October 9-13, Yogyakarta

Overview power plant design

Training for engineers on Geothermal Power Plants
Theo van der Meer

Contents

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

List of Geothermal Power Plant in Indonesia

Geothermal Installed Turbine Data in the Geothermal Power Plant in Indonesia (Compiled by Sanusi Satar)					
Status per January 2016					
Location	No. Of Unit	Capacity	Manufacturer	Operator	Remark
Sibayak	2	5,6 MW / Ea	Harbine Turbine - China		Condensing Single Flash
Mataloko	1	2,5 MW	Qingdao Jieneng - China	PLN	
Kamojang	5				
	Unit 1	30 MW	Mitsubishi - Japan	Indonesia Power	Owned by PLN
	Unit 2	55 MW	Mitsubishi - Japan	Indonesia Power	Owned by PLN
	Unit 3	55 MW	Mitsubishi - Japan	Indonesia Power	Owned by PLN
	Unit 4	60 MW	Fuji - Japan	PGE	
	Unit 5	35 MW	Fuji - Japan	PGE	

List of Geothermal Power Plant in Indonesia

Lahendong	4				
	Unit 1	20 MW	Alstom -	PGE	
	Unit 2	20 MW	Fuji - Japan	PGE	
	Unit 3	20 MW	Fuji - Japan	PGE	
	Unit 4	20 MW	Fuji - Japan	PGE	
Ulubelu	2				
	Unit 1	55 MW	Fuji - Japan	PGE	
	Unit2	55 MW	Fuji - Japan	PGE	
Dieng	1				
	Unit 1	60 MW	Ansaldo Energia - Italy	Geodipa	
Patuha	1				
	Unit 1	55 MW	Toshiba - Japan	Geodipa	Name Plate : 59.8 MW

List of Geothermal Power Plant in Indonesia

Drajat	3					
		Unit 1	55 MW	Mitsubishi - Japan	Indonesia Power	Owned by PLN
		Unit 2	95 MW	Mitsubishi - Japan	Chevron	
		Unit 3	121 MW	Mitsubishi - Japan	Chevron	
Salak	6					
		Unit 1	60 MW	Ansaldo Energia - Italy	Indonesia Power	Owned by PLN
		Unit 2	60 MW	Ansaldo Energia - Italy	Indonesia Power	Owned by PLN
		Unit 3	60 MW	Ansaldo Energia - Italy	Indonesia Power	Owned by PLN
		Unit 4	65.6 MW	Fuji - Japan	Chevron	
		Unit 5	65.6 MW	Fuji - Japan	Chevron	
		Unit 6	65.6 MW	Fuji - Japan	Chevron	
Wayang Windu	2					
		Unit 1	110 MW	Fuji - Japan	Star Energy	
		Unit 2	117 MW	Fuji - Japan	Star Energy	

List of Geothermal Power Plant in Indonesia

## Total installed capacity: 1,428.5 MWatt

- Tenders for:

- Way Ratai, Lampung   70,710 ha, 105 MW reserves, 55 MW capacity
- Marana, Central Sulawesi   48,300 ha, 36 MW reserves, 20 MW capacity
- Gunung Talang Bukit Kili, West Sumatra 27000 ha, 65 MW reserves, 20 MW capacity

List of Geothermal Power Plant in Indonesia

Map of Indonesia showing geothermal power plant capacities by region:

- 1,310 — NAD
- 3,628 — N SUM
- 25 — Riau
- 1,698 — W SUM
- 1,047 — Jambi
- 1,911 — S SUM
- 173 — Bengkulu
- 75 — BABEL
- 50 — W Kal
- 2,855 — Lampung
- 110 — Ulubelu
- 835 — Banten
- 1,626 — C Java
- 5,626 — W Java
- 10 — DIY
- 1,156.5 — E Java
- 310 — Bali
- 144 — W NT
- 1,042 — E NT
- 40 — Lahendong
- 865 — N Sul
- 225 — N Maluku
- 366 — C Sul
- 225 — Maluku
- 40 — Gorontalo
- 310 — SE Sul
- 374 — S Sul
- 50 — Papua

SPECULATIVE =	9,468	MWe
HYPOTHETIC =	4,613	MWe
POSSIBLE =	10,027	MWe
PROBABLE =	728	MWe
PROVEN =	2,305	MWe
TOTAL	27,141	MWe

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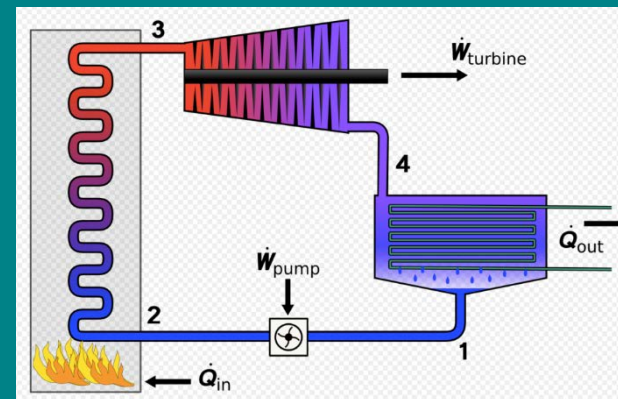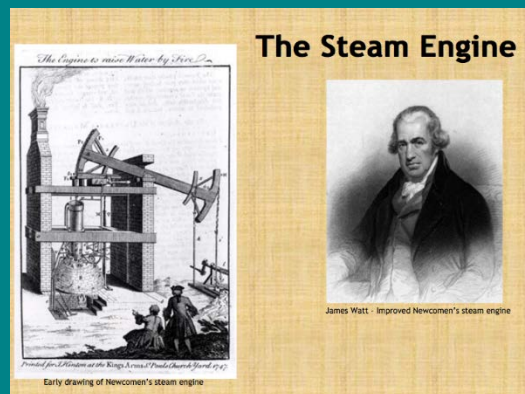
Systems and its boundaries
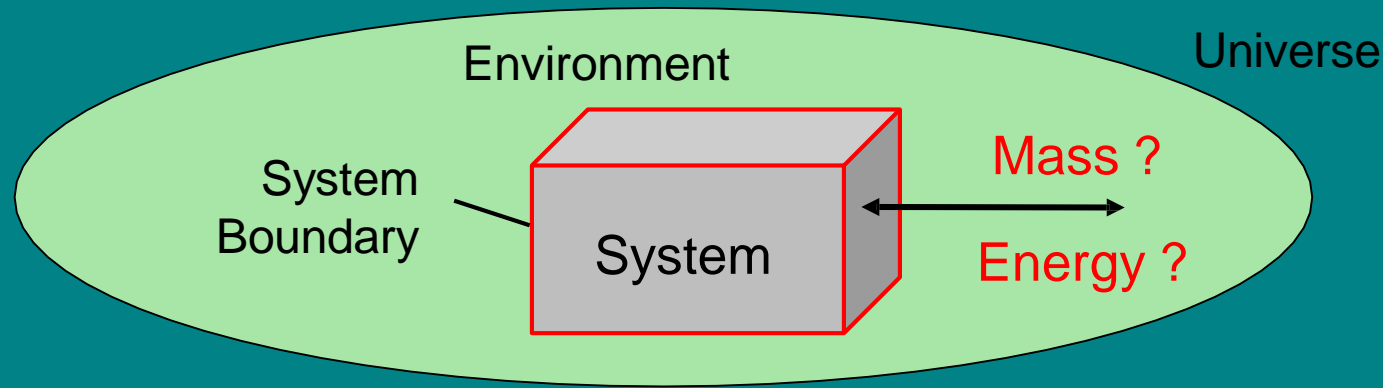
Based on the transport of mass and energy across the system boundary (rigid deformable or moveable) following system can be distinguished

- 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 ($q = 0$)

State B

Process path 2

Process path 1

State A
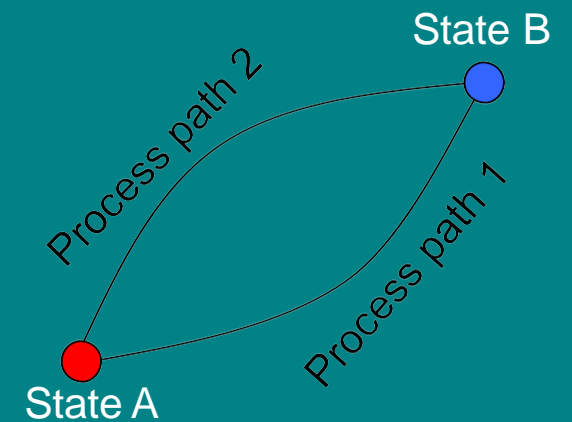
Total energy, work, heat, energy transfer

- 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)
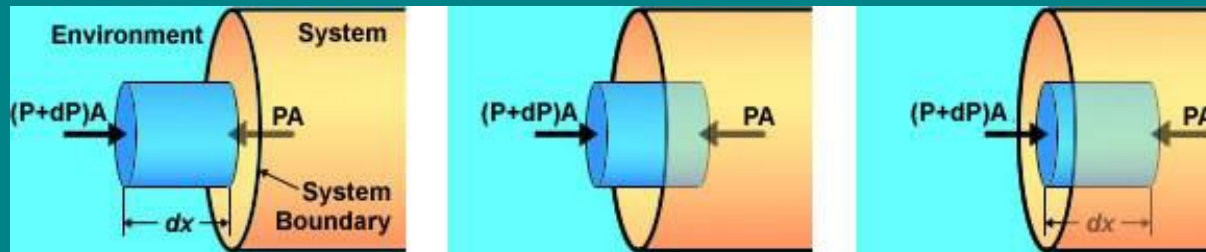
$$\delta W_{flow} = \mathbf{F \cdot dx} = \mathbf{PAdx} = \mathbf{Pd(Ax)} = \mathbf{PdV} = \mathbf{Pd(vm)} = \mathbf{Pvdm} \rightarrow [\mathbf{J}]$$

- 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**
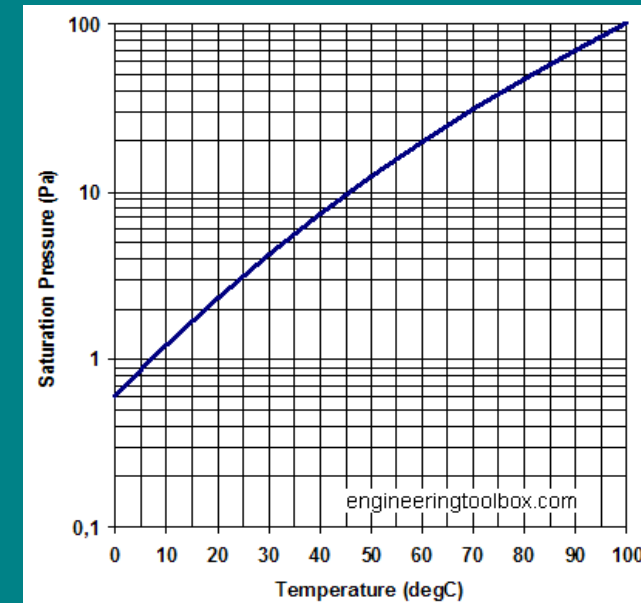
Compressed liquid and superheated vapor

- 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**
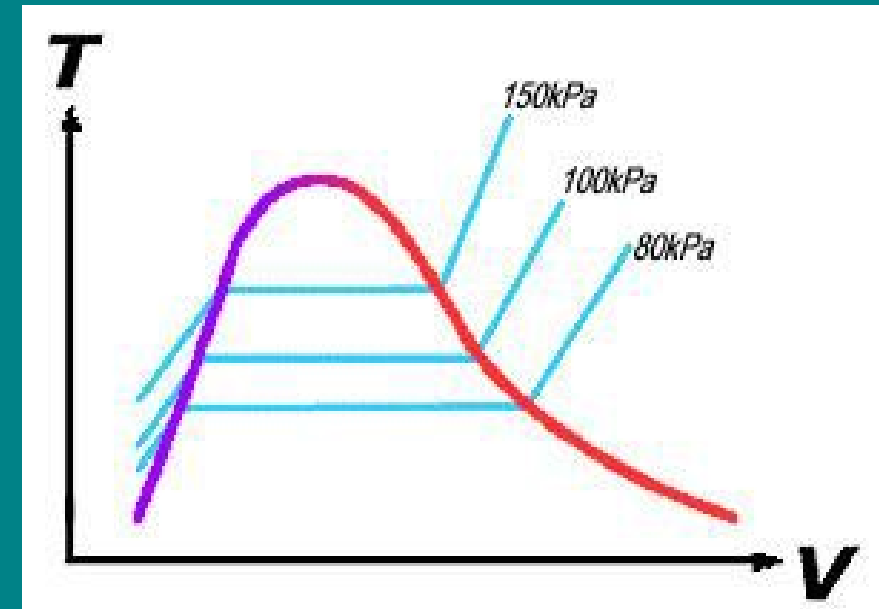
Phase change
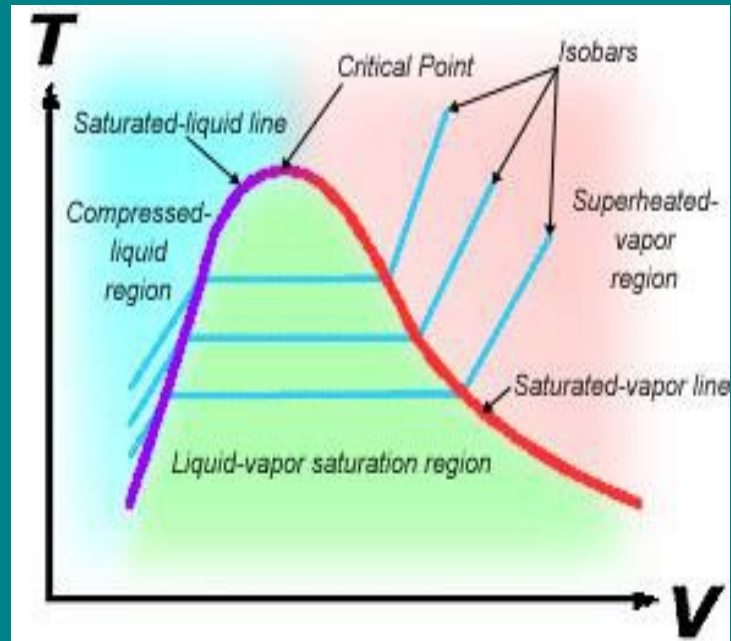
Note directions of isobars (constant pressure lines) horizontal inside the dome and rising slope outside
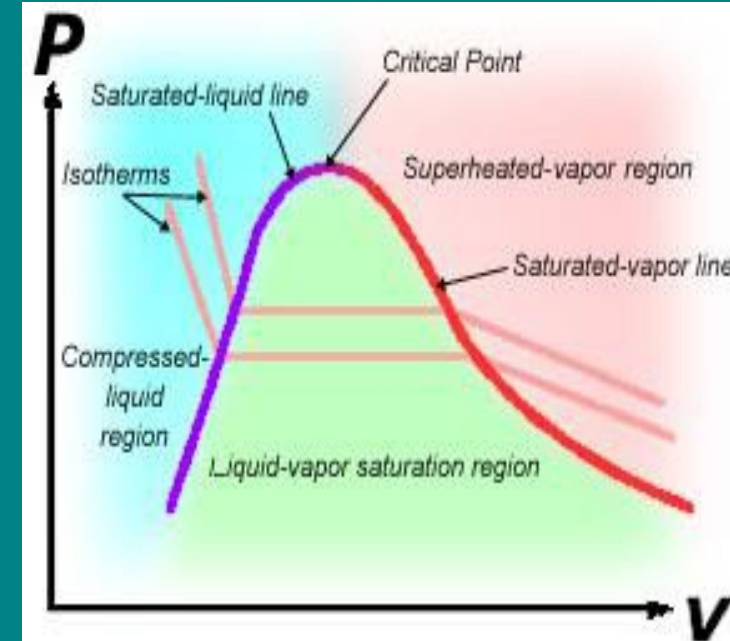
Note directions of isotherms (constant temperature lines) horizontal inside the dome and decreasing slope outside

