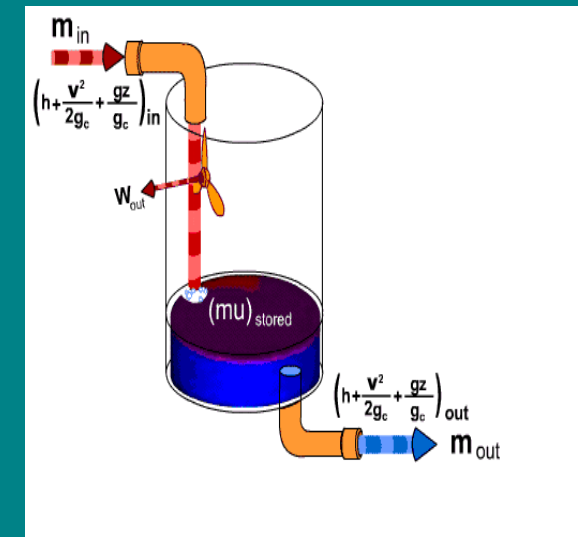
- In applications often KE and PE are constant



First law of thermodynamics

- In an **open system** the energy of a system can also change by mass flowing in and out of the system, the change in energy for an open system is sum of: work (w), heat transfer (q) and energy transfer by mass (flow work)
- In general the change in energy of the system in a rate form is:

$$\frac{dE_{cv}}{dt} = \left[\dot{Q}_{IN} + \dot{W}_{IN} + \sum_{j=1}^N \dot{m}_{IN,i} (h_i + ke_i + pe_i) \right] - \left[\dot{Q}_{OUT} + \dot{W}_{OUT} + \sum_{j=1}^N \dot{m}_{OUT,j} (h_j + ke_j + pe_j) \right]$$



First law of thermodynamics

- In thermodynamic application mostly all properties are independent in time → the system is in **steady-state steady-flow (SSSF)**

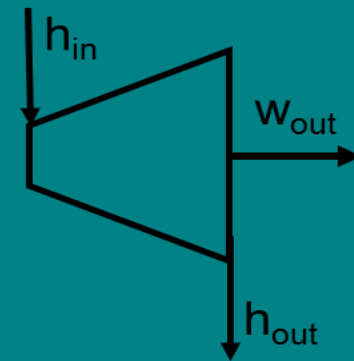
- The energy balance changes to: $\dot{E}_{IN} - \dot{E}_{OUT} = \frac{dE_{cv}}{dt} \overset{0, SS}{\Rightarrow} \dot{E}_{IN} = \dot{E}_{OUT}$

$$\dot{Q}_{IN} + \dot{W}_{IN} + \sum_{i=1}^N \dot{m}_{IN,i} (h_i + ke_i + pe_i) = \dot{Q}_{OUT} + \dot{W}_{OUT} + \sum_{j=1}^N \dot{m}_{OUT,j} (h_j + ke_j + pe_j)$$

- If only one stream in and out →

$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

- This is a general form of the energy balance for an open system



Entropy and second law

- Irreversible processes, entropy
- The first law is very universal and powerful, however it is **not** a complete description of thermodynamic processes
- Not all processes obeying the first law are possible, many processes that are likely to occur in one direction are unlikely to occur in reverse, even if they do not violate the first law
- We need something in addition that we can use to quantitatively study the irreversibility of processes → the 'mystery' property is called nowadays **entropy**



Entropy and second law

- Real live processes are **irreversible** processes because of friction and heat transfer across a finite temperature difference
- Still most people understand entropy intuitively based on expected direction of processes and find **quantification of entropy abstract**
- **Entropy, the measure of irreversibility**
- At **microscopic level** entropy is a measure of degree of randomization or disorder
 - Processes spontaneously always go to equilibrium (random distribution)
 - The more random a state the more entropy it has (maximum in equilibrium)
- Entropy always increase in spontaneous processes

Entropy and second law

- Entropy generation can not be measured directly, but it can be calculated from an entropy balance
- Entropy is a **thermodynamic property** (like temperature, pressure, enthalpy and internal energy), it is an **extensive property** (like energy), it is a **state function** (exact differential), $s(u,v)$

$$ds = \left(\frac{\partial s}{\partial u} \right)_v du + \left(\frac{\partial s}{\partial v} \right)_u dv$$

$$ds = \frac{1}{T} du + \frac{P}{T} dv \rightarrow Tds = du + Pdv$$

$$dh = du + Pdv + vdP \rightarrow Tds = dh - vdP$$

Entropy and second law

- Entropy change for ideal gases
- Evaluating the equations, using $Pv = RT$ and $du = c_v dT$ or $dh = c_p dT$ and assuming c_v or c_p are independent of the temperature it can be shown that the entropy change of an ideal gas is:

$$s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} \quad \text{and} \quad s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

- Entropy change for incompressible liquids
- For incompressible substance, $dv = 0$ and assuming c independent of the temperature ($c_v = c_p = c$ for an incompressible substance)

$$s_2 - s_1 = c \ln \left(\frac{T_2}{T_1} \right)$$

Entropy and second law – entropy generation

- The entropy of a thermodynamic system can change due to the transfer of heat or mass over the system boundary (note: that work does not change the entropy)
- The entropy change due to transfer of heat for a closed system is, given by the inequality of Clausius (T_{res} =temperature of reservoir):

$$ds_{system} \geq \frac{\delta q_{net}}{T_{res}}$$

- For an open system the entropy also changes by the mass flowing into and out of the system:

$$\dot{m}(s_{uit} - s_{in}) \geq \frac{\dot{Q}_{net}}{T_0}$$

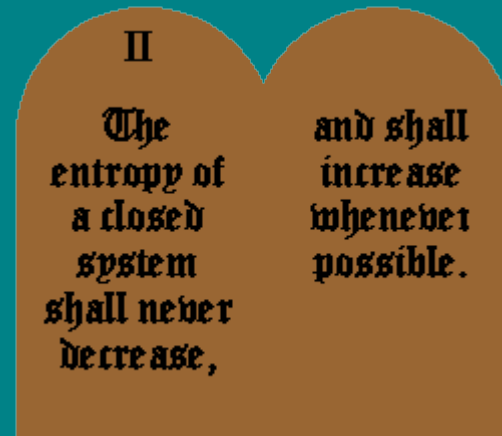
- The entropy generated is:

$$\dot{S}_{gen} = \dot{m}(s_{uit} - s_{in}) - \frac{\dot{Q}_{net}}{T_0} \geq 0$$

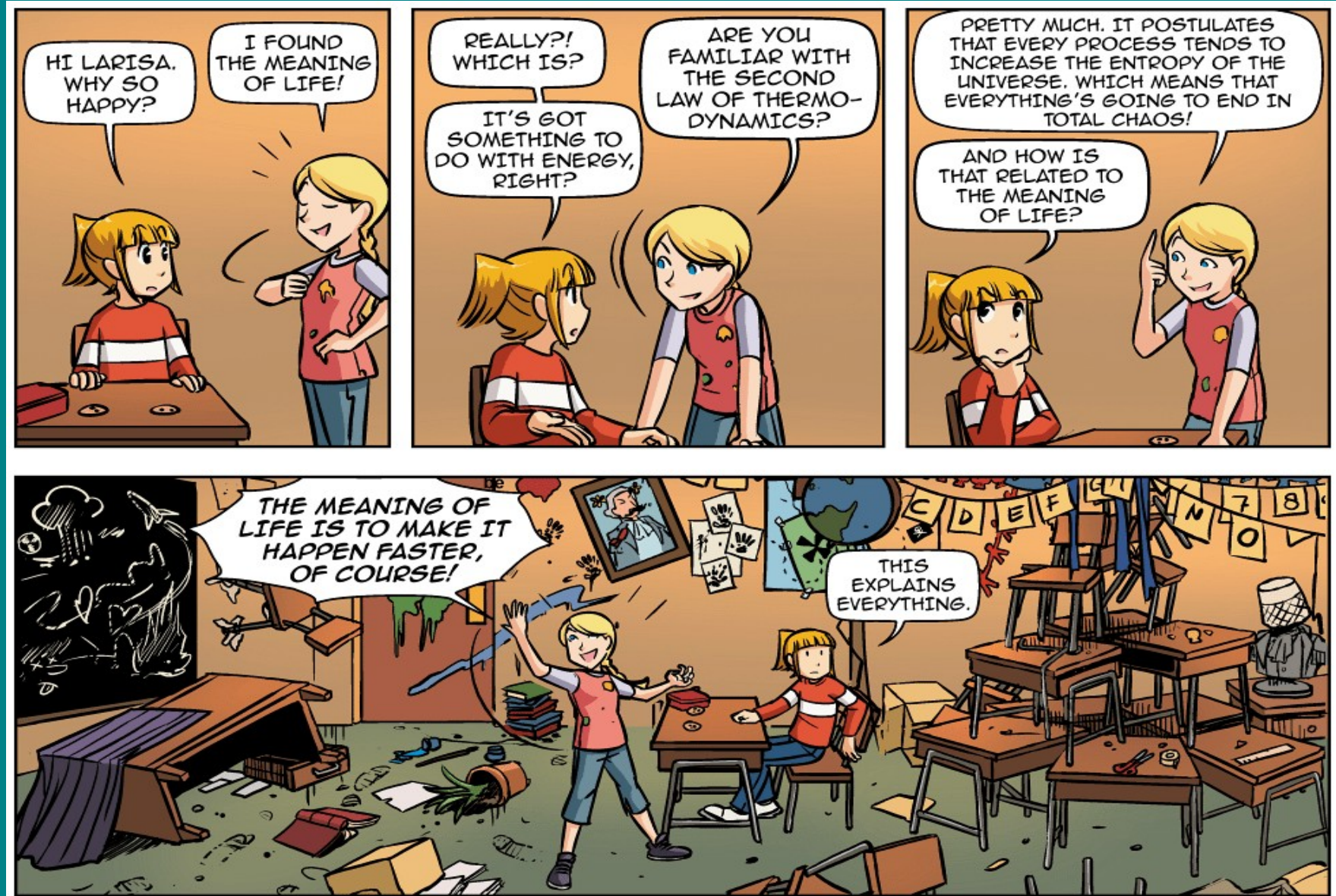
Entropy and second law

- From the equations it is clear that in all irreversible (real) processes entropy is not conserved (like mass and energy) but increases, entropy is always generated in real processes: $\delta s_{\text{gen}} = ds_{\text{system}} + ds_{\text{surroundings}} \geq 0$
- Note: the entropy change for the system can be < 0 , but then the entropy change for the surrounding is larger (in absolute numbers)

The entropy of an isolated system will always increase until it reaches a state of equilibrium at which the entropy is maximized (the most random distributed state)



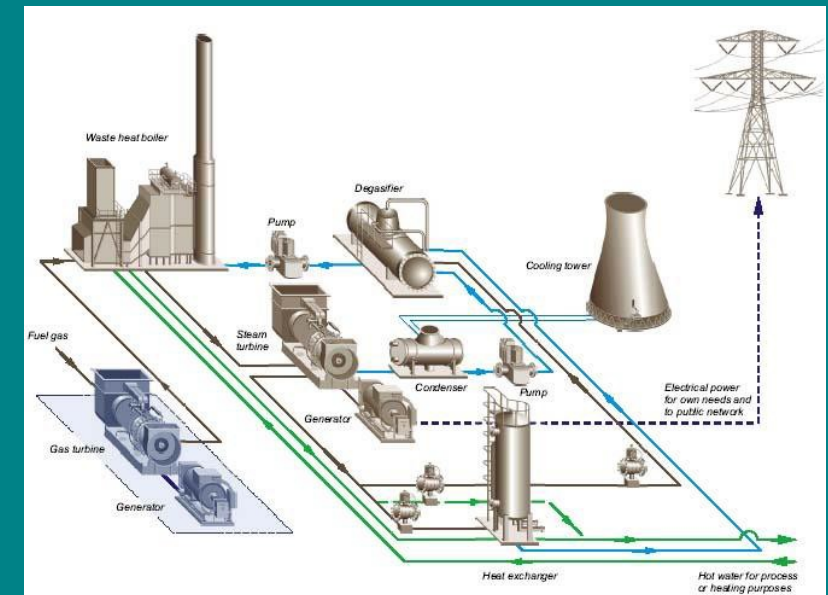
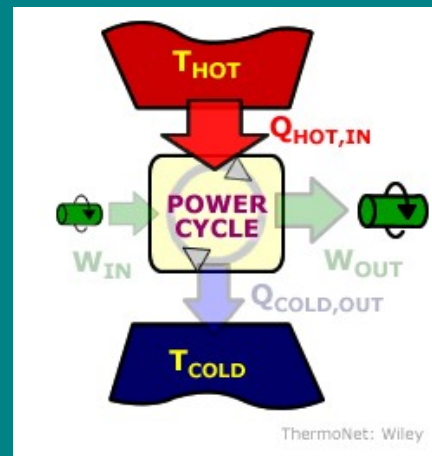
Entropy and second law



Sandra and Woo by Oliver Knörzer (writer), Powree (artist) and Lisa Moore (colorist) - www.sandraandwoo.com