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 → extra parameter, **x** mass fraction of vapor, is needed

  - $m = m_L + m_V$

  - $x = m_V / m$

  - $x = (v-v_L) / (v_{LV})$ → similar for u, h, s, etc.
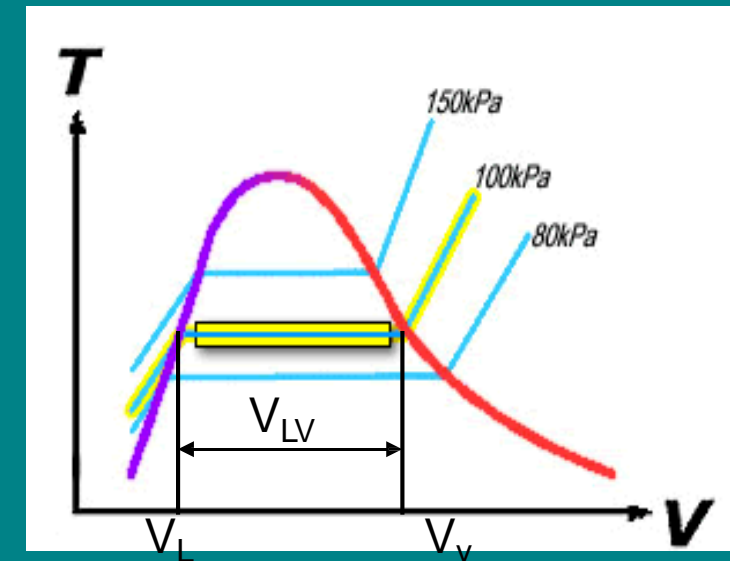
Finding the properties of a substance

- $v, u, s, h \ldots < v_L, u_L, s_L, h_L \ldots \rightarrow$ 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

- ...
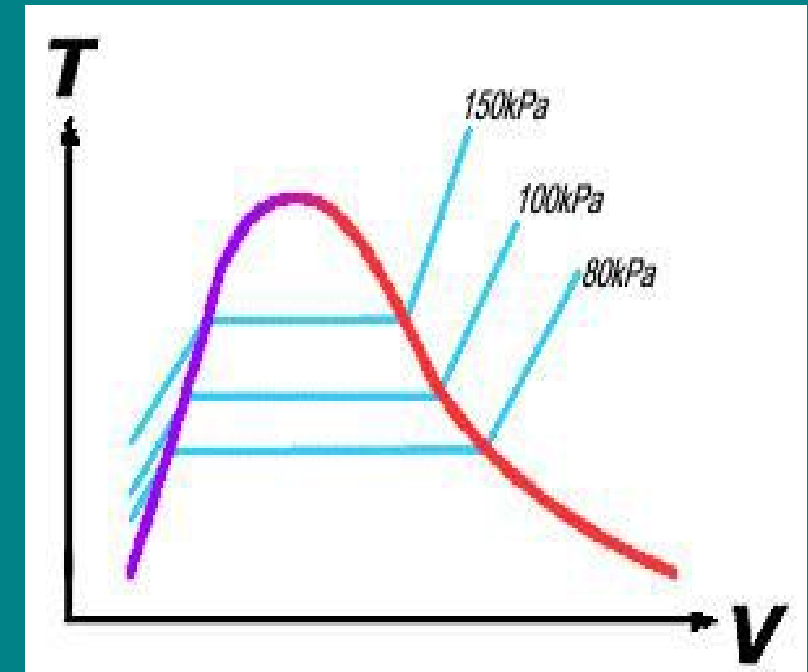
Compressed liquid data approximation

- $v_{CL}(T,P) \cong v_L(T)$

- $u_{CL}(T,P) \cong u_L(T)$

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

  - Recall $h = u + Pv$ → h sensitive to P

  - If $P \cong P_{SAT}(T)$

    → $h_L(T) \gg v_L(T) [P - P_{SAT}(T)]$

    → $h_{CL}(T,P) \cong h_L(T)$

- 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**

Known from the tables [m^3/kg]:
- $v_{CL}(70^0C, 5000$ kPa$) = 0.00102$
- $v_L(70^0C) = 0.00102$
- $v_L(5000$ kPa$) = 0.00129$

Finding the properties of a liquid
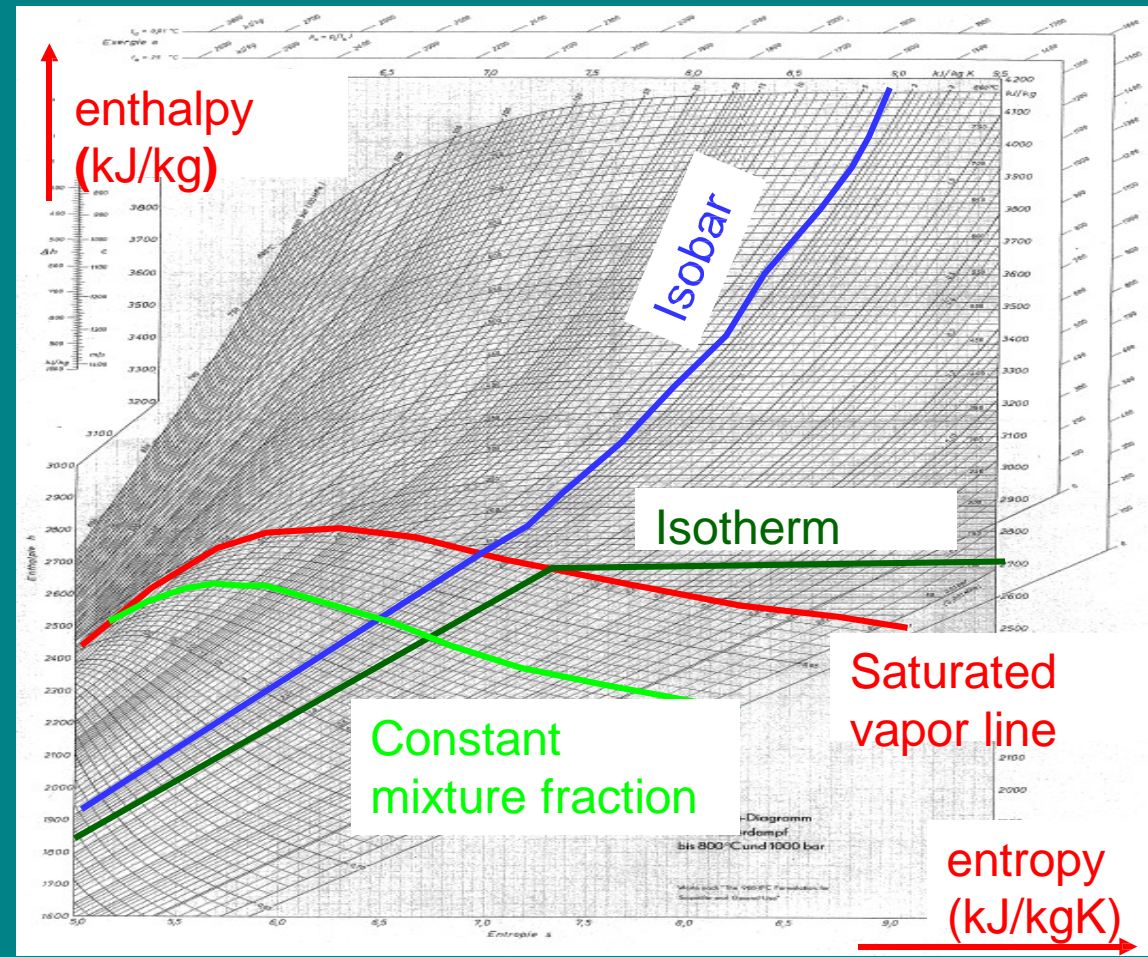
Be carefull with the reference temperature and pressure

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_{air} = 0.287 kJ/(kg K)
- Both are related by $R_u = RM$ where M is the molar mass (M_{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 → $u = u(T) \neq u(P)$
  - **Enthalpy**, $h = u + Pv = u + RT$, for an **ideal gas** also only depends on temperature → $h = h(T) \neq h(P)$
  - 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:

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v \qquad c_P = \left(\frac{\partial h}{\partial T}\right)_P$$

- For an **ideal gas**:

$$\Delta u = \int_{T_1}^{T_2} c_v \, dT \quad \text{and} \quad \Delta h = \int_{T_1}^{T_2} c_P \, dT$$

- Note: In general the specific heat depends on temperature ($c_i = c_i(T)$)

Finding the properties of a gas
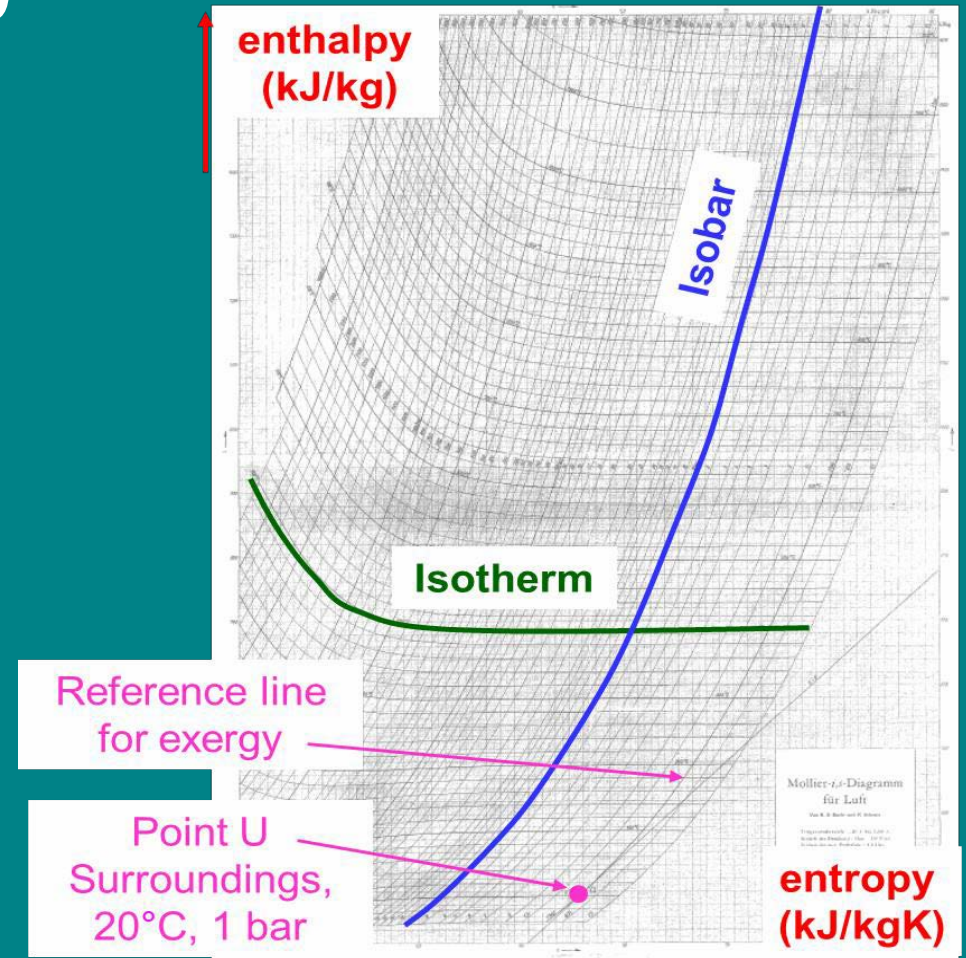
First law of thermodynamics

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

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

- 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
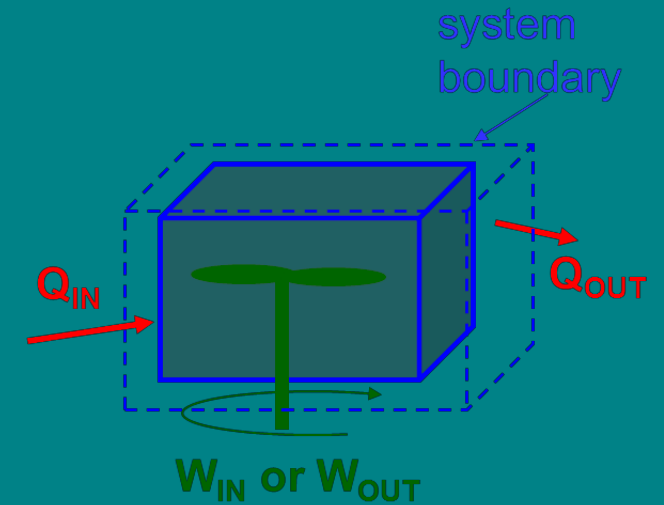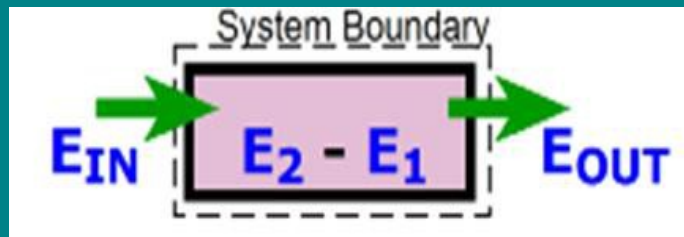
First law of thermodynamics

- 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:

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

$$- \left[\dot{Q}_{OUT} + \dot{W}_{OUT} + \sum_{j=1}^{N} \dot{m}_{OUT,j}\left(h_j + ke_j + pe_j\right) \right]$$
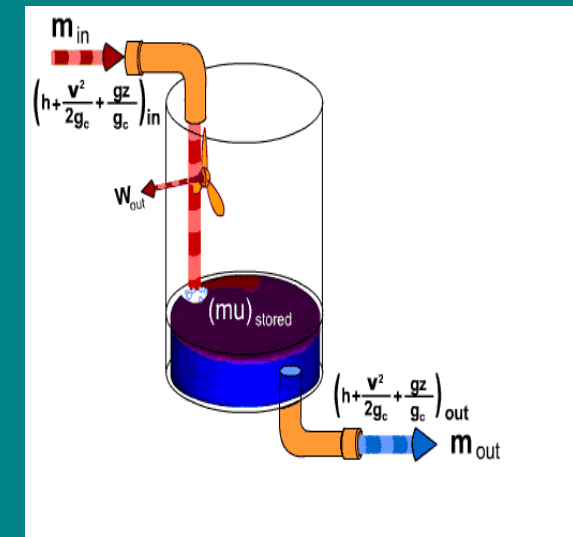
First law of thermodynamics

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

- The **energy balance** changes to:

$$\dot{E}_{IN} - \dot{E}_{OUT} = \frac{dE_{cv}}{dt}^{0,\,SS} \quad \Rightarrow \quad \dot{E}_{IN} = \dot{E}_{OUT}$$

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

- 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
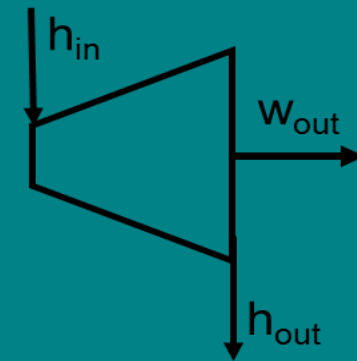
Entropy and second law

- 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)

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

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

$$dh = du + Pdv + vdP \quad \rightarrow \quad \boxed{Tds = dh - vdP}$$

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: $\delta s_{gen} = ds_{system} + ds_{surroundings} \geq 0$

- 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)