Thermodynamic cycles

- A thermodynamic cycle is composed of a series of processes which return to the initial state
 - Heat power cycles produce power from heat
 - Refrigeration / heat pump cycles transport heat using power
- Note: in a thermodynamic cycle always heat (energy) is transported between two temperature reservoirs



Thermodynamic cycles

- The change in any thermodynamic property (T, P, v, s, u, h) over a cycle is 0 as they are state functions
- For all complete thermodynamic cycles the first law reduces to:

$$q_{in} - q_{out} = w_{out} - w_{in} \rightarrow q_{net} = w_{net} \quad (\text{since } \Delta u = 0)$$

- Second law, inequality of Clausius, applied to a complete cycle ($\Delta s = 0$)

$$\sum_{i=1}^n \frac{q_{net,i}}{T_i} \leq 0$$

- Note: the net entropy should increase

Thermodynamic cycles – Carnot efficiency

- Efficiency of the cycle is defined as:

$$\eta_{he} = \frac{\text{What we want}}{\text{What we pay for}}$$

$$\eta_{he} = \frac{w_{net}}{q_{in}} = \frac{w_{out} - w_{in}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

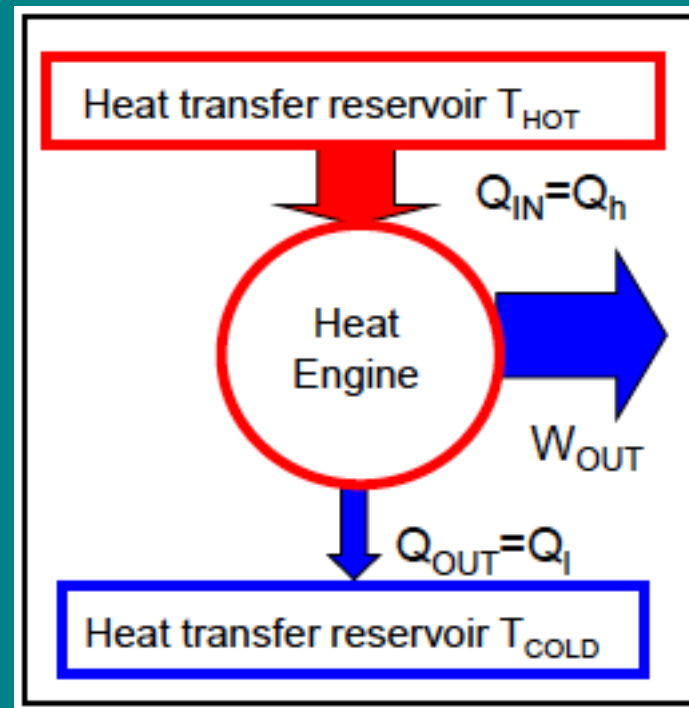
- Note: the efficiency is only 100% if $q_{out} = 0 \rightarrow$ impossible
- **Carnot efficiency:** Maximum efficiency for any power cycle operating between T_{hot} and T_{cold}

$$\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

Real vs theoretical maximum efficiency

- Assume a heat engine 1 working between $T_{1\text{-hot}} = 800^{\circ}\text{C}$ and $T_{1\text{-cold}} = 20^{\circ}\text{C}$ with $\eta_{1\text{-he}} = 40\%$
- Assume a heat engine 2 working between $T_{2\text{-hot}} = 200^{\circ}\text{C}$ and $T_{2\text{-cold}} = 20^{\circ}\text{C}$ with $\eta_{2\text{-he}} = 30\%$

Which of these engines is better?



Real vs theoretical maximum efficiency

We have to compare the thermal efficiency to the Carnot efficiency:

l

Engine 2 is closer to its Carnot efficiency and therefore it performs better with respect to the second law

The property exergy can handle this second law influence

$$\eta_{Car} = 1 - \frac{T_l}{T_H}$$
$$\eta_{2-law} = \frac{\eta_{sys}}{\eta_{Car}}$$

$$\eta_{2-law-1he} = \frac{\eta_{1-he}}{\eta_{Car-1he}} = \frac{0.4}{0.73} = 0.58$$

$$\eta_{2-law-2he} = \frac{\eta_{2-he}}{\eta_{Car-2he}} = \frac{0.3}{0.38} = 0.79$$

2nd law efficiency

- Second law analysis provides information regarding how close processes or cycles approach the ideal limit (Carnot efficiency)
- This gives information how good is our cycle and if it is possible to improve it
- Efficiencies are defined based on 2nd law of thermodynamics

Vapor power cycles

- To produce power a thermodynamic cycle is used
- Vapor power cycle is one of the examples of power systems
- In vapor cycle the working medium is fluid changing phase

Liquid → Vapor → Liquid

- This is external combustion engine, since heat is transferred via boiler to the system



Steam train with piston steam engine

Rankine cycle

- Today the biggest application of vapor cycle is for power generation in the **steam turbine cycles** known also as **Rankine cycles**
- Nowadays, about 80% of world wide produced power comes from steam turbines in vapor power cycles
- **Water** is often a working liquid, however other liquids (especially organic) are possible

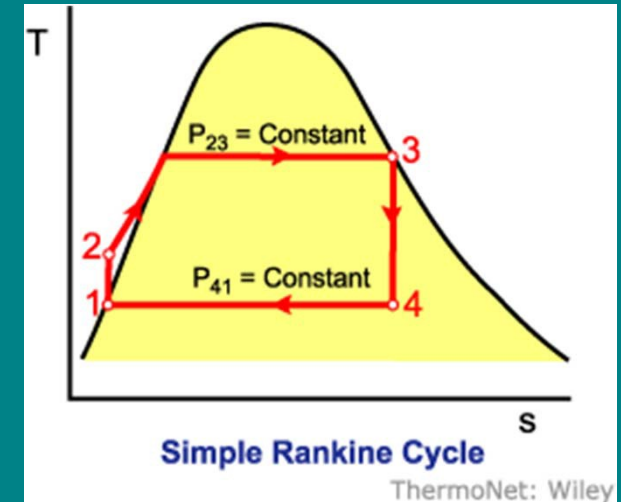


Rotor of steam turbine

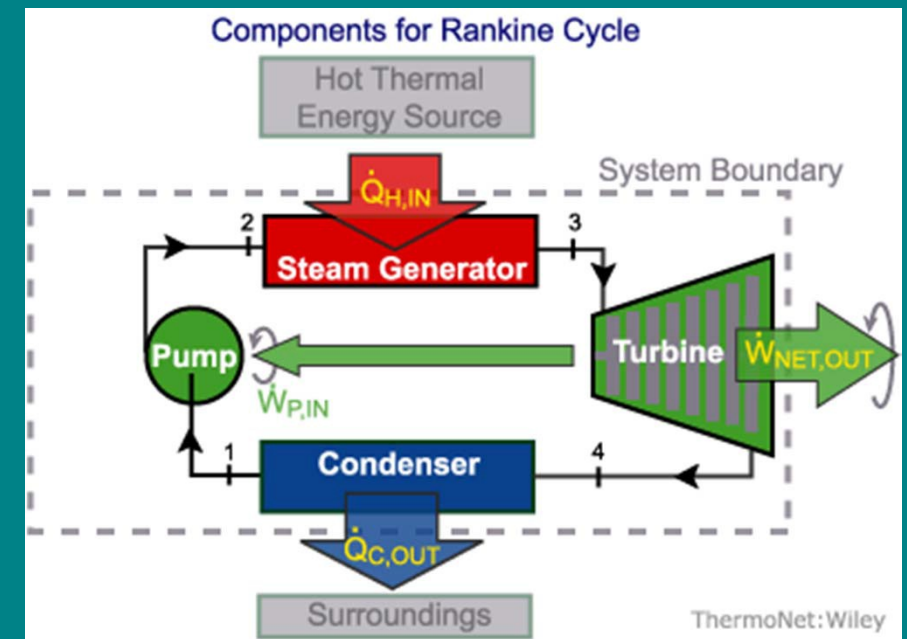
Simple Rankine cycle

- Simple Rankine cycle consist of **four** devices:
 - Pump – to increase pressure
 - Steam generator/Boiler – to add heat and change liquid's phase
 - Steam turbine – to decrease pressure and extract work
 - Condenser – for heat rejection

Simple, ideal Rankine Cycle

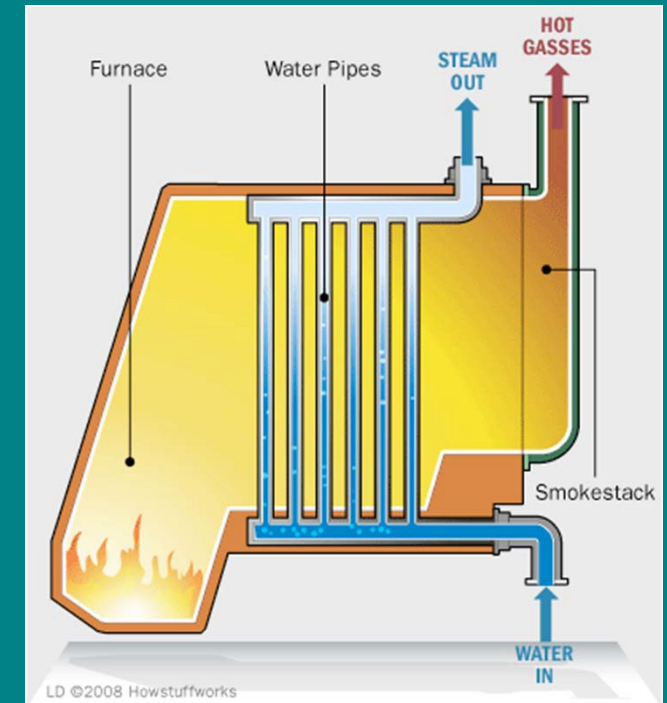


- Process 1→2 isentropic compression (w_{in})
- Process 2→3 isobaric heat addition (q_{in})
- Process 3→4 isentropic expansion (w_{out})
- Process 4→1 isobaric heat rejection (q_{out})



Simple, ideal Rankine Cycle

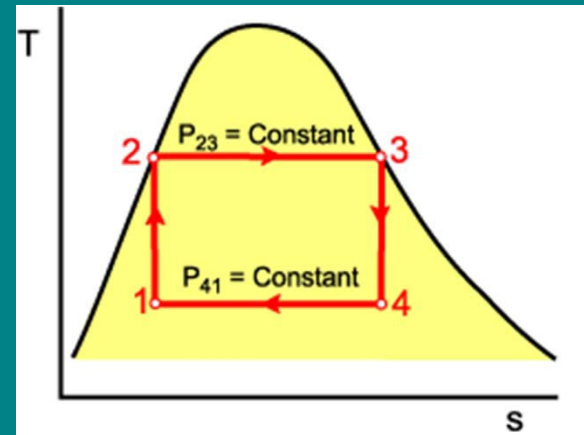
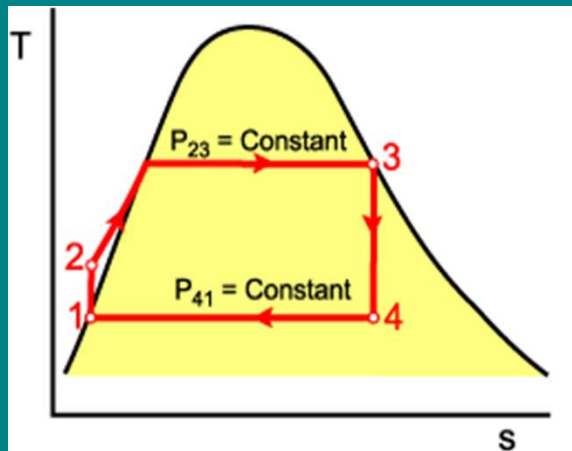
- As an external source of heat a renewable or fossil energy can be used (biomass, sun, waste heat, coal etc.)
- The temperature of the source, thus the amount of heat transferred to the cycle, determines the efficiency and power output of the system
- Temperature of sustainable sources is usually low, but system is CO₂ neutral
- Mostly boiler is used to transfer heat to working medium



<http://science.howstuffworks.com/transport/engines-equipment/steam2.htm>

Ideal Rankine Cycle vs Carnot Cycle

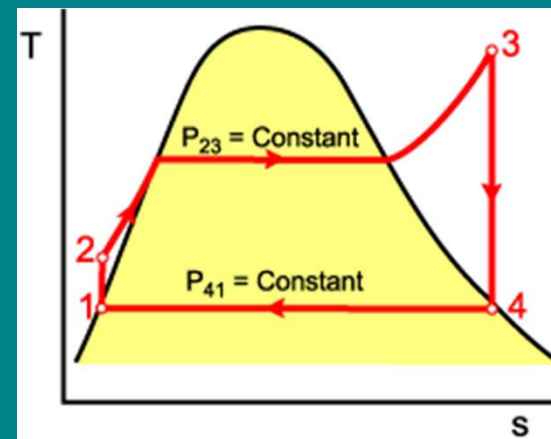
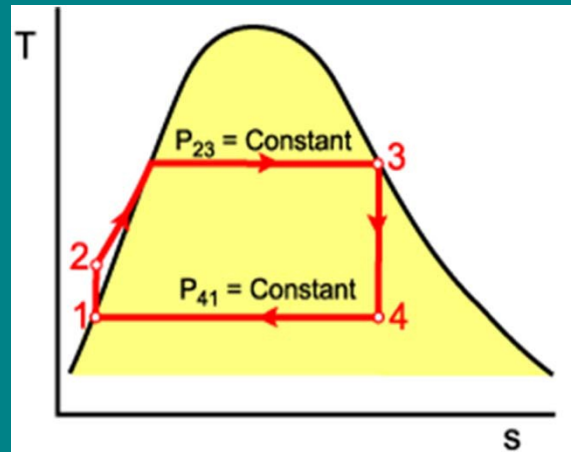
- Both cycles operate between the same pressures and water is working liquid
- Process 1→2 of Carnot cycle is difficult to achieve in Rankine cycle, since increase pressure of mixture is mechanically difficult to perform reliably
- Effect → lower efficiency of ideal Rankine cycle



T-s diagram of Ideal Rankine cycle vs Carnot cycle

Ideal Rankine Cycle vs Superheated Cycle

- Both cycles operate between the same pressures and water is working liquid
- Process 3→4 of Rankine cycle is restricted by quality of mixture, i.e. mixture with $x > 0.85$ can cause erosion and reliability problems
- Solution → superheat the saturated vapor
- Effect → temperature of heat source must be higher; higher power output



Ideal Rankine cycle - assumptions

- Pump – adiabatic, isentropic
- Turbine – adiabatic, isentropic
- No kinetic/potential energy change
- No pressure losses in pipes.
- For the total cycle each device is analyzed separately
- Boiler – no pressure change
- Condenser – no pressure change
- Incompressible liquid, i.e $v=\text{const.}$

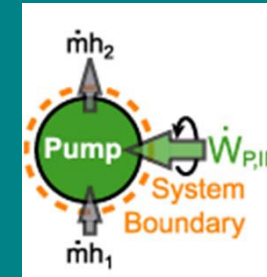
$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}(h + \cancel{ke} + \cancel{pe})_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}(h + \cancel{ke} + \cancel{pe})_{out}$$
$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}h_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}h_{out}$$
$$\dot{Q}_{net} + \dot{W}_{net} = \dot{m}(h_{out} - h_{in})$$

Ideal Rankine cycle – examples

- Process 1→2'

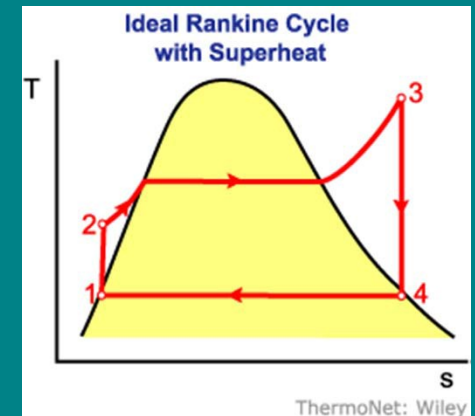
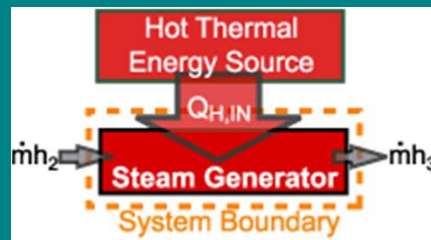
$$\cancel{\dot{Q}_{in}} + \dot{W}_{in} + \dot{m}h_{in} = \cancel{\dot{Q}_{out}} + \cancel{\dot{W}_{out}} + \dot{m}h_{out}$$

or alternatively: $dh = \dot{w}_{pump,in} = \cancel{Tds} + v dP$

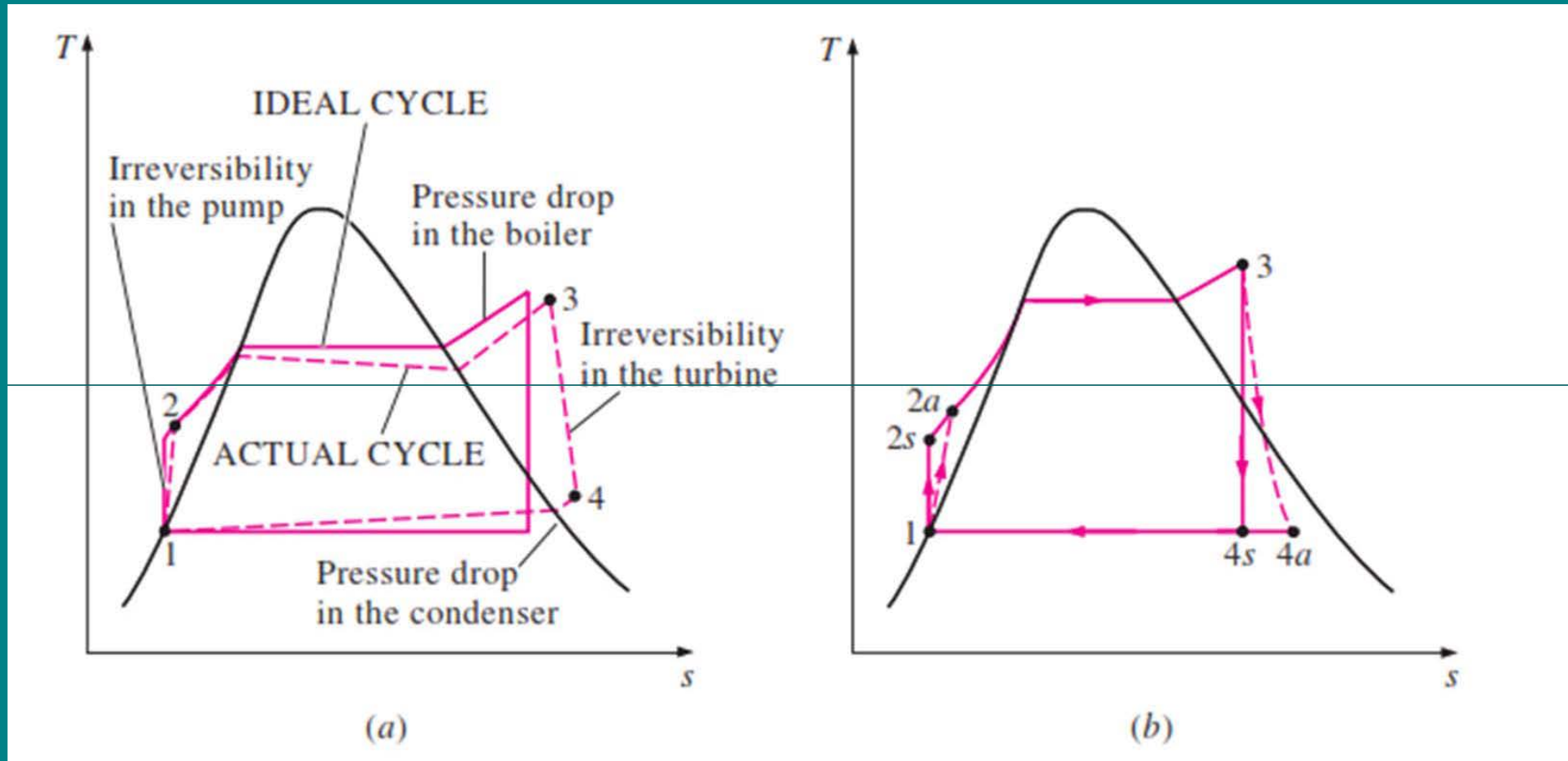


- Process 2→3

$$\dot{Q}_{in} + \cancel{\dot{W}_{in}} + \dot{m}h_{in} = \cancel{\dot{Q}_{out}} + \cancel{\dot{W}_{out}} + \dot{m}h_{out}$$



Ideal Rankine cycle vs non-ideal

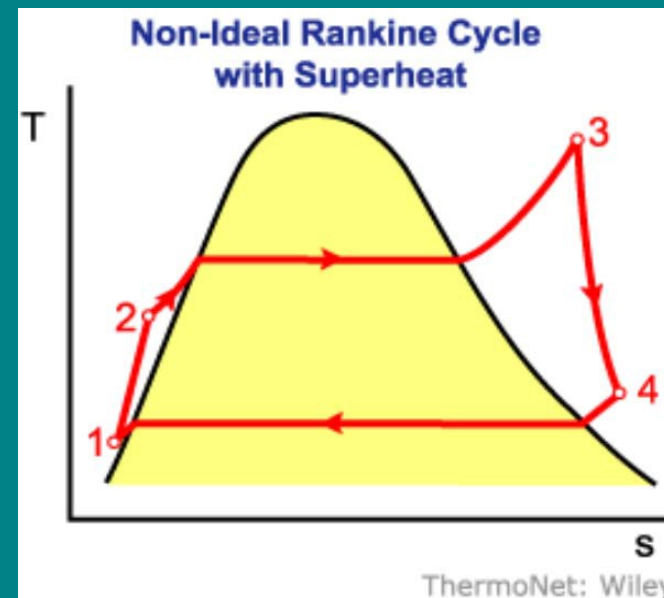
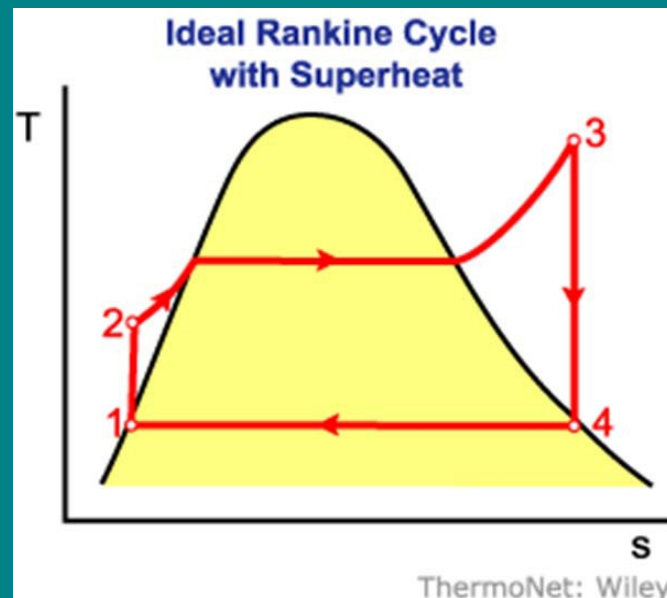


Ideal Rankine cycle vs non-ideal

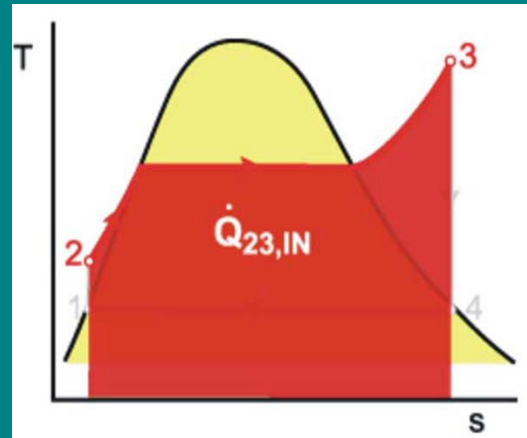
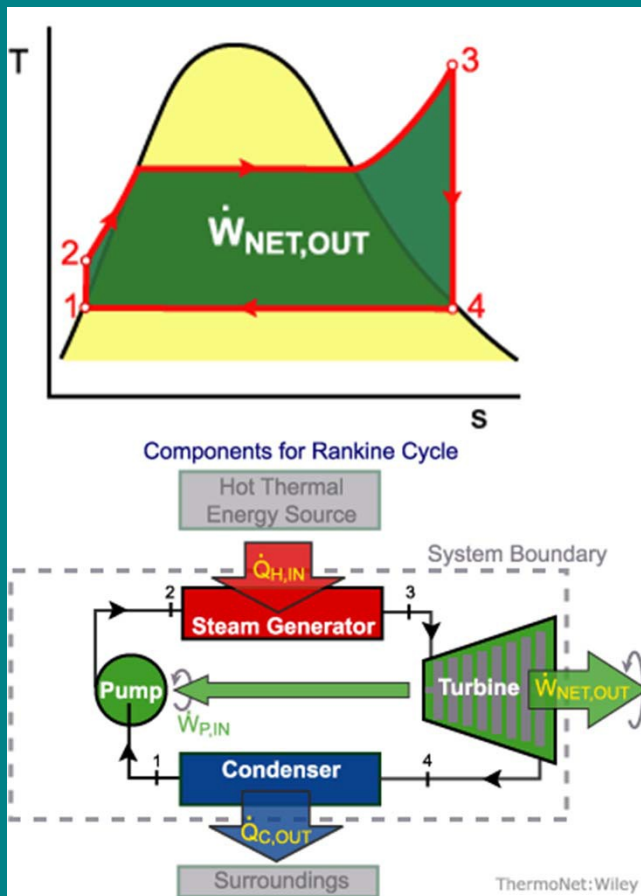
- For a non-ideal (real/actual) Rankine cycle, isentropic efficiencies of pump and turbine have to be included, since entropy increases

$$\eta_{S,Pump} = \frac{work_S}{work_A} = \frac{h_{S,OUT} - h_{IN}}{h_{A,OUT} - h_{IN}}$$

$$\eta_{S,Turb} = \frac{work_A}{work_S} = \frac{h_{IN} - h_{A,OUT}}{h_{IN} - h_{S,OUT}}$$