II

The entropy of a closed system shall never decrease, and shall increase whenever possible.
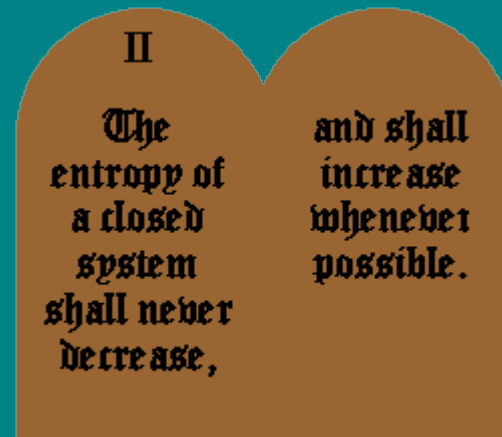
Entropy and second law
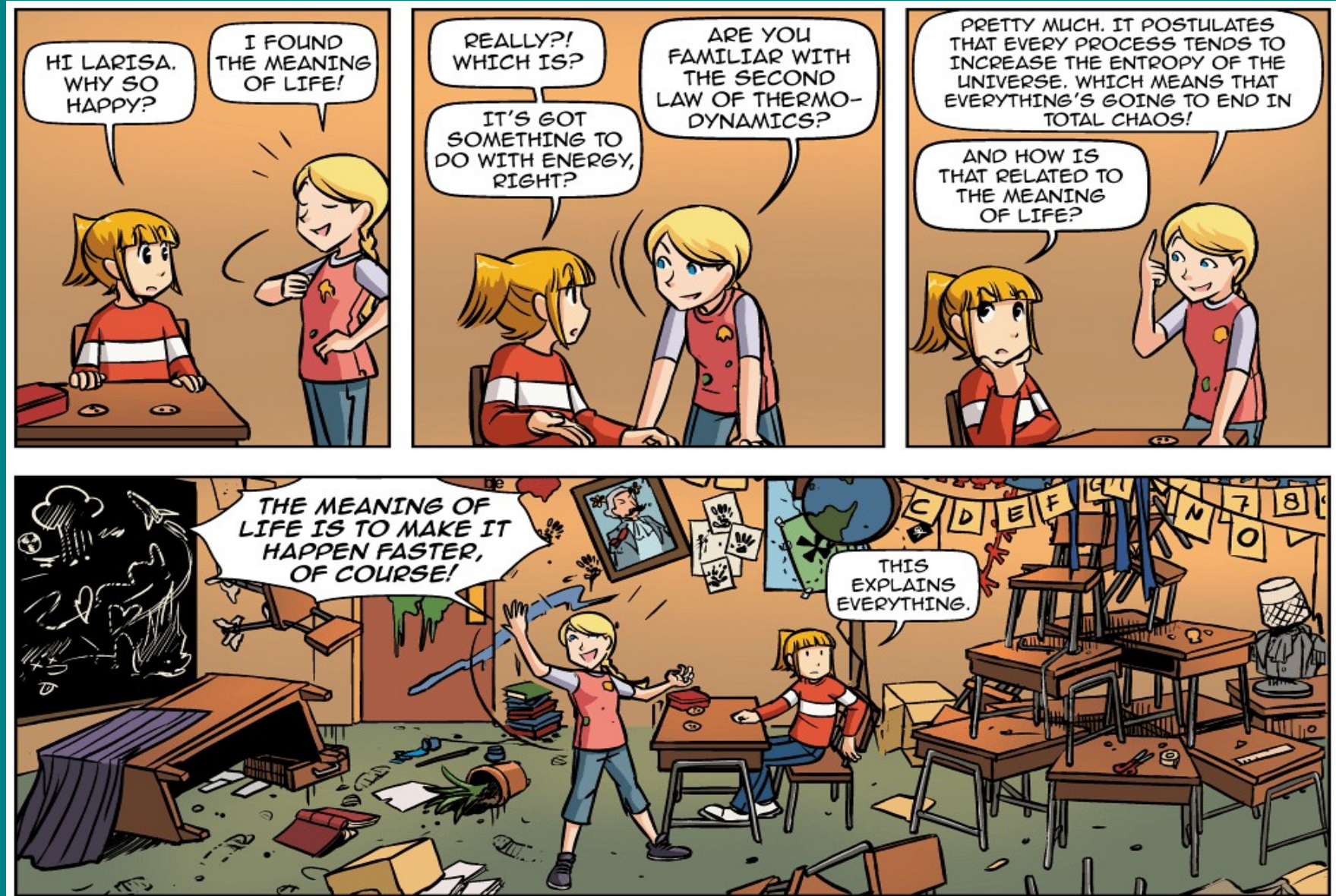
Sandra and Woo by Oliver Knörzer (writer), Powree (artist) and Lisa Moore (colorist) - www.sandraandwoo.com

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
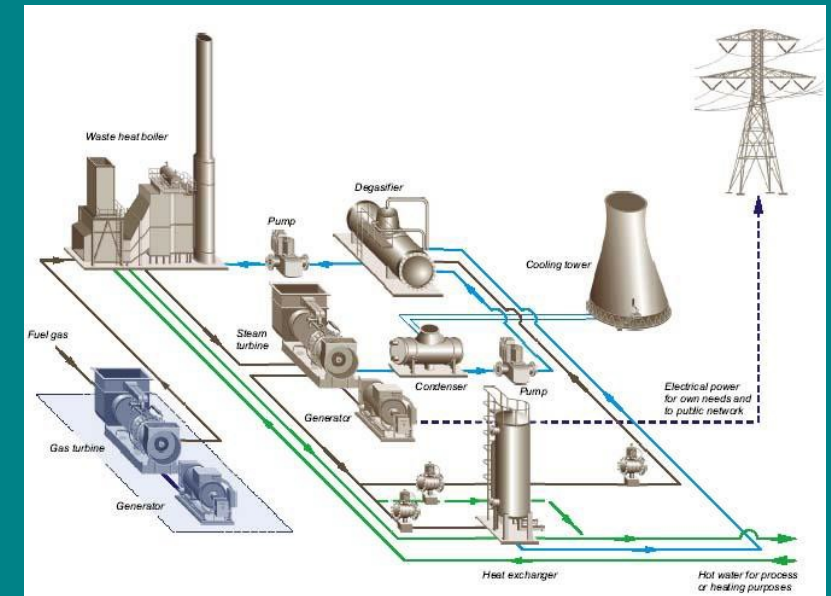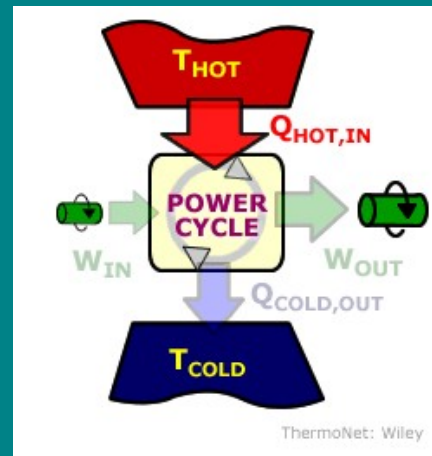
Thermodynamic cycles

- 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:**

$$q_{in} - q_{out} = w_{out} - w_{in} \rightarrow q_{net} = w_{net}$$

(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:

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

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

- Note: the efficiency is only 100% if $q_{out} = 0$ → 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-hot} = 800°C and T_{1-cold} = 20°C with η_{1-he} = 40%
- Assume a heat engine 2 working between T_{2-hot} = 200°C and T_{2-cold} = 20°C with η_{2-he} = 30%

Which of these engines is better?
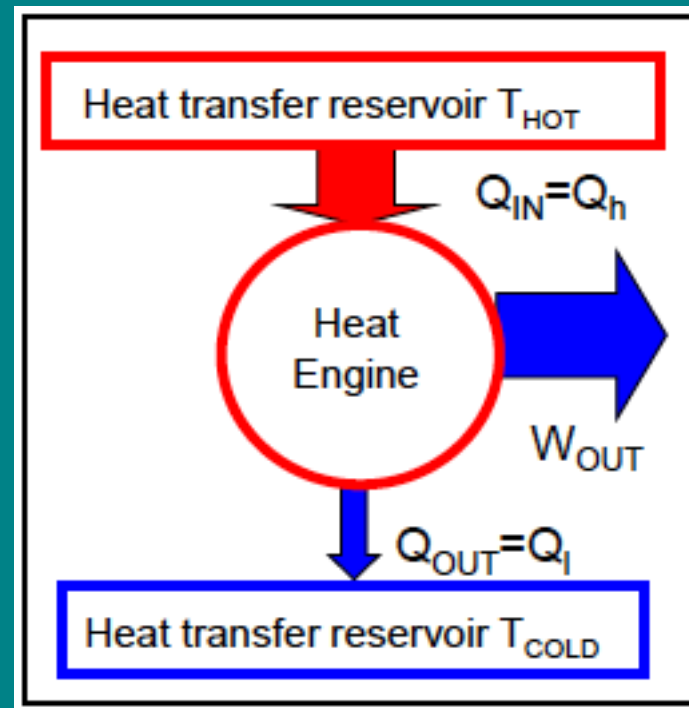
Real vs theoretical maximum efficiency

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

Efficiency of a cyclic process – closed system

Consider a cyclic reversible process exchanging in a cycle heat Q, at temperature T, to a fluid in a closed system, with two heat reservoirs indicated with indices h and l. Qh is received, Ql is released by the process. Work W is generated.

$$\oint \frac{\delta Q}{T} \leq 0$$

$$\frac{Q_h}{T_h} - \frac{Q_l}{T_l} \leq 0$$

Reversible process: $\frac{Q_h}{T_h} - \frac{Q_l}{T_l} = 0$
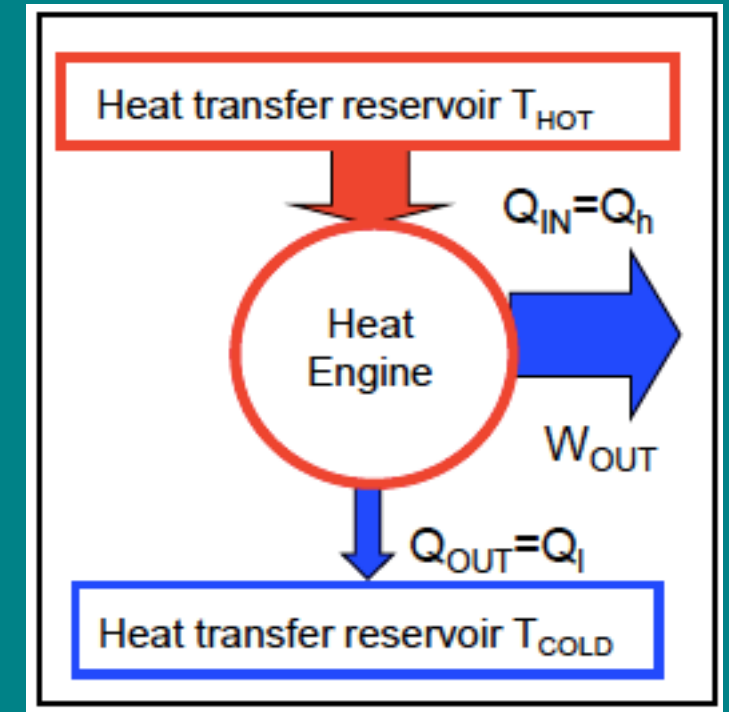
$$\frac{Q_l}{Q_h} \geq \frac{T_l}{T_H}$$

Efficiency of a cyclic process – closed system

For a closed cycle (first law) dU=0, thus dU=Qh-Ql-W=0

The efficiency of the system is given by:

$$\eta = \frac{W}{Q_h}$$

$$W = Q_h - Q_l$$

$$\eta = \frac{Q_h - Q_l}{Q_h} = 1 - \frac{Q_l}{Q_h}$$

$$\frac{Q_l}{Q_h} \geq \frac{T_l}{T_H}$$

which implies:

$$\eta \leq 1 - \frac{T_l}{T_h}$$
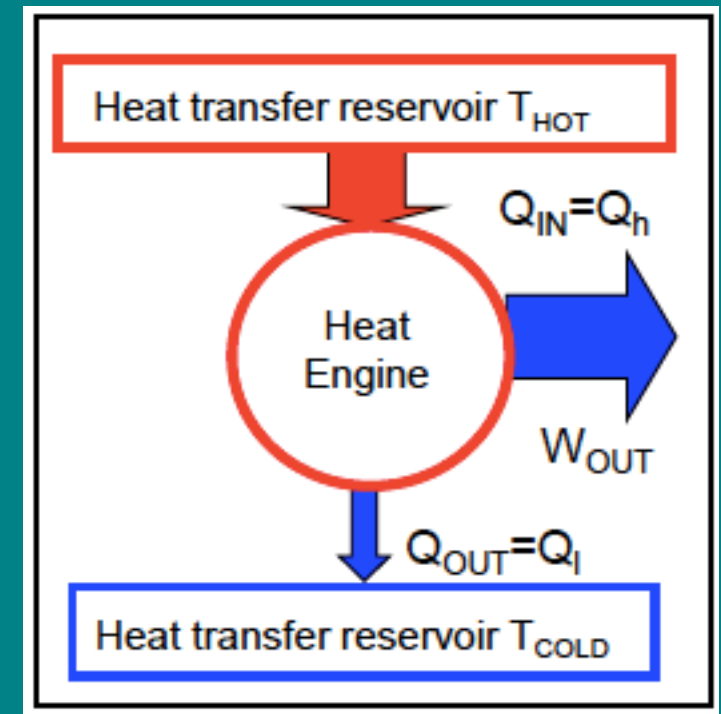
Efficiency of a cyclic process – closed system

It means that: $$\eta \leq 1 - \frac{T_l}{T_h}$$

All work can be converted into heat but heat is only partly converted into work, the rest of heat is transferred to heat of low temperature

The amount of energy converted into work is called EXERGY [J] Energy that can not be converted into work is called ANERGY [J]

Exergy is a measure for the **quality of energy** rather than for the quantity. Work is exergy

Exergy

There are limitations on conversion of energy

All work (100% exergy) can be converted to heat, but not vice versa !
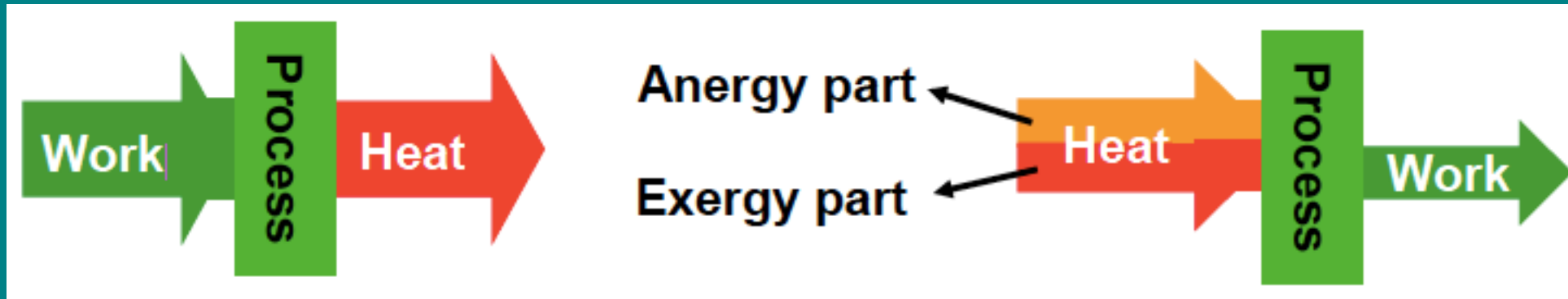
Heat can be subdivided in exergy and anergy. Exergy is completely convertible into work; anergy is not convertible to work

In engineering practice heat is always stored in a fluid, e.g. in a steam power plant we will encounter **a flow of steam or hot gas** with a certain *enthalpy,* in a piston engine - **a volume of gas** with a certain *internal energy*.

Exergy

- In the second law analysis we are interested in what is the **maximum work** that heat, mostly in the form of internal energy or enthalpy in a flow, can generate

- Therefore we use the property **exergy** (Ψ or B or Ex) with the dimensions of energy [J] or specific exergy ($\square$ or b or ex) with dimension [J/kg]

- **Exergy** is the energy available to do **useful** work, the unavailable energy or the **non-useful** work is described by **anergy**
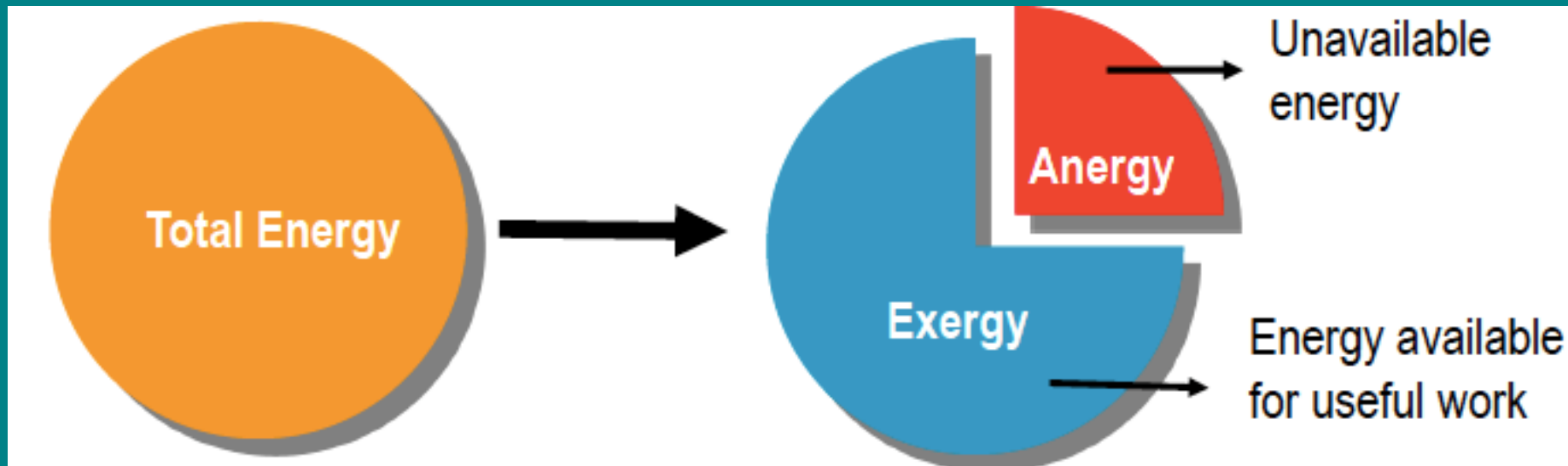
Exergy

- **Exergy** is not an absolute quantity

- **Exergy** is measured relative to a **reference state** (often equilibrium with the surroundings (dead state))

- A system **in equilibrium with its surroundings** is said to be in its **dead state**, it cannot undergo a spontaneous process and produce useful work

- At the dead state, the system temperature ($T0$), pressure ($P0$), velocity ($v0$) and height ($z0$) are: **$T0 = TSURR$, $P0 = PSURR$, $v0 = vSURR$, $z0 = zSURR$**

- At the dead state the useful work potential of a system is zero

- Dead state equals typically to atmospheric conditions

Exergy

- To see how internal energy is related to exergy assume a closed system
- A reversible process produces the maximum amount of work
- The first law for a closed system is: $w_{out} - w_{in} + q_{out} - q_{in} = \Delta u$
- Reversible heat transfer to the surroundings is: $q_{net,rev} = T_0(s - s_0)$
- Combining both equations gives: $w_{net,rev} + T_0(s - s_0) = \Delta u$
- Remember that $w_{net,rev} = w_{useful} + w_{non\text{-}useful}$ therefore

$$w_{useful} + w_{non\text{-}useful} + T_0(s_1 - s_0) = \Delta u = u_1 - u_0$$

- Exergy is useful work and given by: $\psi_u = u_1 - u_0 - w_{non\text{-}useful} - T_0(s_1 - s_0)$
- Remember: $w_{non\text{-}useful} = -P_0(v_1 - v_0)$
- The exergy associated with the internal energy is:

$$\psi_u = u_1 - u_0 + P_0(v_1 - v_0) - T_0(s_1 - s_0)$$

- The first term: $u_1 - u_0$, is the internal energy relative to the dead state
- The second term: $P_0(v_1 - v_0)$, is the work done on the surroundings
- The third term: $T_0(s_1 - s_0)$, is the heat transfer to the surroundings

Energy conservation

- Energy balance over a turbine

In: $\dot{E}_{in} = \dot{m}(h_1 - h_0)$

Out: $\dot{E}_{out} = \dot{m}(h_{2a} - h_0)$ and $\dot{W} = \dot{m}(h_1 - h_{2a})$

Thus : $\dot{E}_{out} + \dot{W} = \dot{m}(h_1 - h_0)$

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

$\Delta\dot{E}_{tot} = \dot{E}_{out} - \dot{E}_{in} = 0$

Energy is conserved !
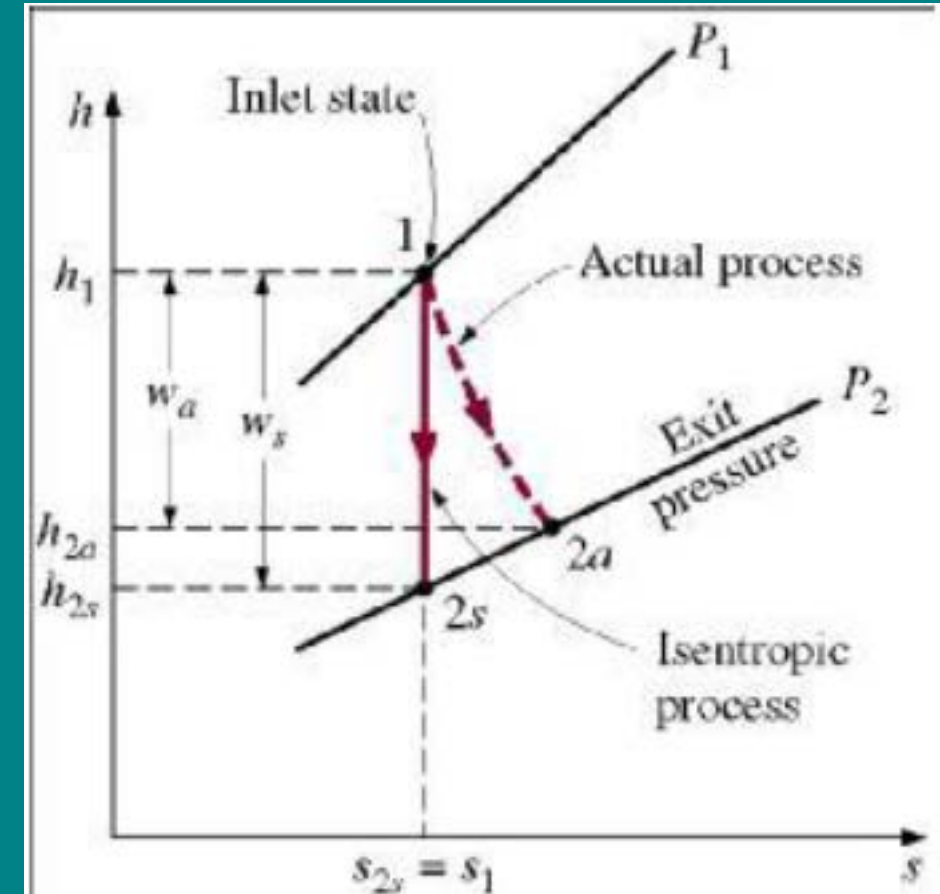
Exergy conservation????

• Exergy balans over a turbine

In: $\dot{\Psi}_{in} = \dot{m}((h_1 - h_0) - T_0(s_1 - s_0))$

Out: $\dot{\Psi}_{out} = \dot{m}((h_{2a} - h_0) - T_0(s_{2a} - s_0))$ and $\dot{W} = \dot{m}(h_1 - h_{2a})$

Thus : $\dot{\Psi}_{out} + \dot{W} = \dot{m}((h_1 - h_0) - T_0(s_{2a} - s_0))$

$\Delta\dot{\Psi}_{tot} = \dot{\Psi}_{out} - \dot{\Psi}_{in} = -T_0(s_{2a} - s_1)$

$\dot{Ex}_{in} > \dot{Ex}_{out}$

Exergy is not conserved !
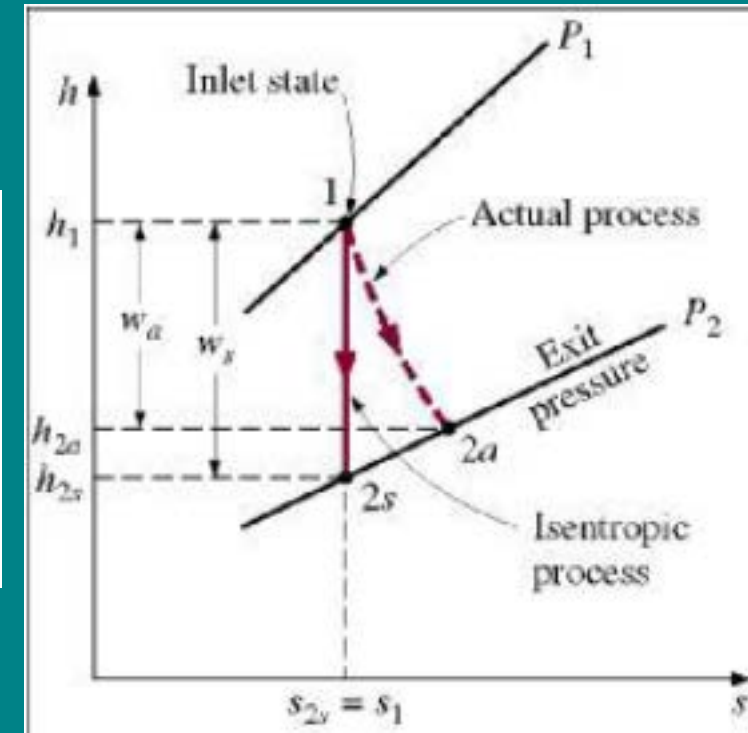
Exergy

Not all heat can be converted into work,

- Heat that can be converted is the **exergy** part

- Heat that can not be converted is the **anergy** part

- The maximum amount of heat that can be converted to work = exergy of the heat

- To convert heat into work a heat engine is used

- The maximum efficiency is achieved by a Carnot heat engine and is determined by the highest and lowest temperature

$$\eta_{CARNOT} = 1 - \frac{T_{COLD}}{T_{HOT}} = \frac{W_{net,rev}}{Q_{in}} \rightarrow W_{net,rev} = Q_{in}\left(1 - \frac{T_{COLD}}{T_{HOT}}\right)$$

T_{COLD} is the temperature of the environment = T_0 and T_{HOT} is the temperature of the heat source = T
The exergy transferred to the system due to heat transfer is: $\Psi_Q = Q\left(1 - \frac{T_0}{T}\right)$

Exergetic efficiency

Exergetic efficiency: $\eta_{ex} = \dfrac{exergy\ recovered}{exergy\ supplied}$ (LHV of fuels = exergy)

For a device with work output:

$$\eta_{SECOND\ LAW,OUTPUT} = \frac{W_{OUT}}{W_{OUT,REV}} = \frac{h_1 - h_2}{\psi_1 - \psi_2} = \frac{h_1 - h_2}{(h_1 - h_2) - T_0(s_1 - s_2)}$$

For a device with work input:

$$\eta_{SECOND\ LAW,INPUT} = \frac{W_{IN,REV}}{W_{IN}} = \frac{\psi_2 - \psi_1}{h_2 - h_1} = \frac{(h_2 - h_1) - T_0(s_2 - s_1)}{h_2 - h_1}$$

For heat engines:

$$\eta_{SECOND\ LAW,HE} = \frac{\eta_{HE}}{\eta_{HE,REV}} = \frac{\eta_{HE}}{\eta_{CAR,HE}}$$

Exergy/Anergy

- Exergy:
  - measures the quality of energy
  - It is the energy available for work
  - Is not conserved and it can be destroyed

- Anergy:
  - Not usefull energy
  - Can be created (like entropy)

Energy and exergy in flow diagrams

To have a good and clear overview of energy and exergy flows in complicated systems they are visualized in diagrams

Sankey diagrams are used for **energy flows**

Grassmann diagrams are used for **exergy flows**
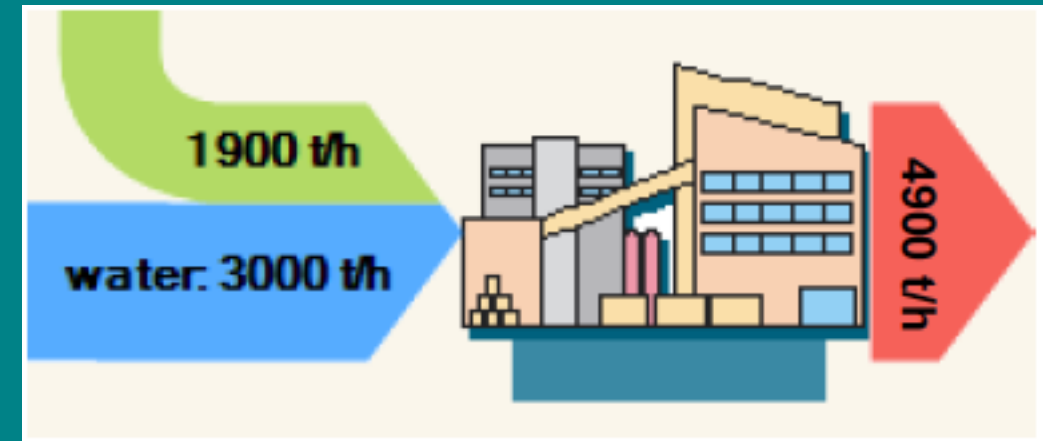
Comparing both gives insight into where significant losses occur that can be usefully addressed to achieve higher efficiency

Sankey diagram– energy flow diagram

Device is schematically depicted by a block and the process between the devices by an arrow between blocks

• One block could have more than one arrow entering / leaving

• The width of the arrows is proportionally to the flow quantity

• Different fluids or types of energy have different colors or striping

• The block or arrow contains:

• name of the device or the fluid type

• amount of energy or exergy,

absolute as well as relative to the total input

• The total amount of energy entering

and leaving one block should be the same

Superheated steam
$h_1 = 3213$ kJ/kg
100%

Turbine, $\eta = 0.85$

Sat. mixture
$h_2 = 2670$ kJ/kg
83 %

$w = h_1 - h_2 =$
542 kJ/kg, 17%
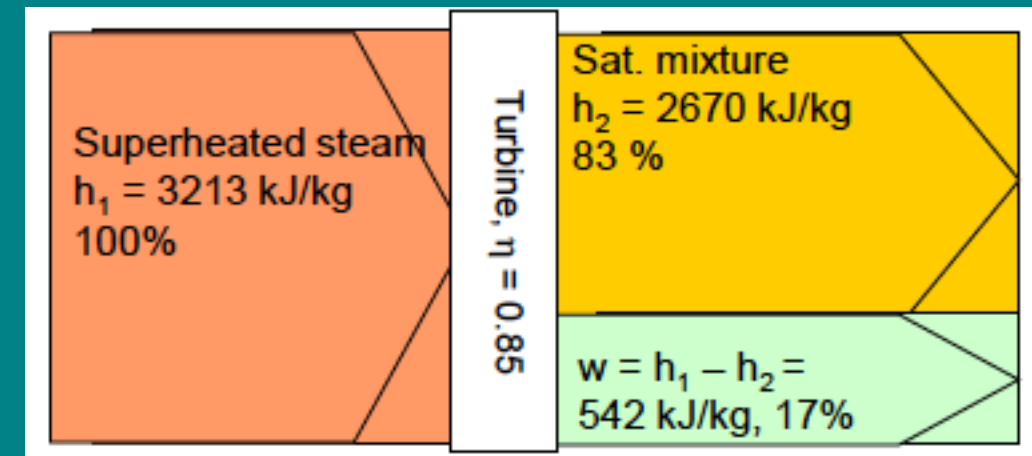
Grassmann diagram (exergy flow)