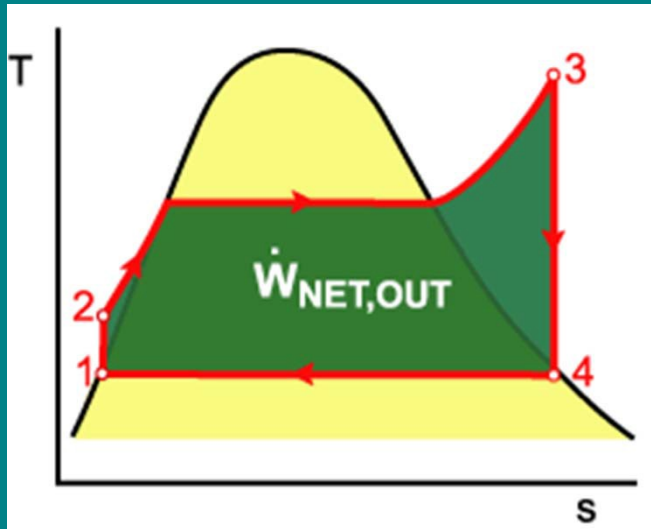


Rankine Cycle Efficiency



$$\begin{aligned}\eta_{Rankine} &= \frac{\text{get}}{\text{pay}} \\ &= \frac{\text{net work output}}{\text{heat added}} \\ &= \frac{\dot{W}_{turb} - \dot{W}_{pump}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \\ &= \frac{\dot{m}(h_3 - h_4) - \dot{m}(h_2 - h_1)}{\dot{m}(h_3 - h_2)}\end{aligned}$$

Rankine Cycle Efficiency



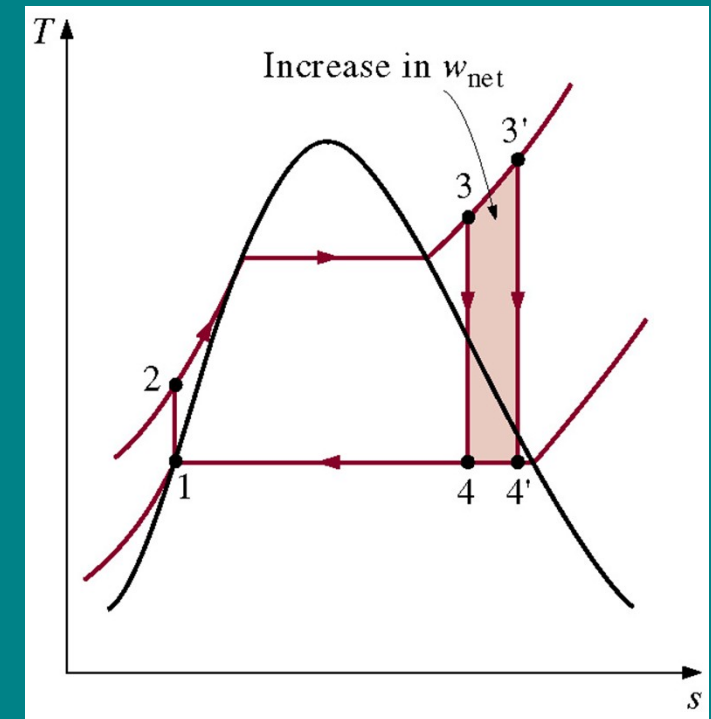
$$\eta_{Rankine} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

- Cycle efficiency can be changed by:
 - Changing pressure at turbine or/and condenser
 - Changing temperature at turbine or/and condenser

Rankine efficiency

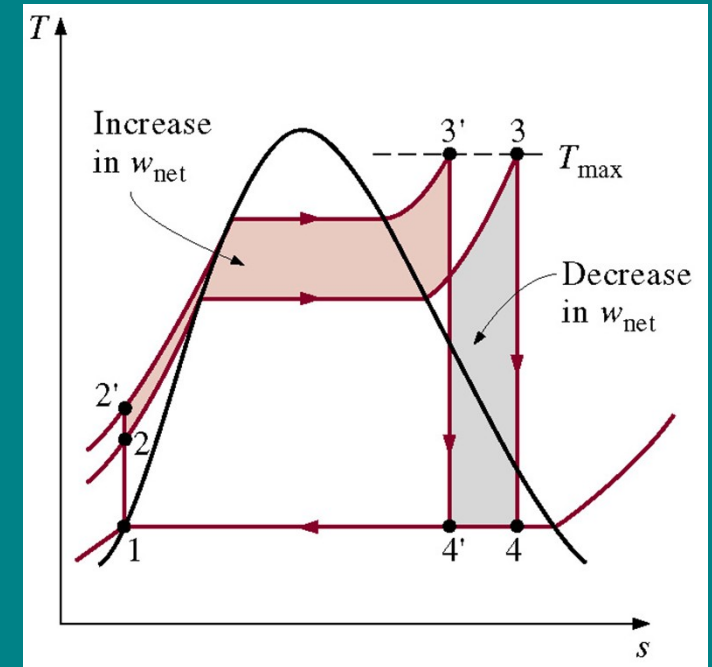
$$\eta_{Rankine} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

- Superheating
 - Power output – increases
 - Heat input – increases
 - Efficiency – increases (due to heat added at higher average T)
 - Decreases the moisture content of the steam at turbine exit
 - Maximum temperature of steam is restricted by material properties of boiler and turbine to approx. 650°C



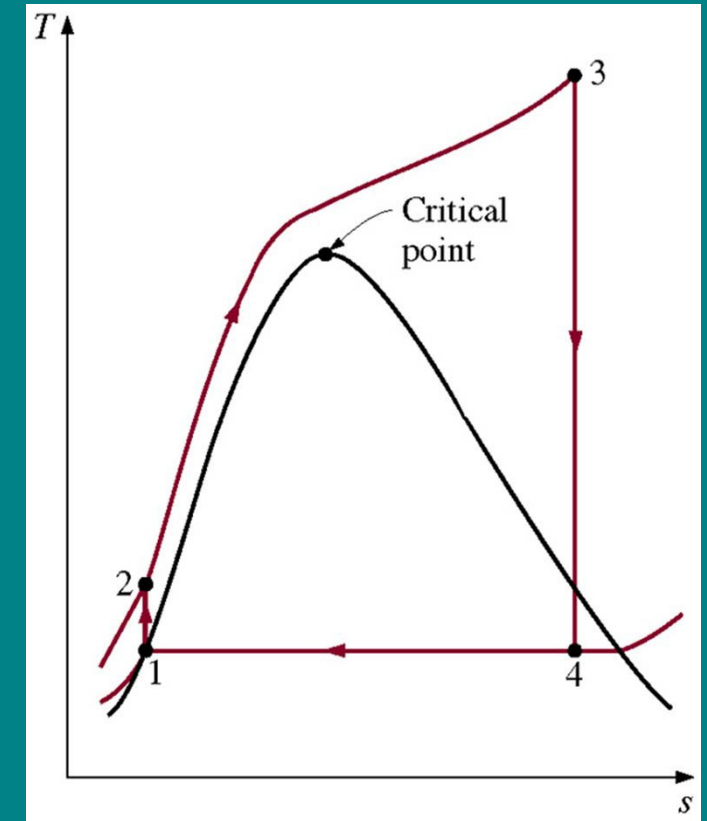
Rankine Cycle Efficiency

- Increasing boiling pressure
 - Power output – similar
 - Heat input – similar
 - Efficiency – increases (due to heat added at higher average T)
 - Decreases the quality of steam at turbine exit



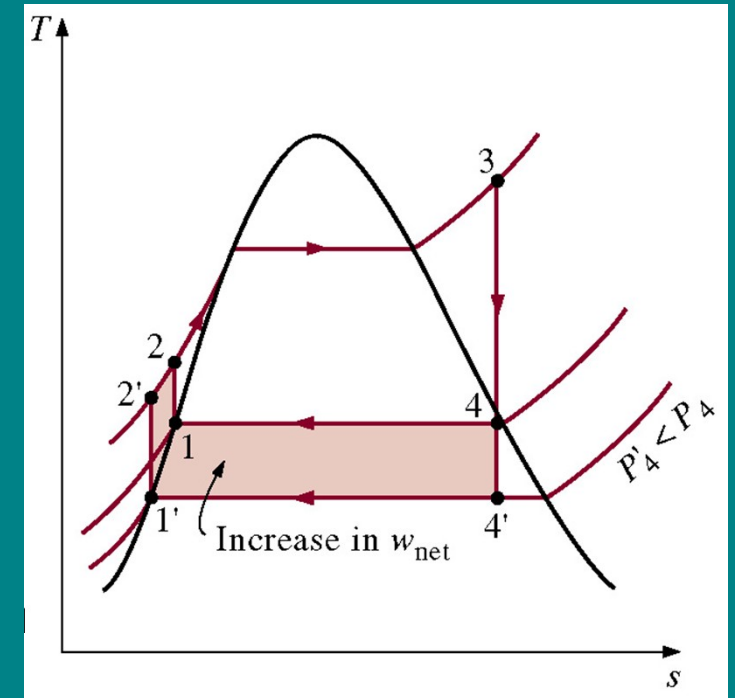
Rankine Cycle Efficiency

- Supercritical Rankine cycle
 - Power output – increases
 - Heat input – increases
 - Efficiency – increases (due to heat added at higher average T)
 - In supercritical configurations of Rankine cycle, maximum pressure can reach 30 MPa



Rankine Cycle Efficiency

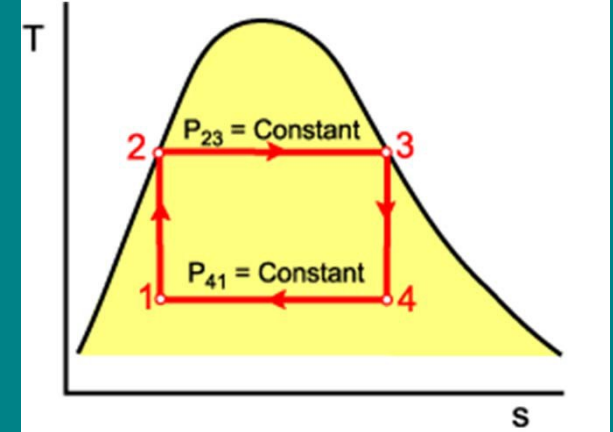
- Lowering condenser pressure/temperature
 - Power output – increases
 - Heat input – increases slightly
 - Efficiency – increases
 - Quality of the mixture at turbine exit decreases
 - Pressure/temperature are restricted by temperature of cooling medium condenser (usually to 20-25°C) in
 - Condenser may work at below atmospheric pressure



Improved Rankine cycle

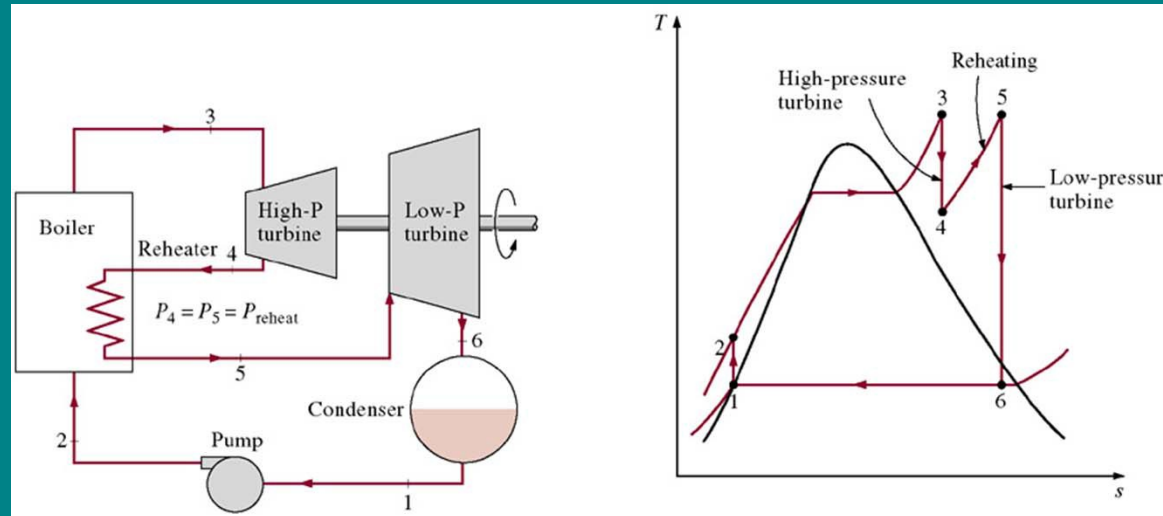
- Improvement with respect to increased efficiency and/or power output by adding extra devices. Two main processes which increase the mean temperature of heat addition are:
 - Reheating
 - Regeneration
- From Carnot engine (with isothermal heat addition)