The **Grassmann** diagram is the same as the Sankey diagram except that the quantities depicted by the arrows are not energy but **exergy**

Exergy can be destroyed during the process, therefore the total **exergy entering the block is less than the exergy leaving the block**
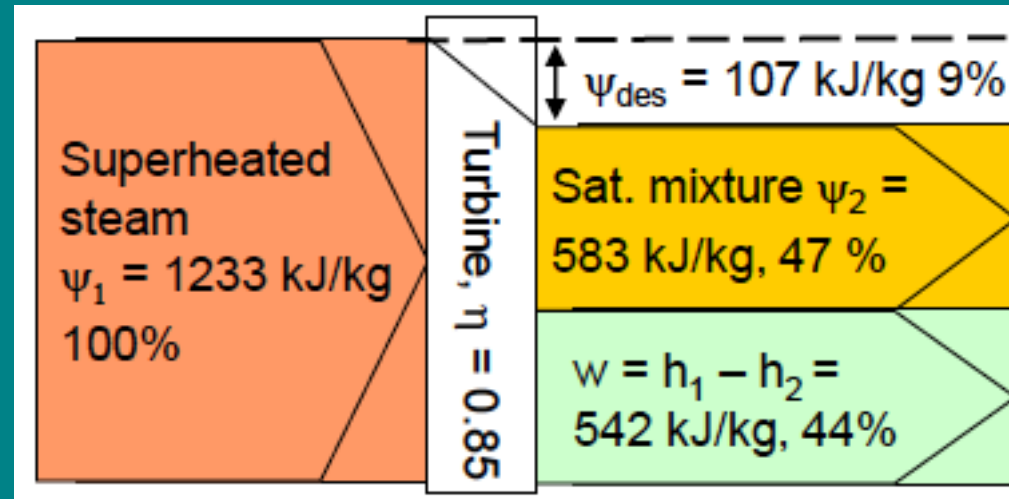
By comparing both diagrams one gets insight in where energy available for work is lost during the thermodynamic process

Vapor power cycles

- To produce power a thermodynamic cycle is used

- Vapor power cycle is on 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

Rotor of steam turbine

- 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

Simple Rankine cycle

- **Simple Rankin**e cycle consist of **four** devices:

  - **Pump** – to increase pressure

  - **Steam generator/Boil**er – to add heat and change liquid's phase

  - **Steam turbine** – to decrease pressure and extract work

  - **Condenser** – for heat rejection

Simple, ideal Rankine Cycle

Simple Rankine Cycle
ThermoNet: Wiley
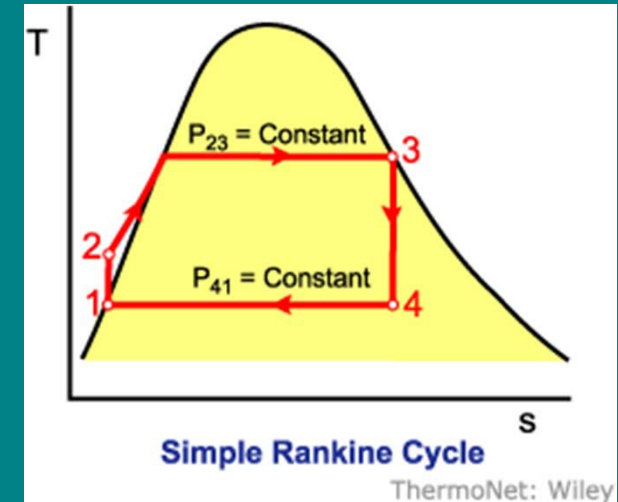
- Process 1→2 isentropic compression (w_{in})

- Process 2→3 isobaric heat addition (q_{in})

- Process 3→4 isentropic expansion (w_{out})

- Process 4→1 isobaric heat rejection (q_{out})

Components for Rankine Cycle
ThermoNet: Wiley
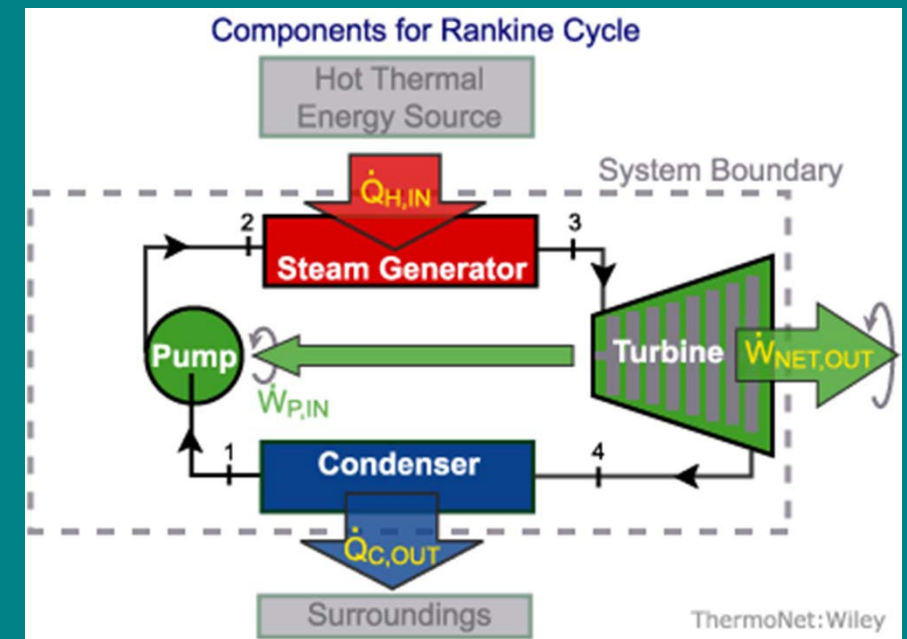
Simple, ideal Rankine Cycle

- 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 CO_2 neutral

- Mostly boiler is used to transfer heat to working medium

http://science.howstuffworks.com/transport/engines-equipment/steam2.htm
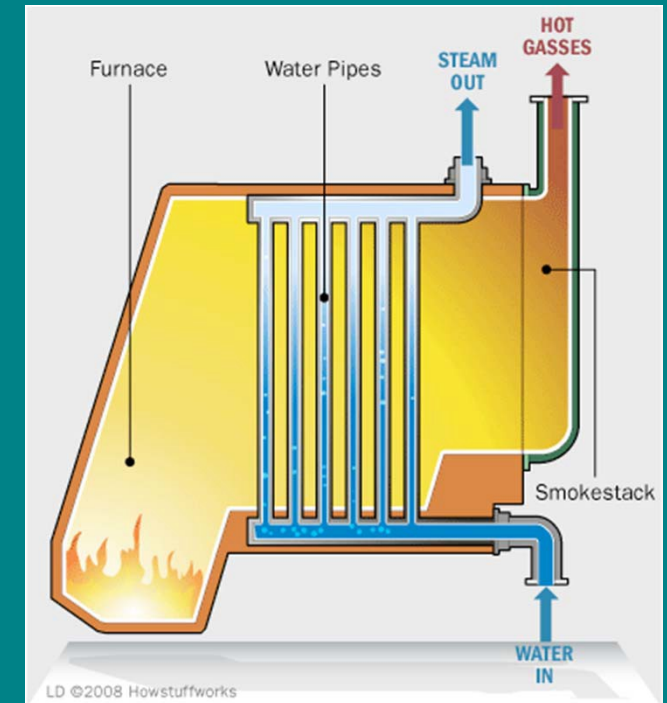
Ideal Rankine Cycle vs Carnot Cycle

- 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
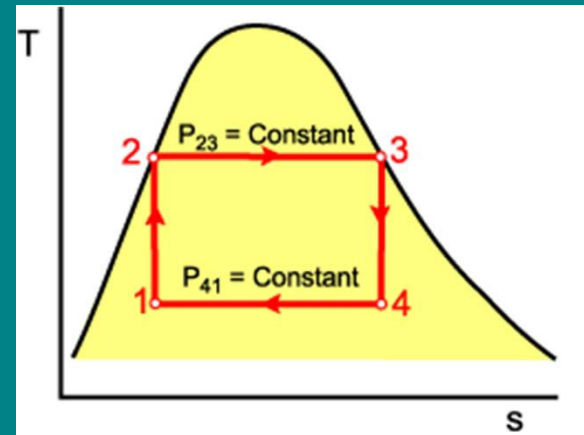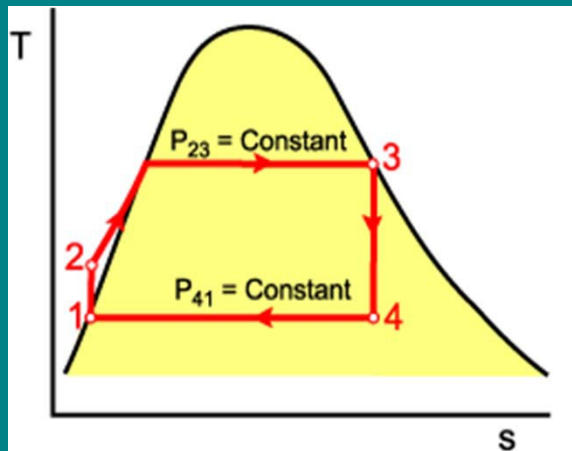
T-s diagram of Ideal Rankine cycle vs Carnot cycle

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
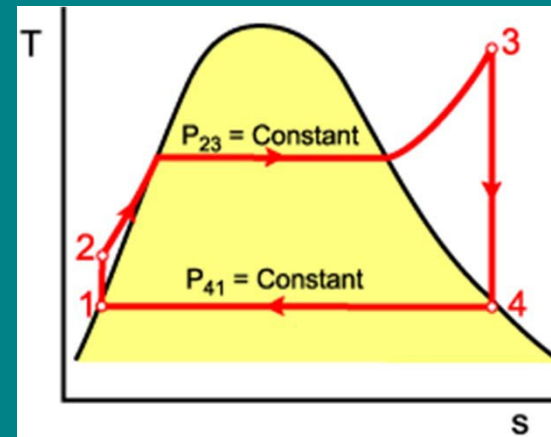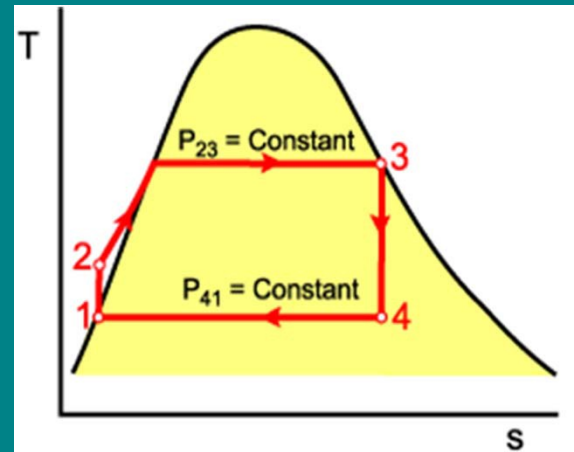
Ideal Rankine cycle - assumptions

- 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=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'

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

or alternatively: $dh = \dot{w}_{pump,in} = \cancel{Tds} + vdP$
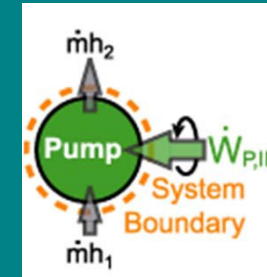
- Process 2→3

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

Ideal Rankine Cycle with Superheat
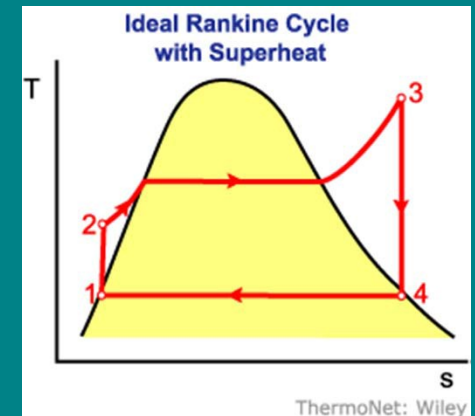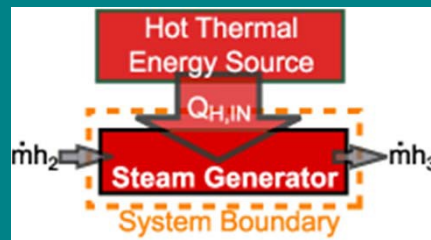
Ideal Rankine cycle vs non-ideal
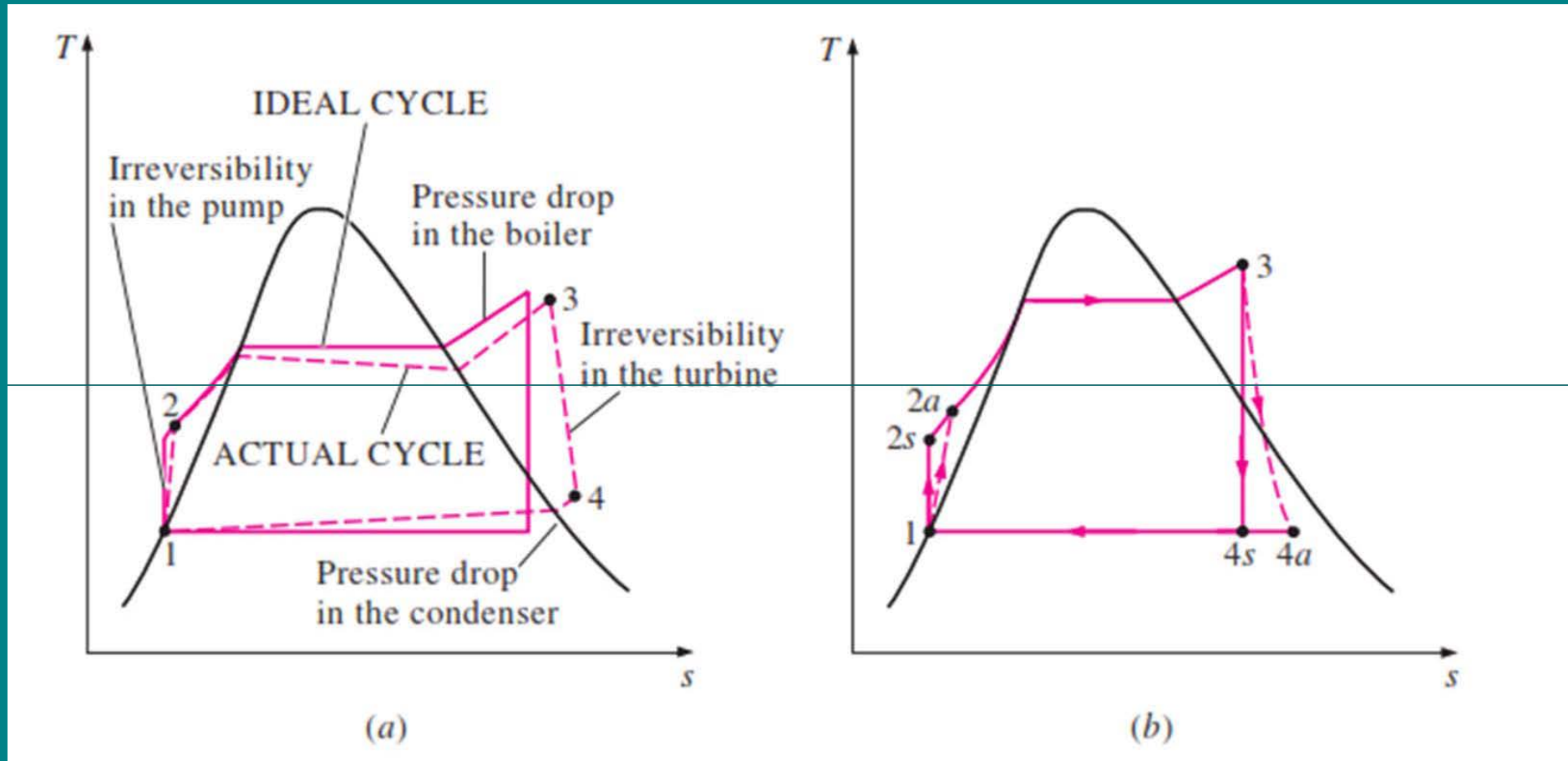
Ideal Rankine cycle vs non-ideal