$$\eta_{Carnot} = 1 - \frac{T_{Cold}}{T_{Hot}}$$

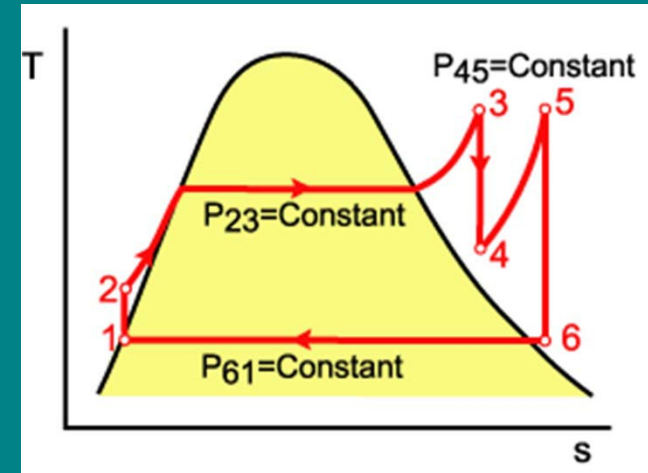
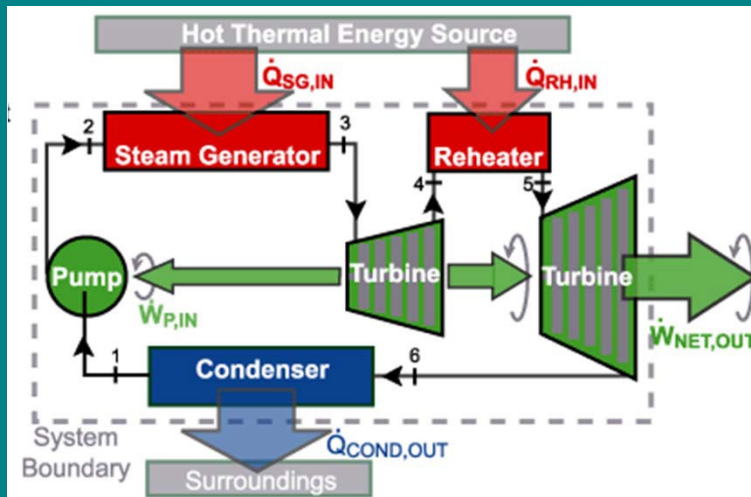


Improved Rankine cycle - Reheating

- In order to get benefit of improved efficiency due to increased boiler pressure and to overcome problems related to maximum temperature allowed in the cycle (about 650°C) and moisture content (should not be $x < 0.85$) a reheating was introduced
- In reheating a second turbine is added, thus expansion takes place in two steps



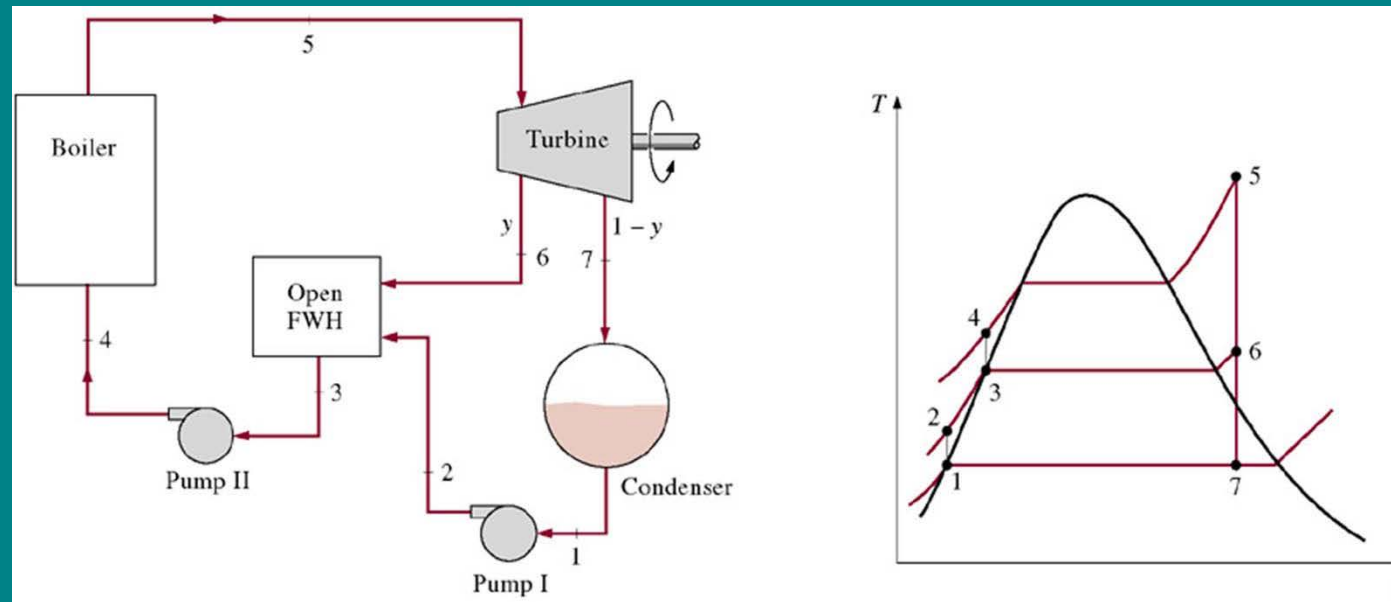
Improved Rankine cycle - Reheating



$$\begin{aligned}
 \eta_{\text{Rankine}} &= \frac{\text{get}}{\text{pay}} = \frac{\text{net work output}}{\text{heat added}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} \\
 &= \frac{\dot{W}_{\text{turb},1} + \dot{W}_{\text{turb},2} - \dot{W}_{\text{pump}}}{\dot{Q}_{\text{in},1} + \dot{Q}_{\text{in},2}} = \\
 &= \frac{\dot{m}(h_3 - h_4) + \dot{m}(h_5 - h_6) - \dot{m}(h_2 - h_1)}{\dot{m}(h_3 - h_2) + \dot{m}(h_5 - h_4)}
 \end{aligned}$$

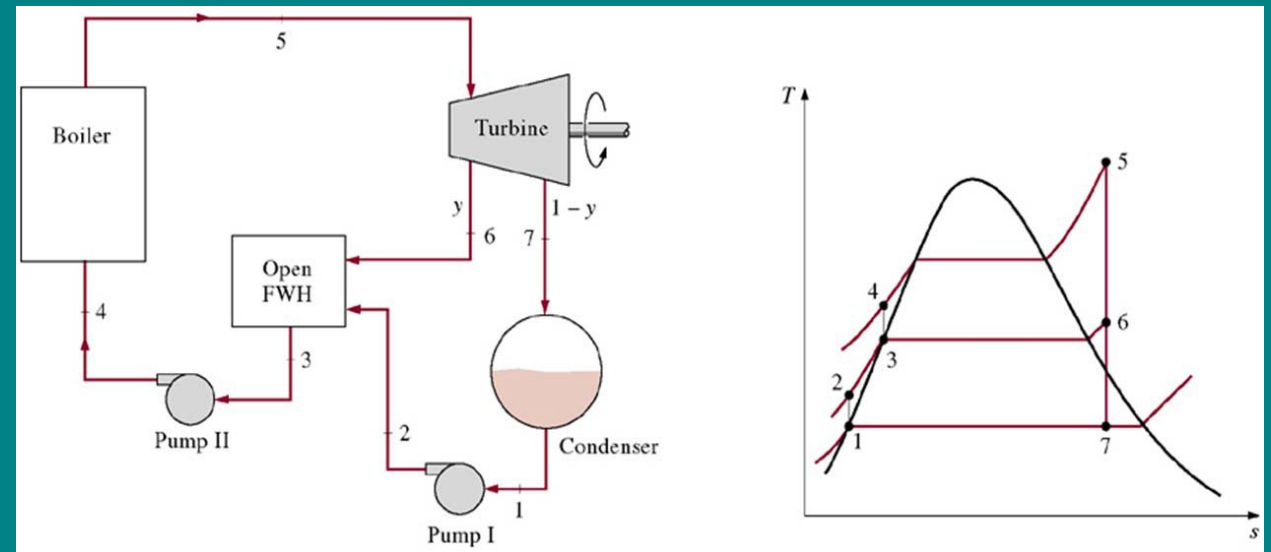
Improved Rankine cycle - Regeneration

- To increase the average temperature of heat addition, a part of steam is used to preheat the feedwater, after the pump
- The device where this process is performed is called a feedwater preheater



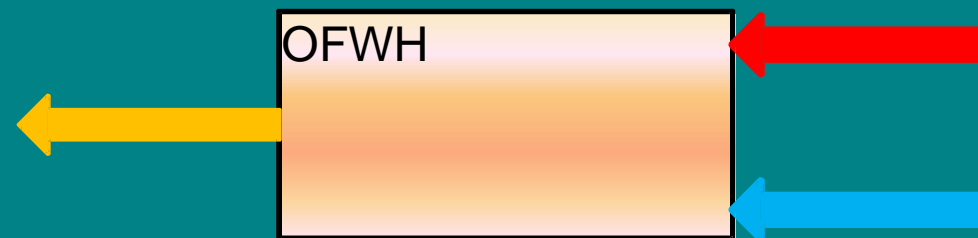
Improved Rankine cycle - Regeneration

- Extracting steam from turbine results in:
 - Reduced work output (lower mass flow rate at second stage turbine)
 - Reduced heat output (lower mfr)
 - Reduced heat input
 - Increased thermal efficiency



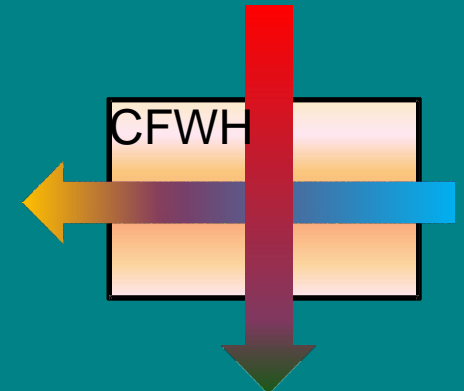
Improved Rankine cycle - Regeneration

- Two types of heat water heaters are in use: open and closed. Most steam power plants use a combination of both.
- Open feedwater heater (OFWH)
 - mixing chamber where hot and cold flows are mixed
 - ideally, the mixture leaves the OFWH as a saturated liquid at boiler pressure
 - OFWH is cheap, simple and has a good heat transfer characteristics, but additional pump is required



Improved Rankine cycle - Regeneration

- Closed feedwater heater (CFWH)
 - heat exchanger, in which heat is transferred from steam to cold liquid
 - since there is no mixing involved, both stream can be at different pressures
 - ideally, the mixture leaves the CFWH as a saturated liquid and temperature of feedwater equal to exit temperature of extracted steam
 - Condensed steam directed to feedwater line or routed to another heat water or to the condenser via a trap (throttle valve, $h=\text{const.}$)
 - CFWH is more complex, more expensive and heat transfer is less efficient than OFWH, however, it does not require separate pumps (flows at different pressures)

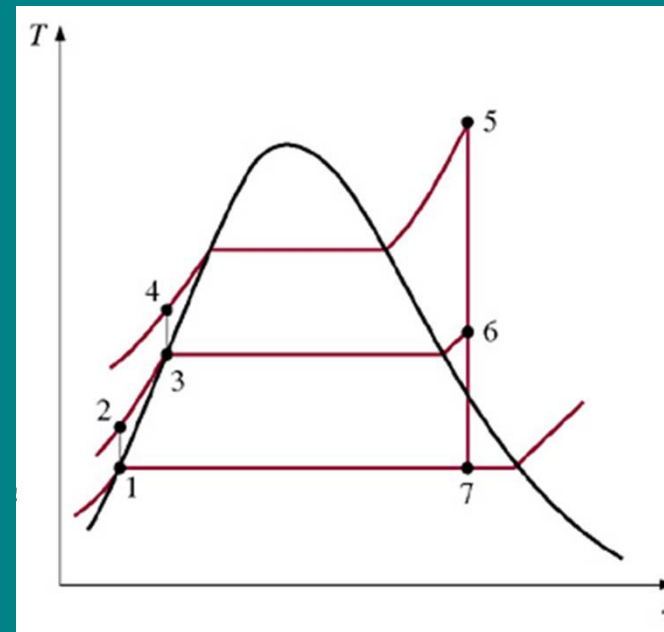
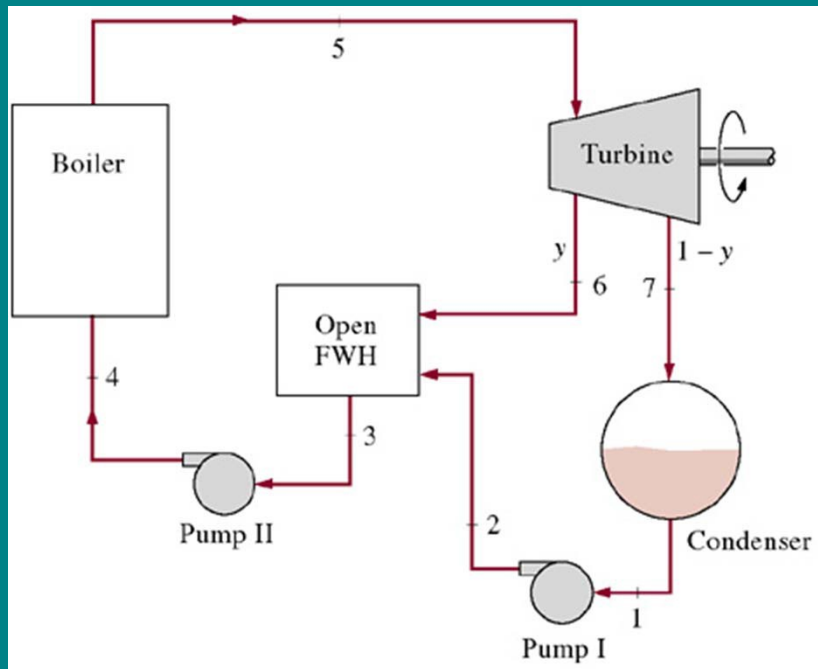


Improved Rankine cycle - Regeneration

- Rankine cycle with open feedwater heater
 - Mass balance (3 different flows)
 - Energy balance for OFWH (mixing chamber)

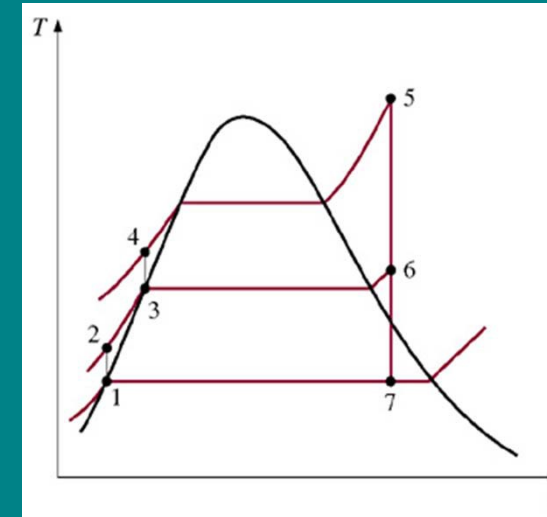
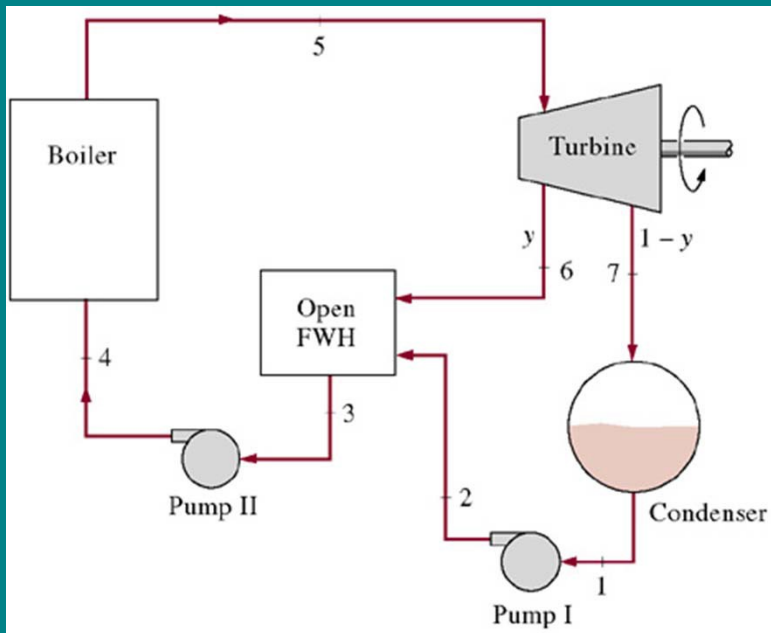
$$\dot{m}_3 = \dot{m}_2 + \dot{m}_6$$

$$\dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_6 h_6$$



Improved Rankine cycle - Regeneration

- Rankine cycle with open feedwater heater

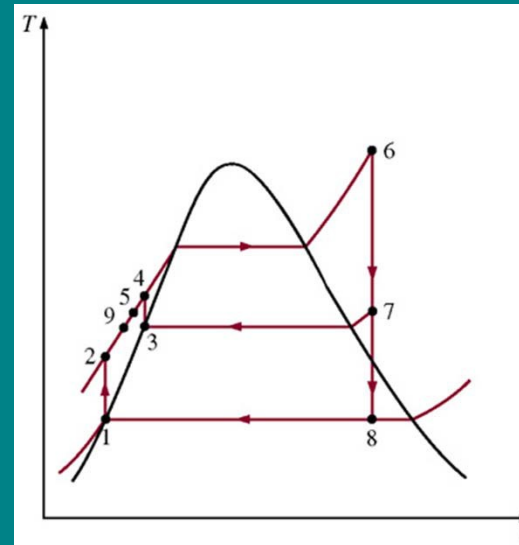
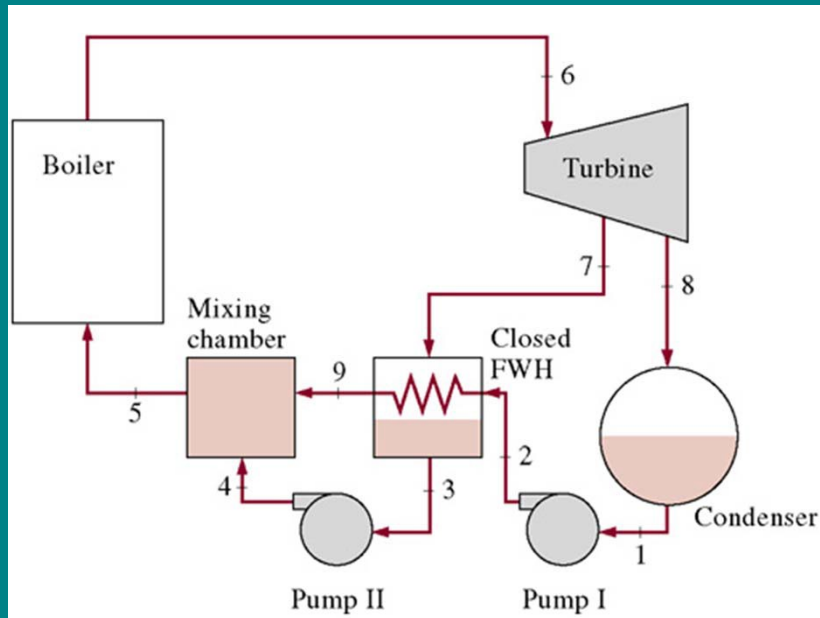


$$\eta_{\text{Rankine}} = \frac{\text{get}}{\text{pay}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{\dot{W}_{\text{turb},1} + \dot{W}_{\text{turb},2} - \dot{W}_{\text{pump},1} - \dot{W}_{\text{pump},2}}{\dot{Q}_{\text{in}}} =$$

$$= \frac{\dot{m}_3(h_5 - h_6) + \dot{m}_2(h_6 - h_7) - \dot{m}_2(h_2 - h_1) - \dot{m}_3(h_4 - h_3)}{\dot{m}_3(h_5 - h_4)}$$

Improved Rankine cycle - Regeneration

- Rankine cycle with closed feedwater heater
 - Mass balance (3 different flows)
 - Energy balance for mixing chamber and CFWH



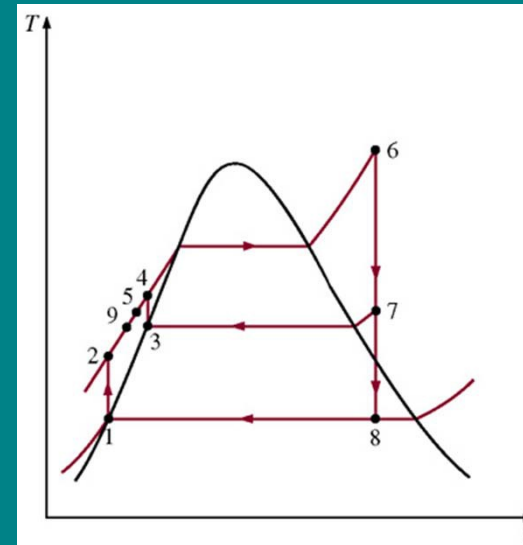
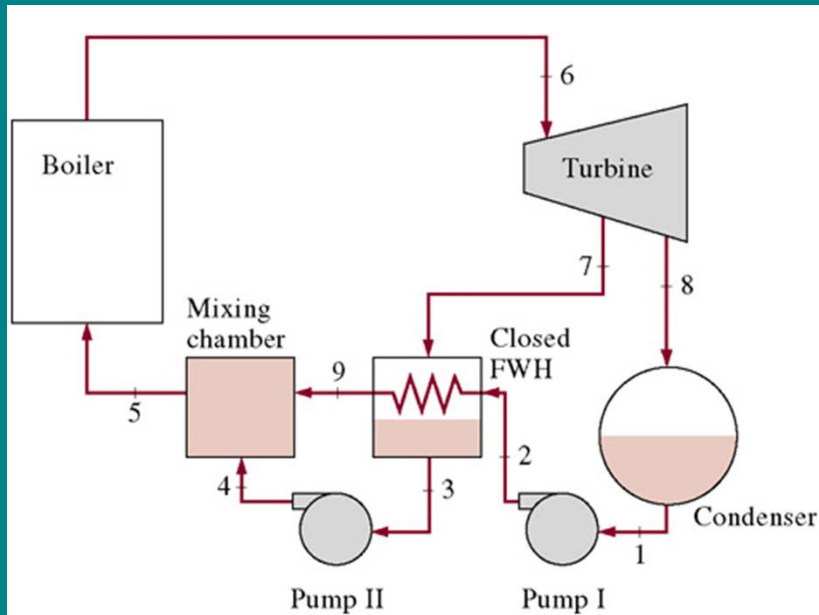
$$\dot{m}_5 = \dot{m}_4 + \dot{m}_9$$

$$\dot{m}_5 h_5 = \dot{m}_4 h_4 + \dot{m}_9 h_9$$

$$\dot{m}_4(h_7 - h_3) = \dot{m}_9(h_9 - h_2)$$

Improved Rankine cycle - Regeneration

- Rankine cycle with closed feedwater heater



$$\eta_{Rankine} = \frac{get}{pay} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{turb,1} + \dot{W}_{turb,2} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{Q}_{in}} =$$

$$= \frac{\dot{m}_5(h_6 - h_7) + \dot{m}_9(h_7 - h_8) - \dot{m}_9(h_2 - h_1) - \dot{m}_4(h_4 - h_3)}{\dot{m}_5(h_6 - h_5)}$$

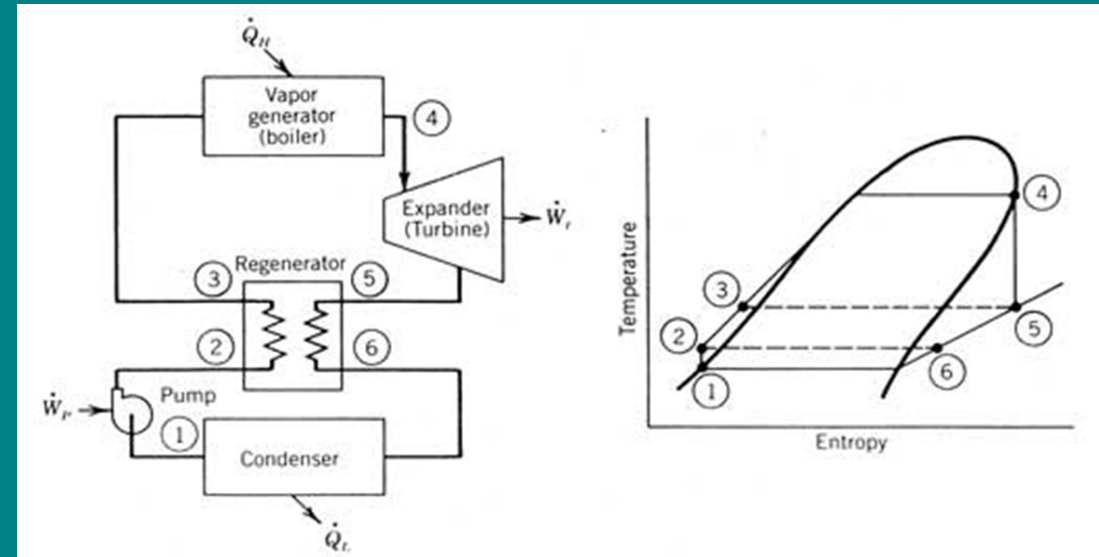
Organic Rankine Cycle (ORC)

- Organic liquid instead of water
- Typical operational range from few kW up to 3-4 MW
- High efficiency turbine
- No corrosion and erosion problems
- Long lifetime