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

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

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

Ideal Rankine Cycle with Superheat

ThermoNet: Wiley

Non-Ideal Rankine Cycle with Superheat

ThermoNet: Wiley
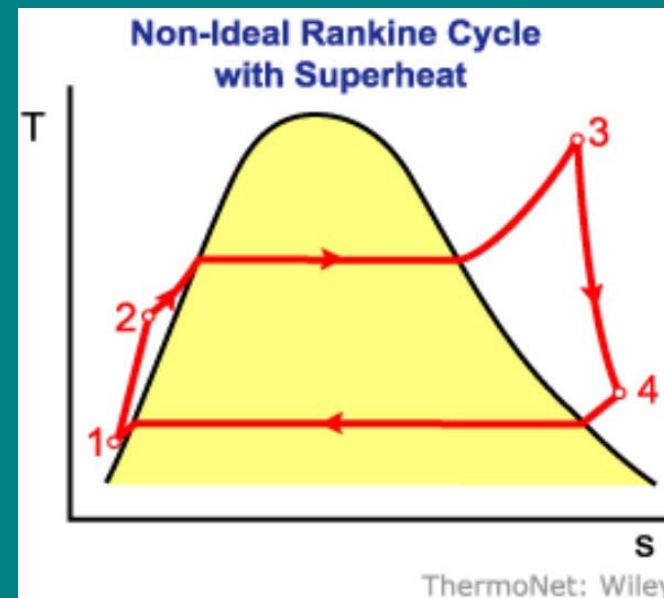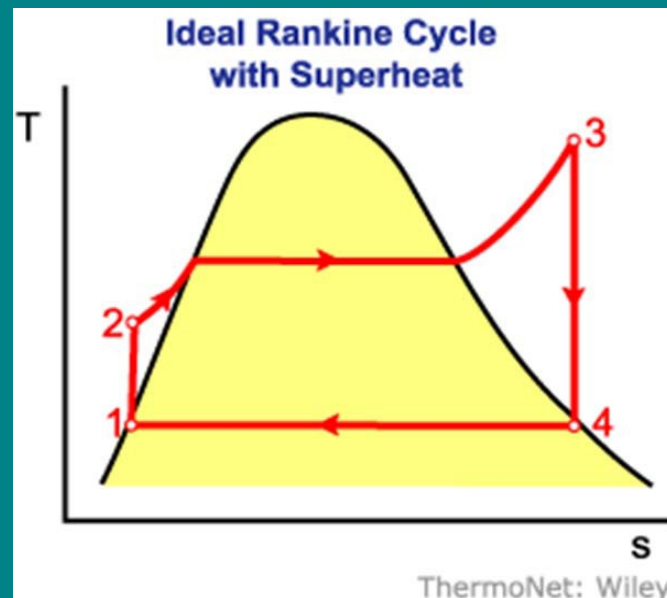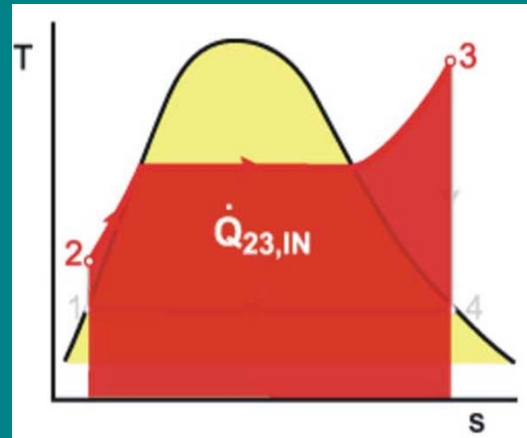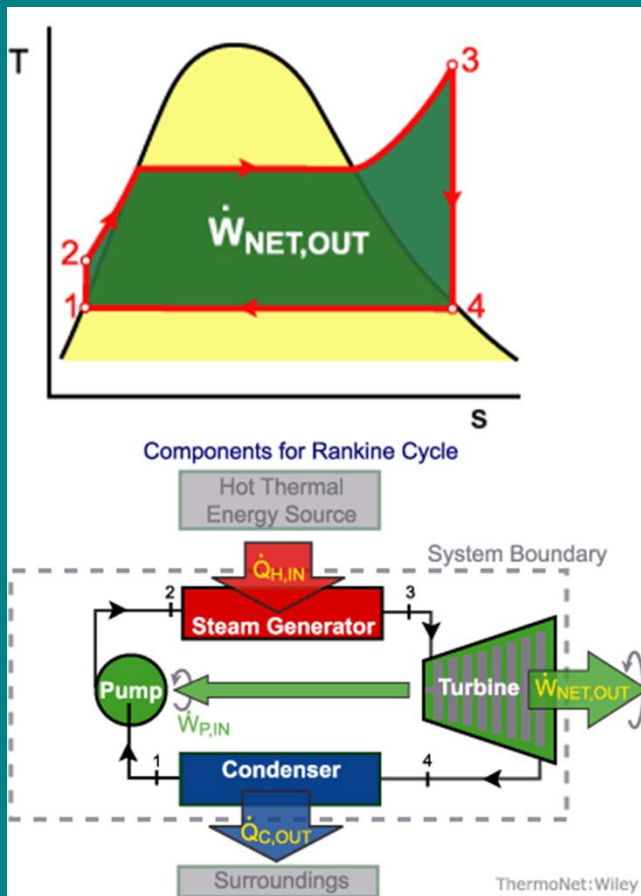
Rankine Cycle Efficiency

$$\eta_{Rankine} = \frac{get}{pay}$$

$$= \frac{net\ work\ output}{heat\ added}$$

$$= \frac{\dot{W}_{turb} - \dot{W}_{pump}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

$$= \frac{\dot{m}(h_3 - h_4) - \dot{m}(h_2 - h_1)}{\dot{m}(h_3 - h_2)}$$

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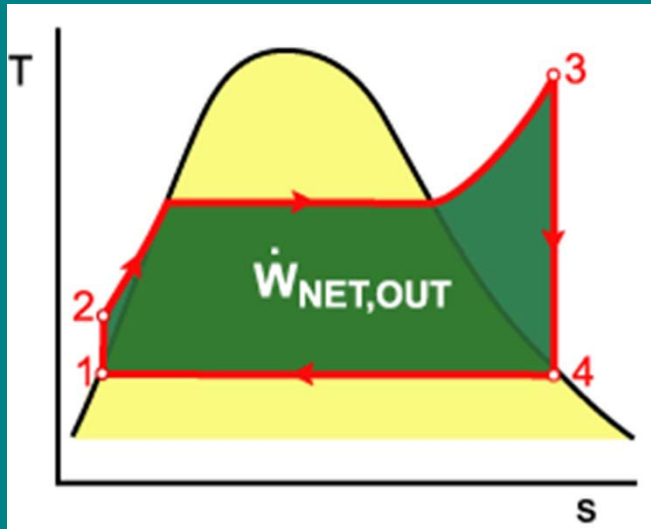
$$\eta_{Rankine} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

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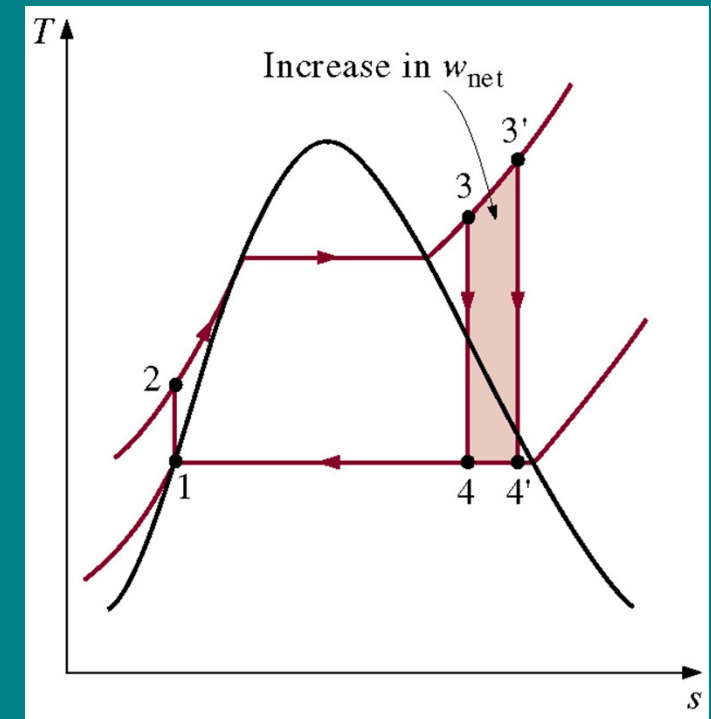
Rankine Cycle Efficiency

- **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
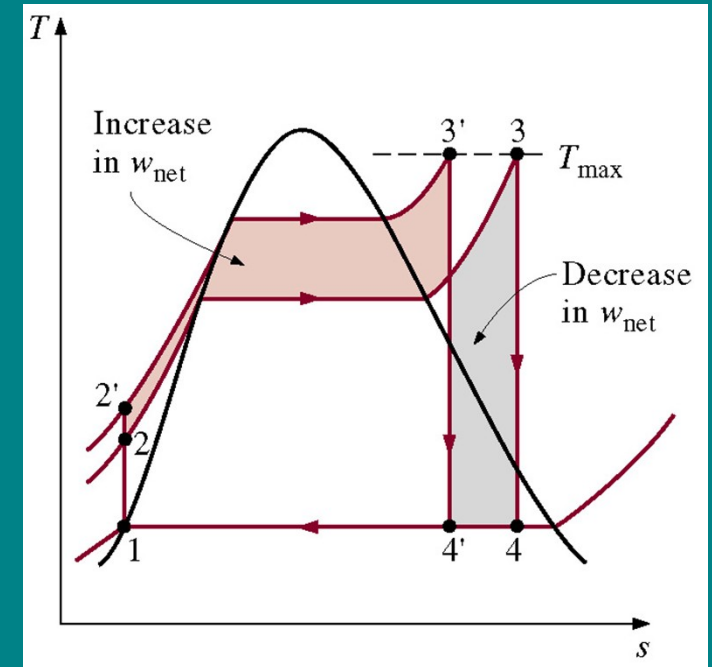
Rankine Cycle Efficiency

- **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
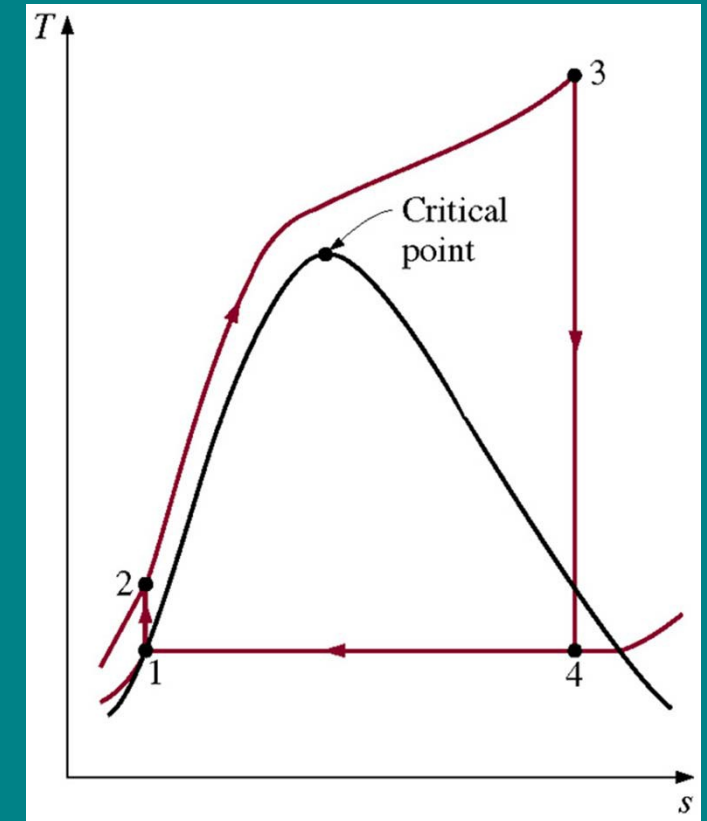
Rankine Cycle Efficiency

- 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)

  - Condenser may work at below atmospheric pressure
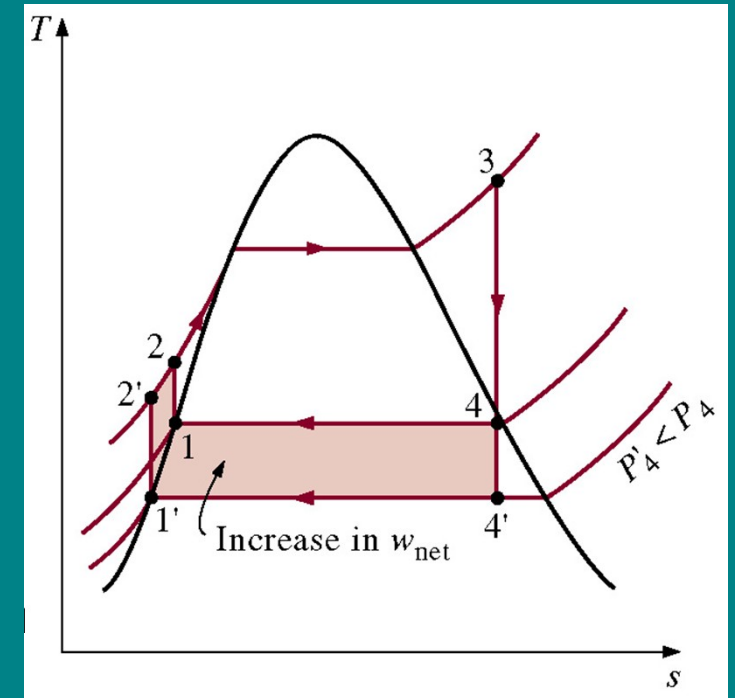
Improved Rankine cycle

- 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)

$$\eta_{Carnot} = 1 - \frac{T_{Cold}}{T_{Hot}}$$
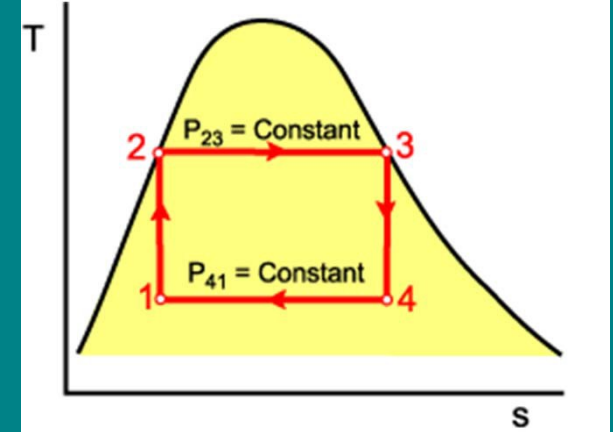
Improved Rankine cycle - Reheating