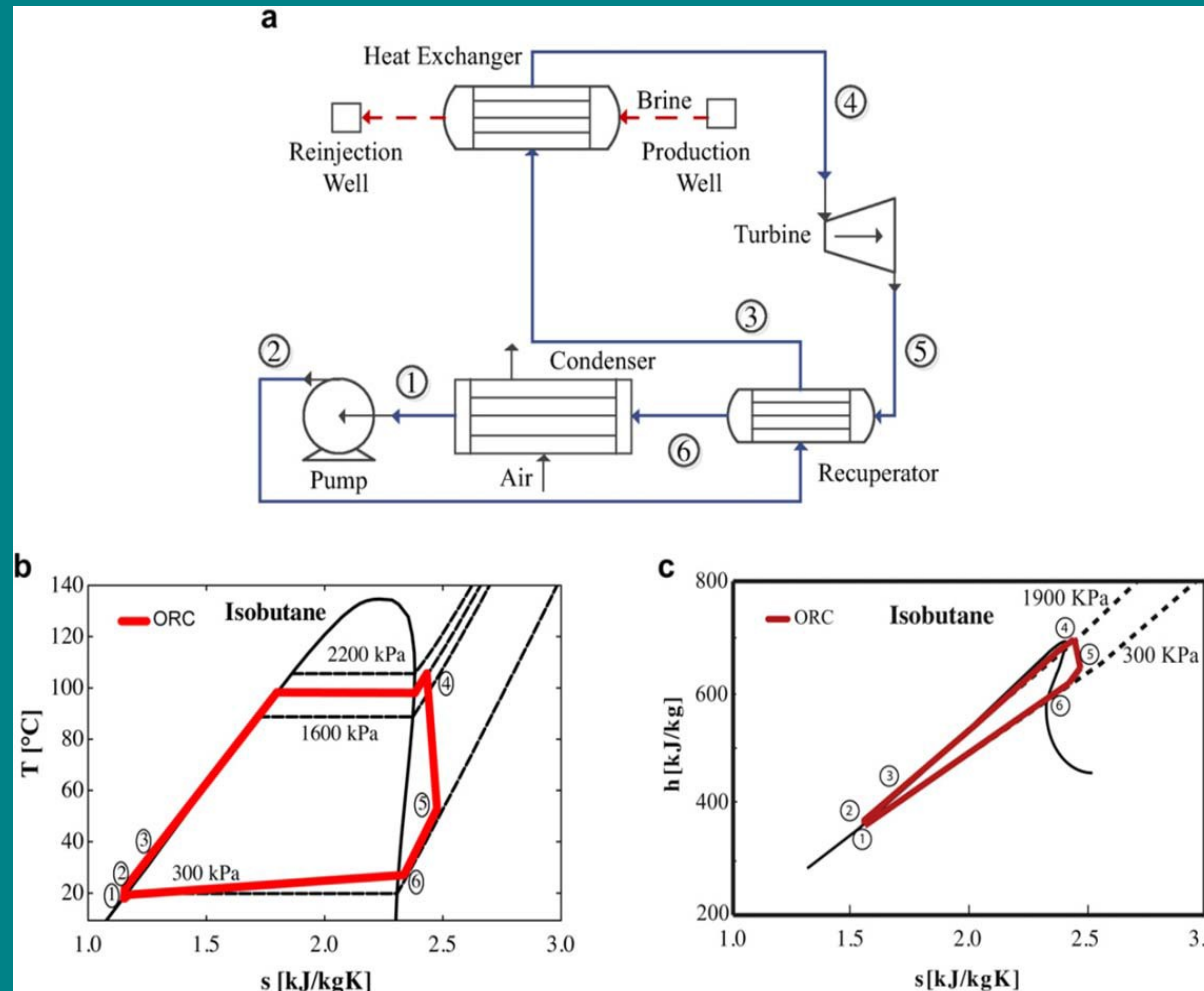


Organic Rankine cycle (ORC)

- For low temperature sources (solar/geothermal/waste heat) the conventional (water) Rankine cycle has very low efficiency. To improve that an organic Rankine cycle was introduced
- Main difference is in working liquid which for ORC is an organic, high molecular mass liquid with boiling point at lower temperature (octane, isopentane, toluene etc.).
- Organic liquids have also different (from water) liquid-vapor dome, which promotes them to application for ORC systems with regenerator



Organic Rankine cycle (ORC)



Ghasemi et al., Modeling and optimization of a binary geothermal power plant, *Energy* (2013), 412-428

Lets' set the stage for the ORC



‘External’ thermal energy source (no internal combustion)

Y Geothermal reservoir

Y Solar radiation

Y (“Dirty”) biomass combustion/gasification, landfill gas, waste incineration

Y Thermal power recovery: recip engines, gas turbines, industrial waste heat

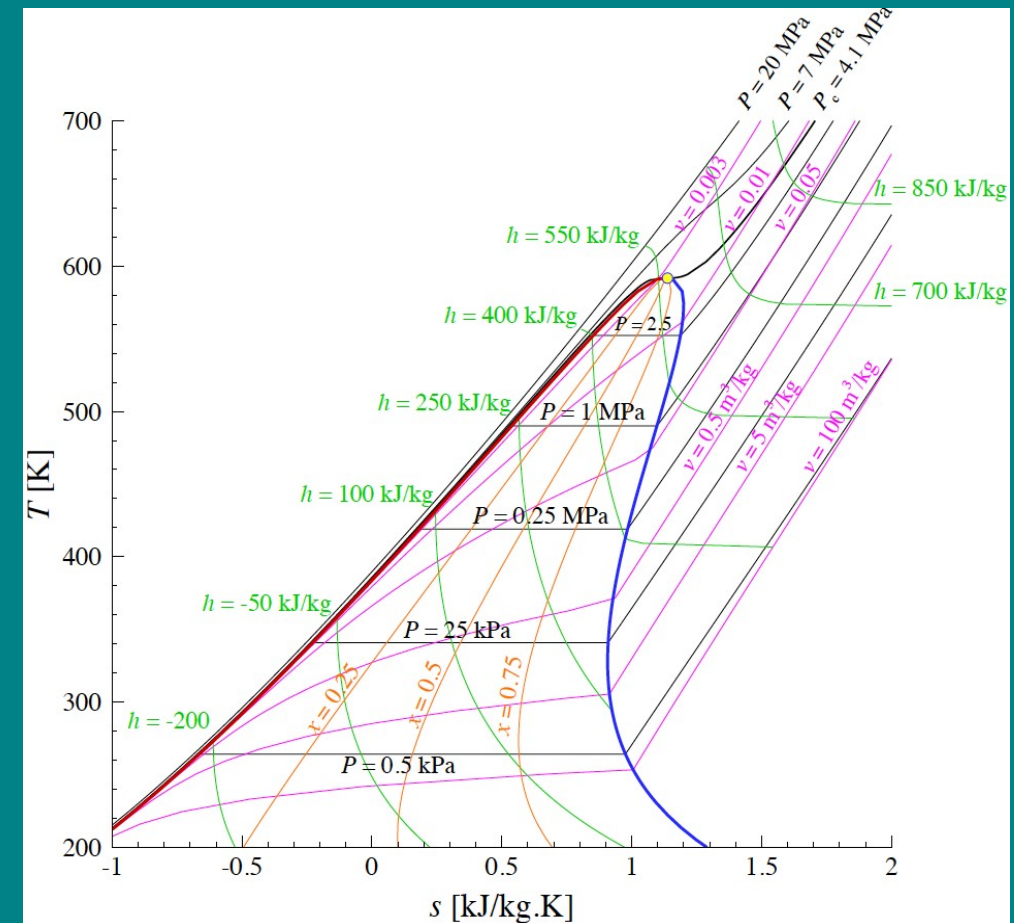
AND

Small-to-medium power capacity (few kW_e to few MW_e per unit)

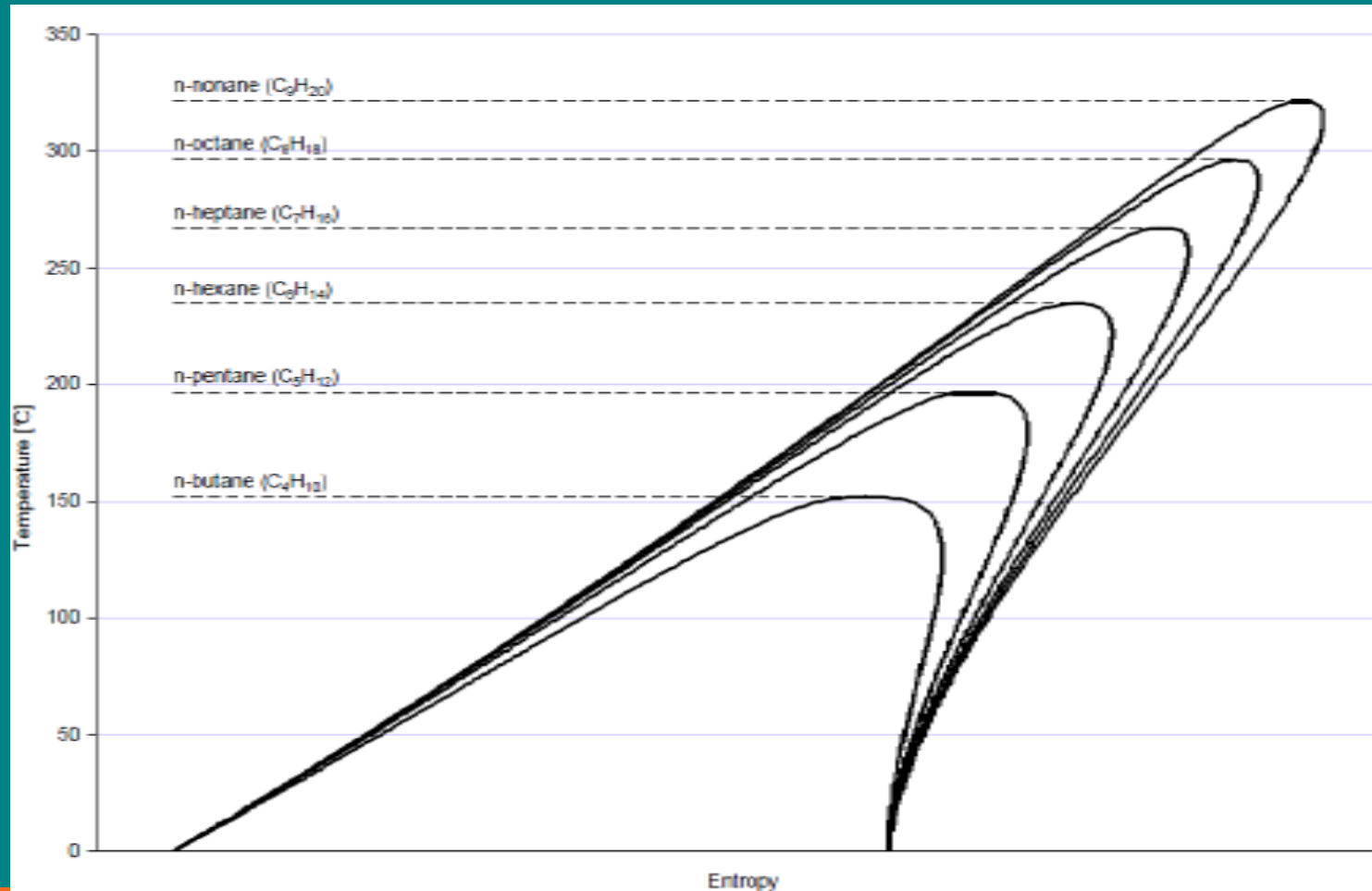
Rankine cycle but... WATER

Why an organic fluid?

- Y Fluid $\rightarrow T_c, P_c, \Delta h, \beta$, volume flow, (condenser P)
- Y P and T level of the cycle
- Y Cycle configurations: saturated, superheated, supercritical (at low P)
- Y Simple layout even for high TIT/T_{cond}
- Y Non-extractive regeneration
- Y Dry expansion
- Y Working fluid can be used as lubricant



Some ORC Working Fluids



Working fluids

Not only cycle thermodynamics and turbine design...

Thermal stability

Toxicity Availability

(cost)

Flammability

ODP

GWP

Options:

- ./ Linear and aromatic hydrocarbons
- ./ Fluorocarbons (Refrigerants)
- ./ Perfluorocarbons
- ./ Linear and cyclic Siloxanes

Status

Geothermal: ~1500 MW_e installed

Biomass combustion:
in Europe impressive growth (several hundreds of plants)

Solar: pilot plants, large potential

Heat recovery: few plants and quickly increasing (process and oil industry)

Ideas and early developments: automotive heat, Domestic μ CHP, recovery,
ship and train engines HR



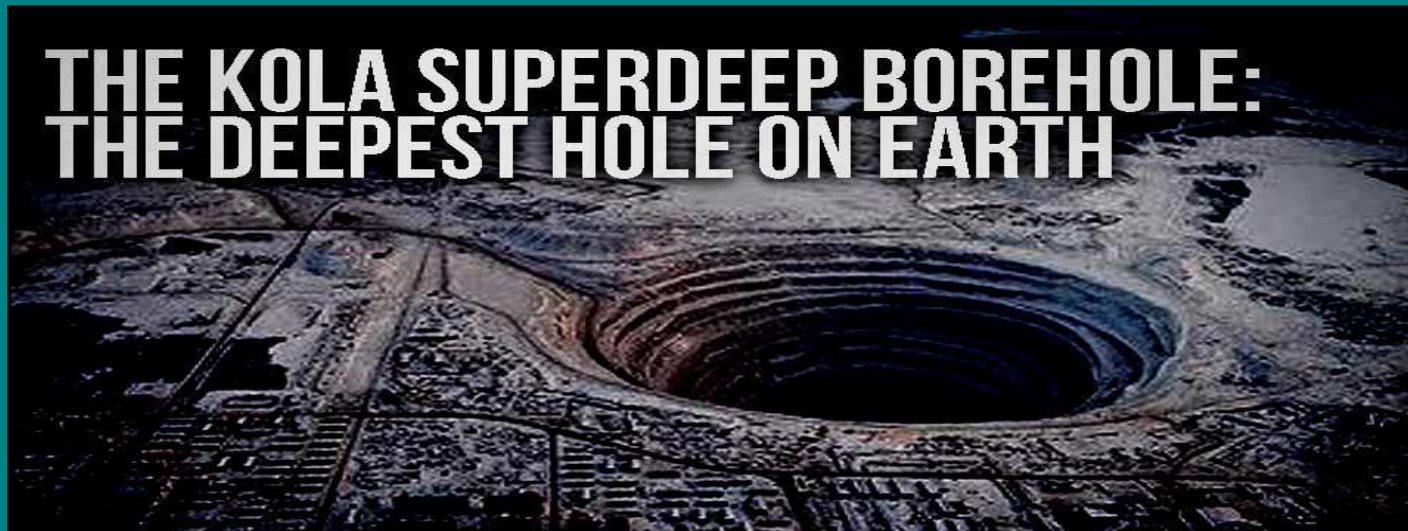
Geothermal power systems

- The Earth's heat content is about 10^{31} J. This heat naturally flows to the surface by conduction at a rate of 44.2 TW.
- Most of this power is very diffuse (approximately 0.1 W/m^2 on average) to be recoverable.
- Geothermal gradient is approx. $25\text{--}30 \text{ }^\circ\text{C/km}$ in most of the world, and wells would have to be several kilometers deep to permit electricity generation.
- The quantity and quality of recoverable resources improves with drilling depth and proximity to tectonic plate boundaries
- At present, geothermal wells are rarely more than 3 km deep



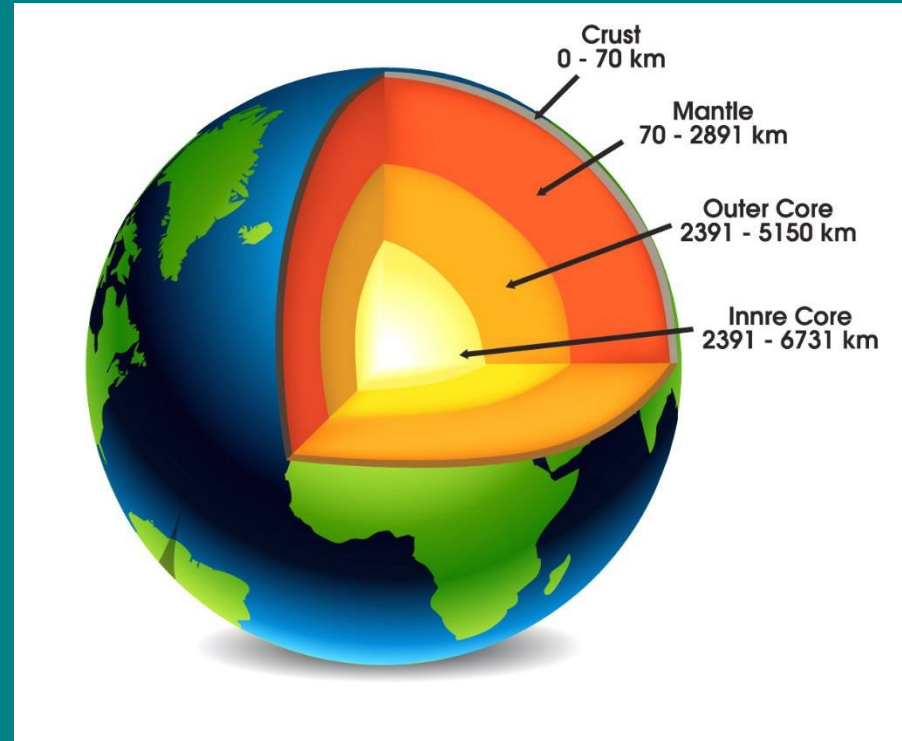
Geothermal power systems

- Oil companies are already drilling down to 5-10 km where temperatures can reach up to 300°C. However, drilling becomes a challenge due to the high temperatures and pressures. Wells drilled to depths greater than 4 km generally incur drilling costs in the tens of millions of dollars.
- The deepest research well in the world, the Kola superdeep borehole, is 12.3 km deep.
- Typical efficiency of a geothermal power plant is about 15-20%



Geothermal plants

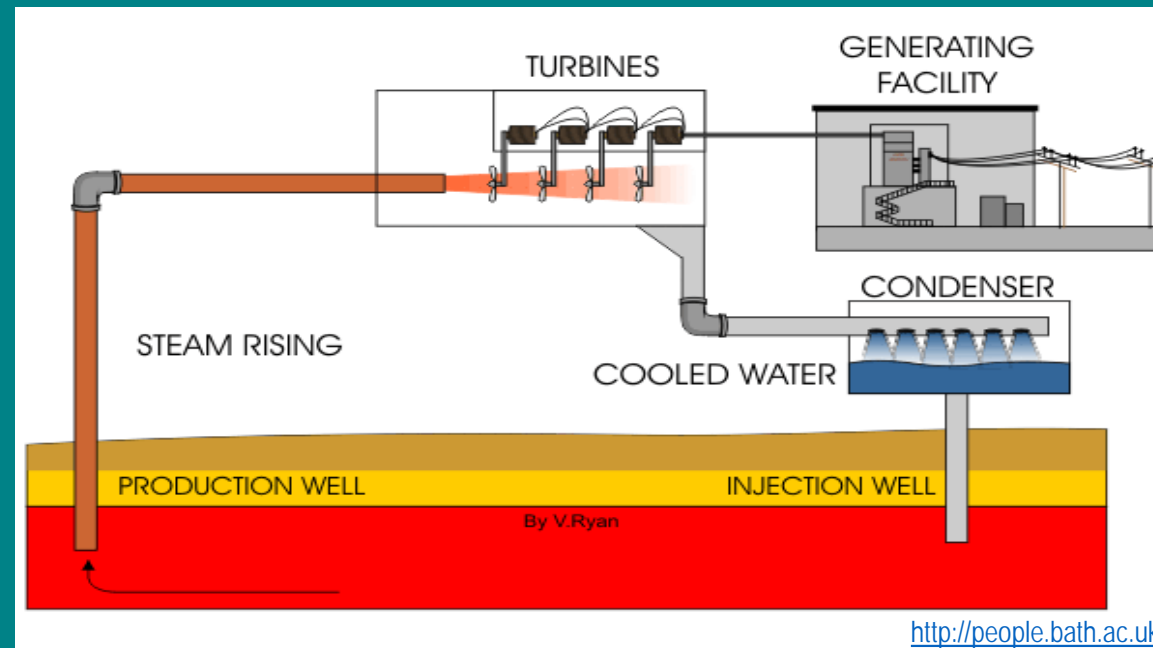
- The following types of geothermal power plants have been used for power generation:
 - Dry steam
 - Flash steam
 - Binary cycle
- Key features of geothermal systems
 - Small land footprint
 - High availability
 - High capacity



Dry steam power plant

- Dry steam power plants operate directly on steam from geothermal reservoir
 - High cost effectiveness
 - High quality/pure steam
 - Steam dominated reservoirs are very rare

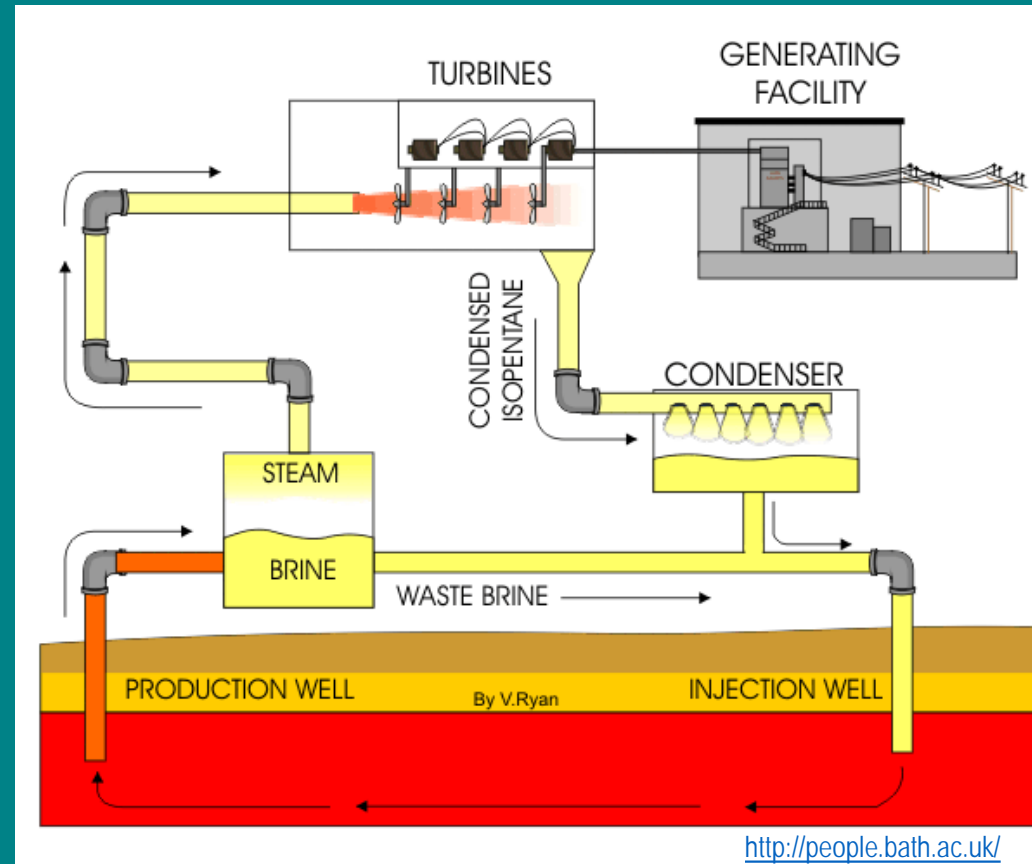
What is missing?



Flash steam power plant

- Flash steam power plants operate on steam separated from liquid
- The most common type of geothermal power plants

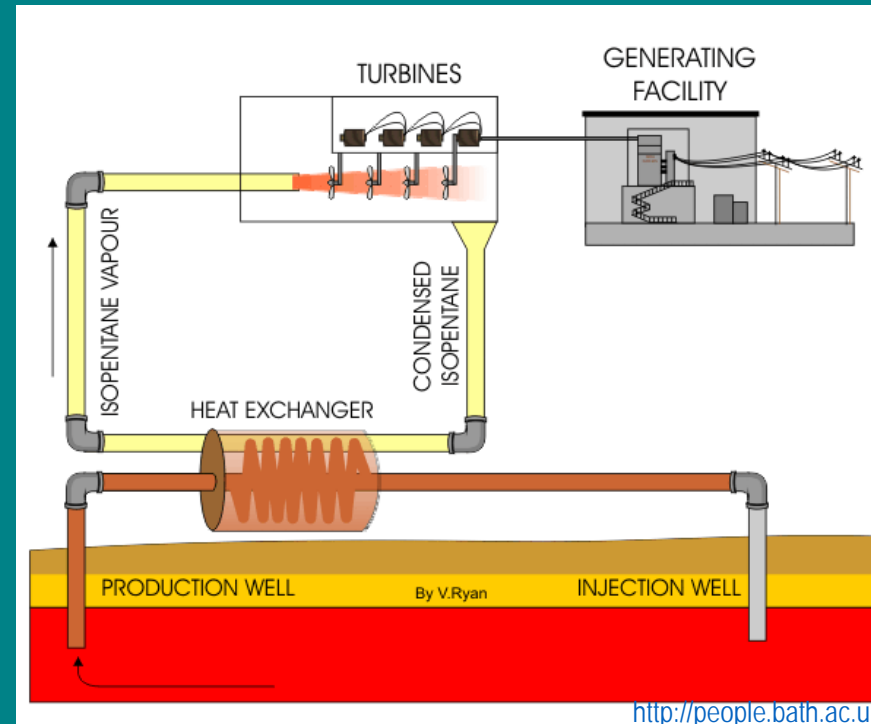
What is missing?



Binary power plant

- Binary power plants operate on two liquids i.e. geothermal water from the well and organic liquid or steam
- No emissions - working fluid has no contact with atmosphere

What is missing?



Assingment

1. Under which conditions do you make a choice for a flash, dry or binary system?
2. What happens when you lower the pressure of the liquid fraction after the water-vapor separator in a flash system, and how can the system be improved by making use of this?
3. Some efficiency improvements of a Rankine cycle have been discussed, such as:
 - a) Superheating
 - b) Lowering condensing pressure and temperature
 - c) Reheating
 - d) Add a feedwater pre-heaterIs it possible or usefull to make similar improvements to a flash system, to a binary system and to a dry system?

<http://people.bath.ac.uk/>