- 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
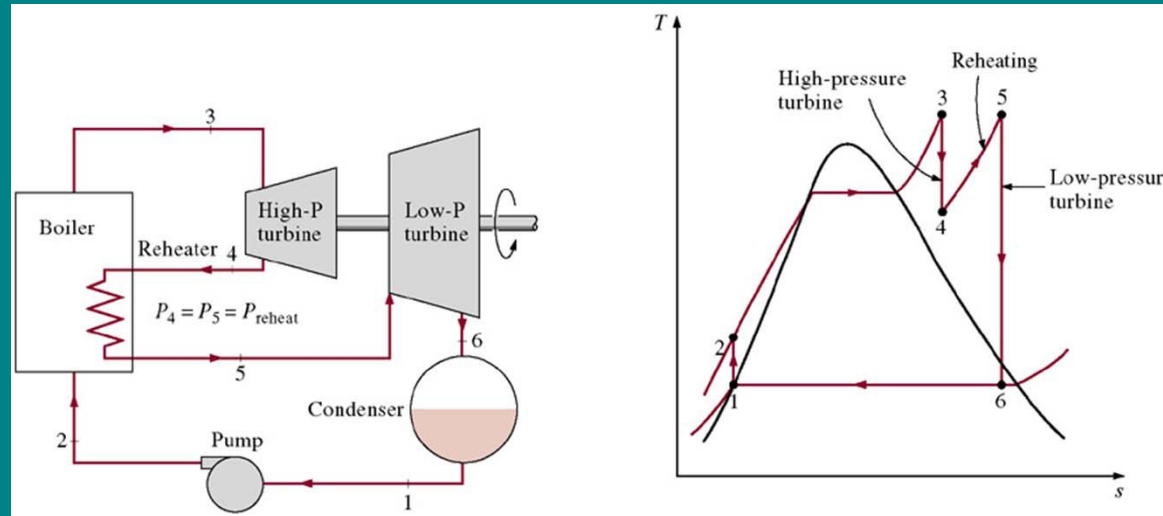
Improved Rankine cycle - Reheating
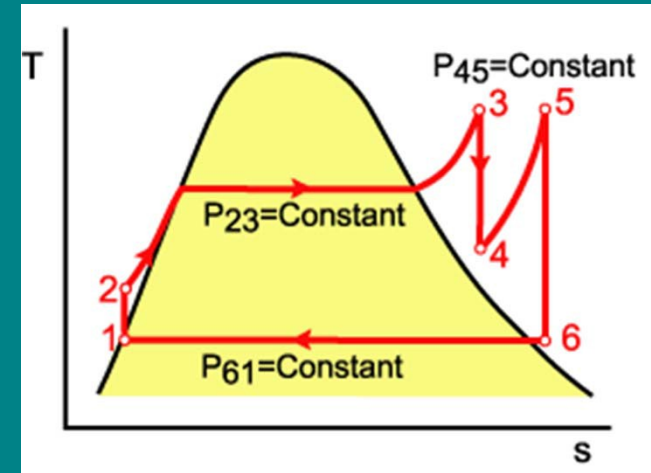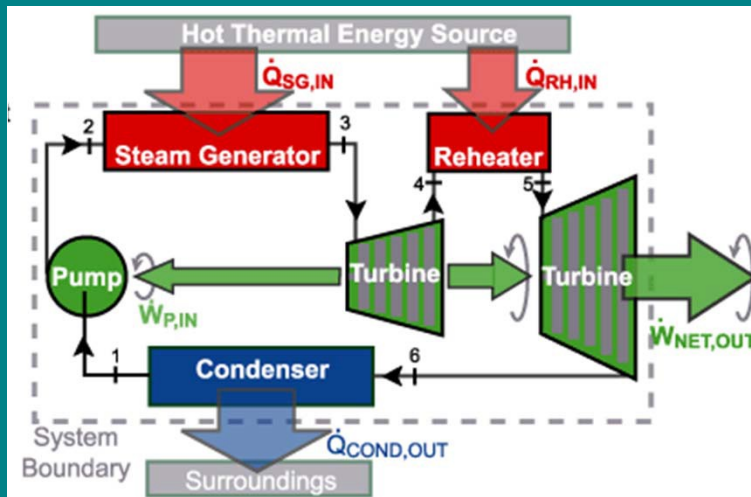
$$\eta_{Rankine} = \frac{get}{pay} = \frac{net\ work\ output}{heat\ added} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

$$= \frac{\dot{W}_{turb,1} + \dot{W}_{turb,2} - \dot{W}_{pump}}{\dot{Q}_{in,1} + \dot{Q}_{in,2}} =$$

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

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
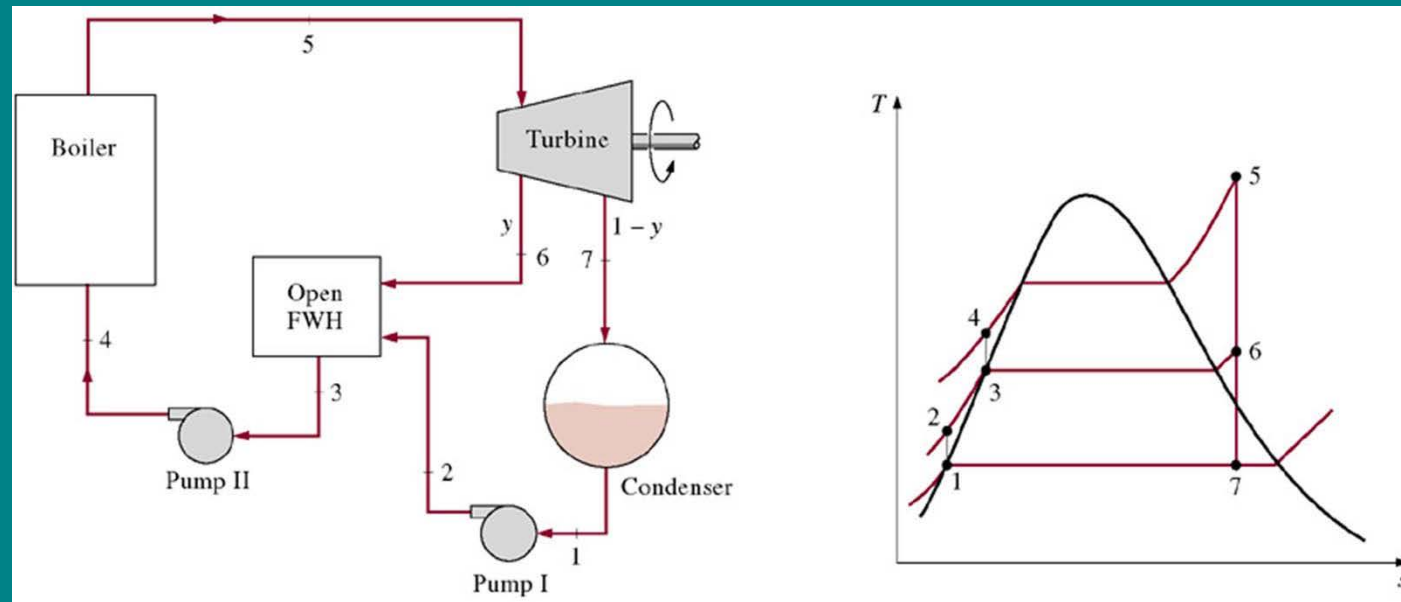
Improved Rankine cycle - Regeneration

- 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
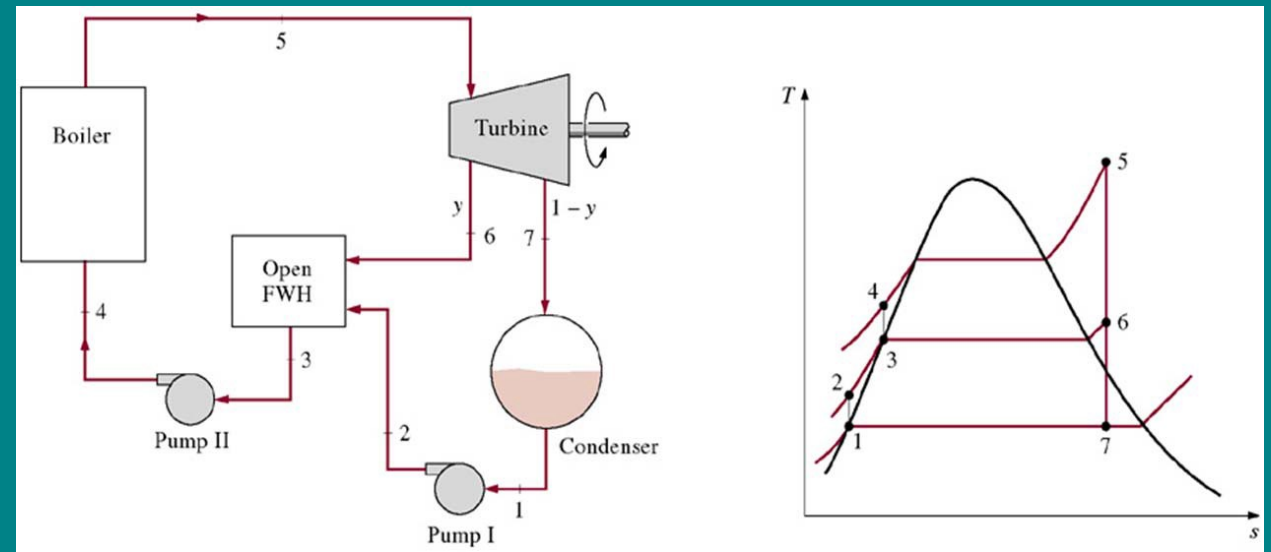
Improved Rankine cycle - Regeneration

- 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

OFWH
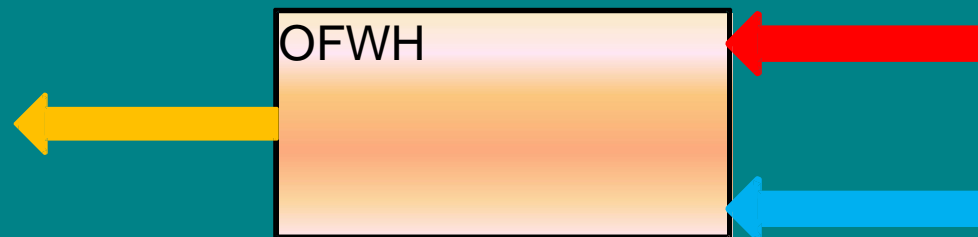
Improved Rankine cycle - Regeneration

- 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=const.)

  - CFWH is more complex, more expensive and heat transfer is less efficient then OFWH, however, it does not require separate pumps (flows at different pressures)
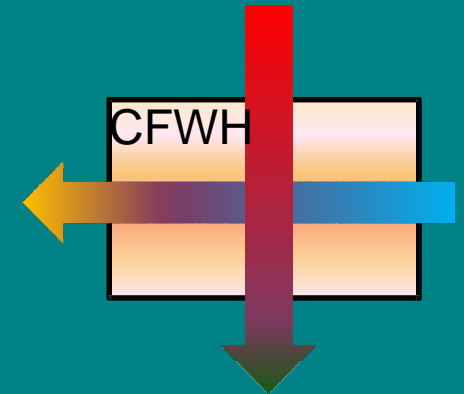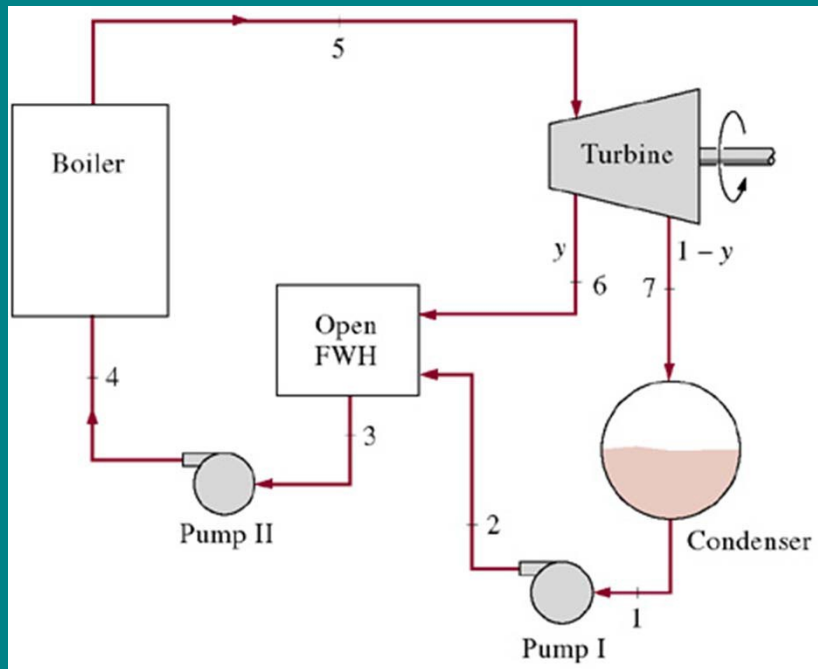
CFWH

Improved Rankine cycle - Regeneration

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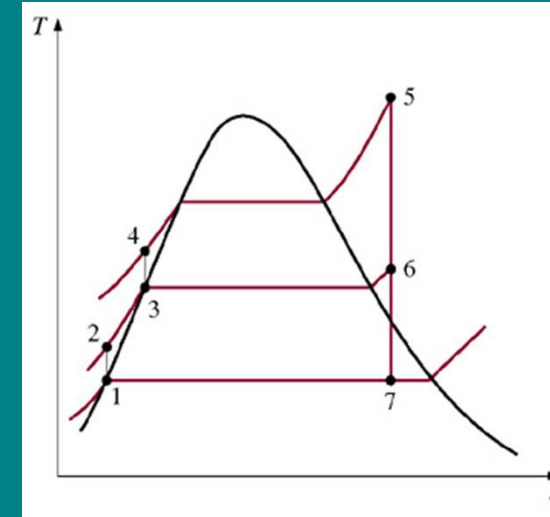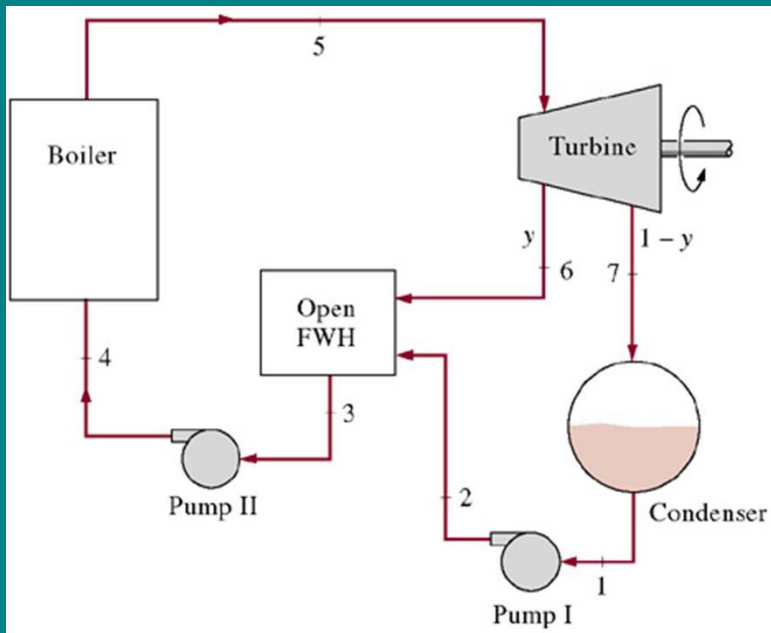   - Energy balance for OFWH (mixing chamber)

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

$$\dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_6 h_6$$
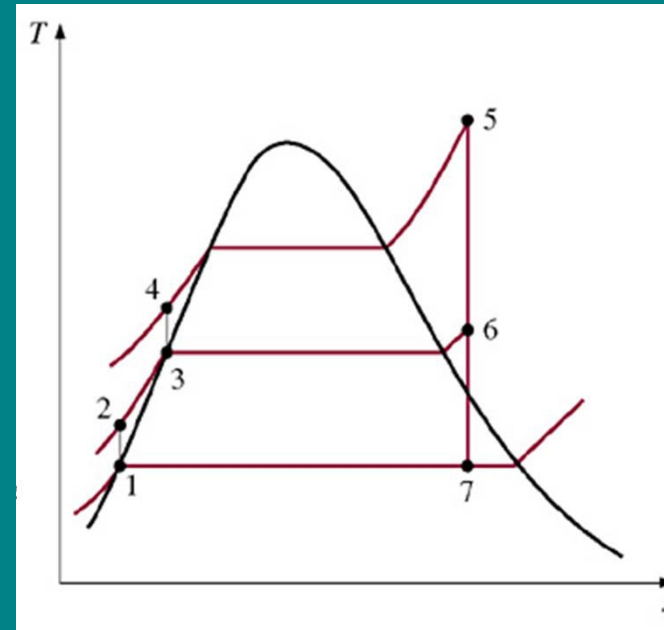
Improved Rankine cycle - Regeneration
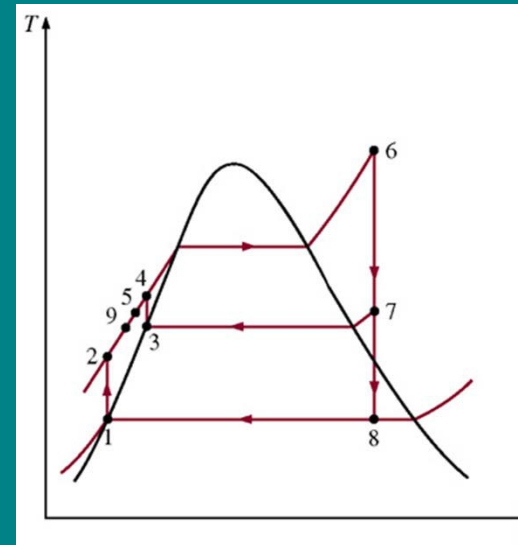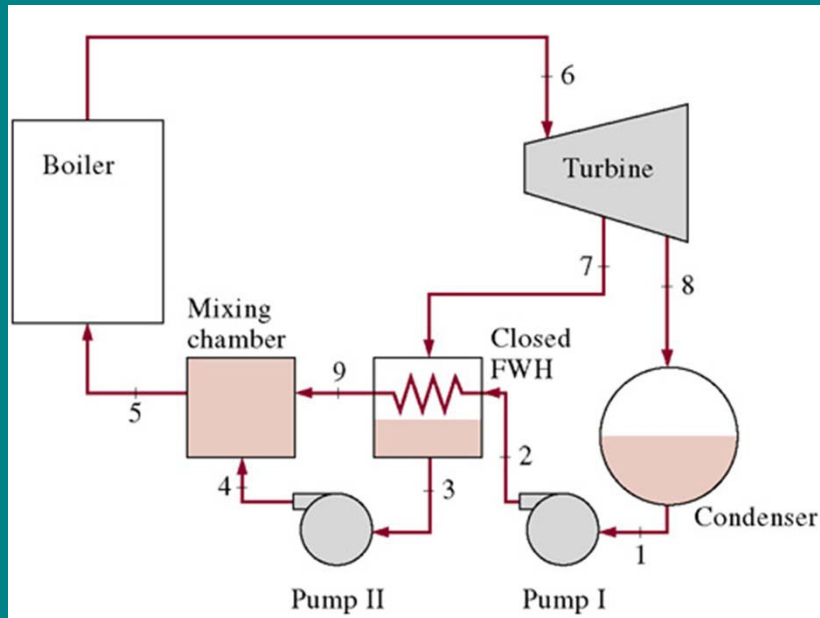
- Rankine cycle with open feedwater heater

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

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

Improved Rankine cycle - Regeneration

- Rankine cycle with closed feedwater heater

  - Mass balance (3 different flows)

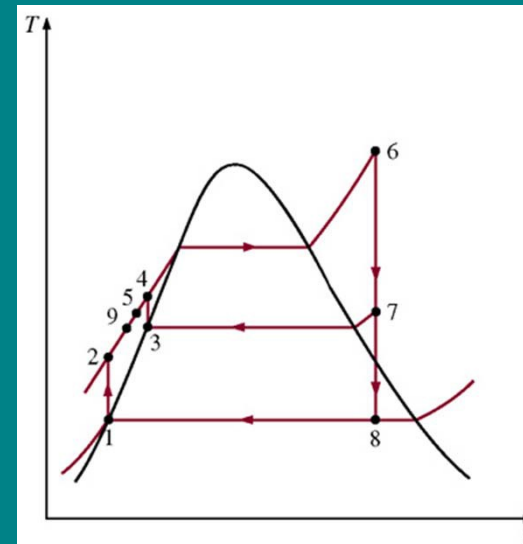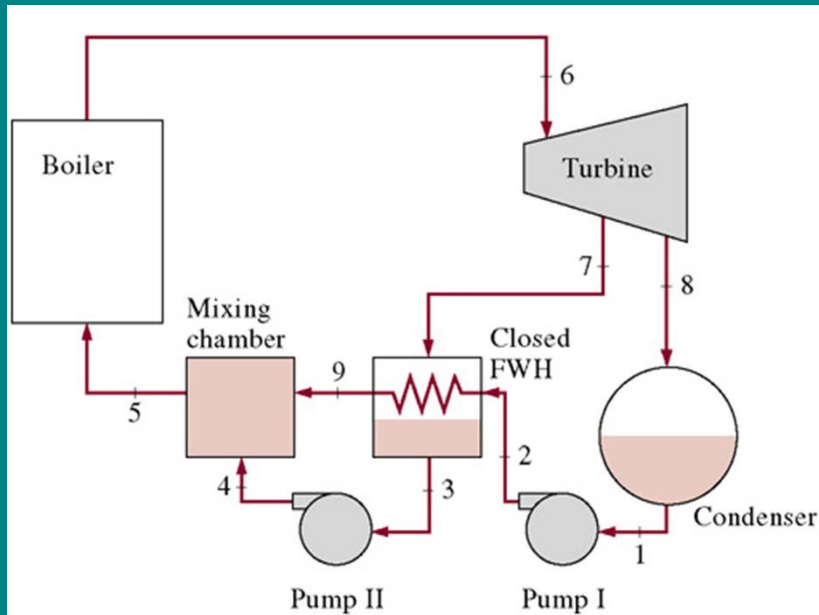 - Energy balance for mixing chamber and CFWH

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

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

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

Improved Rankine cycle - Regeneration

- Rankine cycle with closed feedwater heater

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

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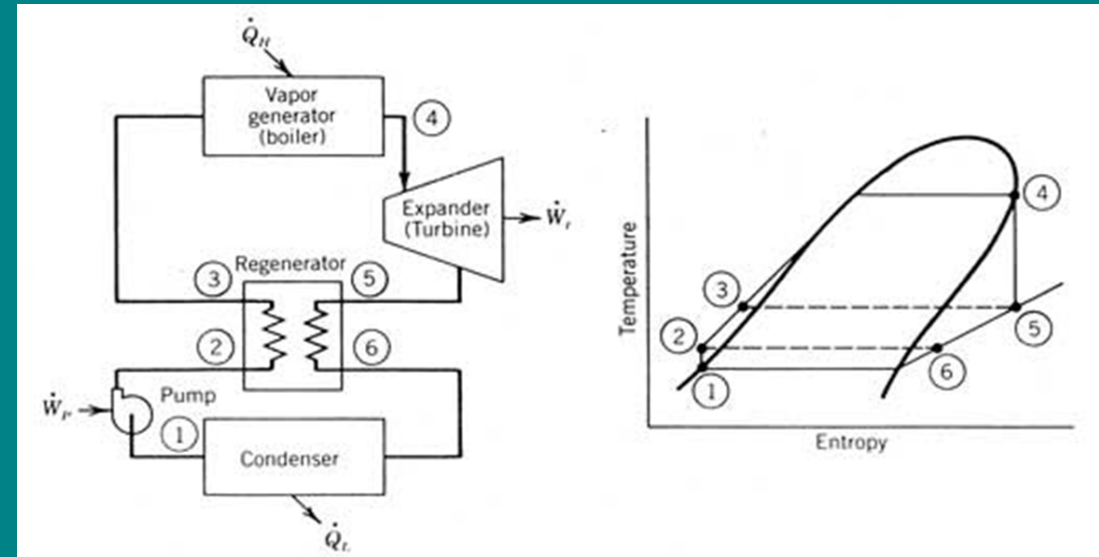
Organic Rankine Cycle (ORC)

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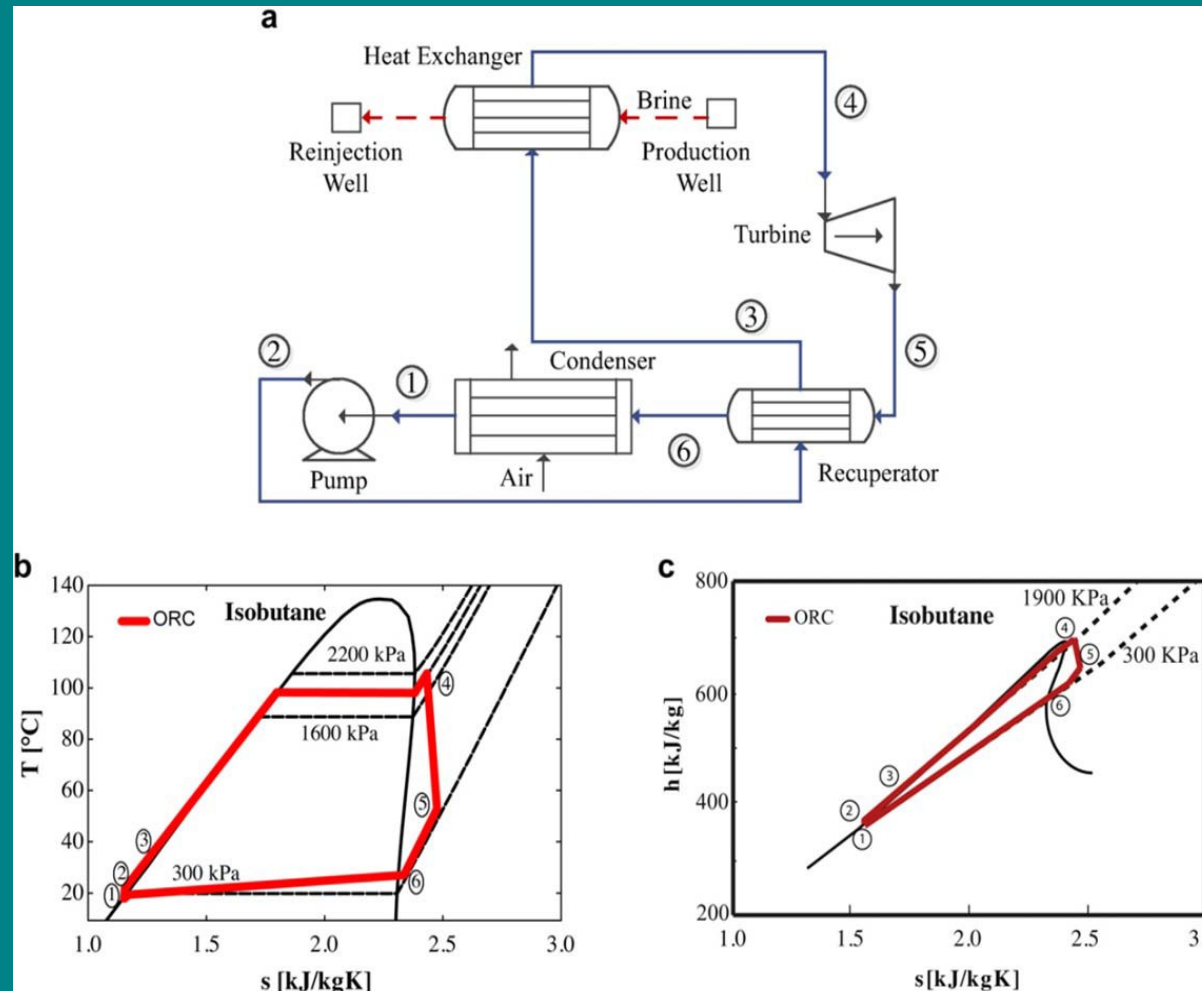
Ghasemi et al., Modeling and optimization of a binary geothermal power plant, Energy (2013), 412-428

Lets' set the stage for the ORC

'External' thermal energy source (no internal combustion)

- ϒ Geothermal reservoir

- ϒ Solar radiation

- ϒ ("Dirty") biomass combustion/gasification, landfill gas, waste incineration

- ϒ 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 -> T_c, P_c, Δh, β, 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
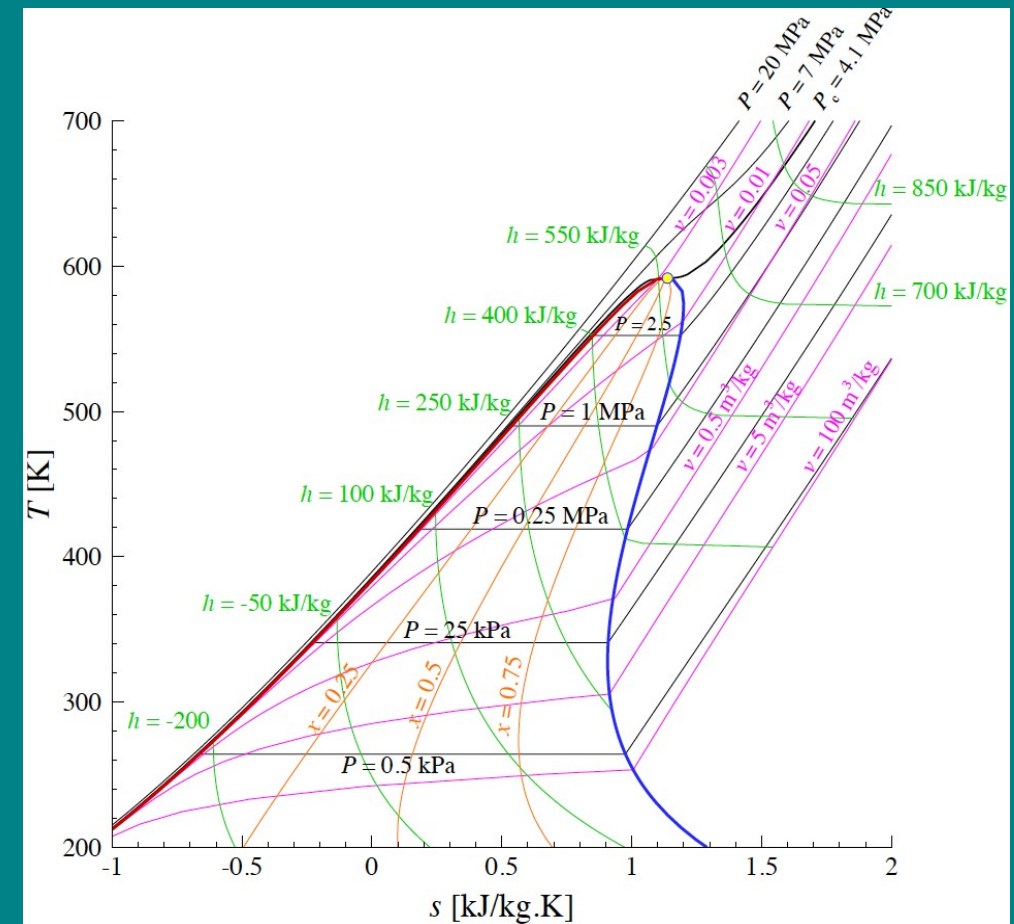
Some ORC Working Fluids
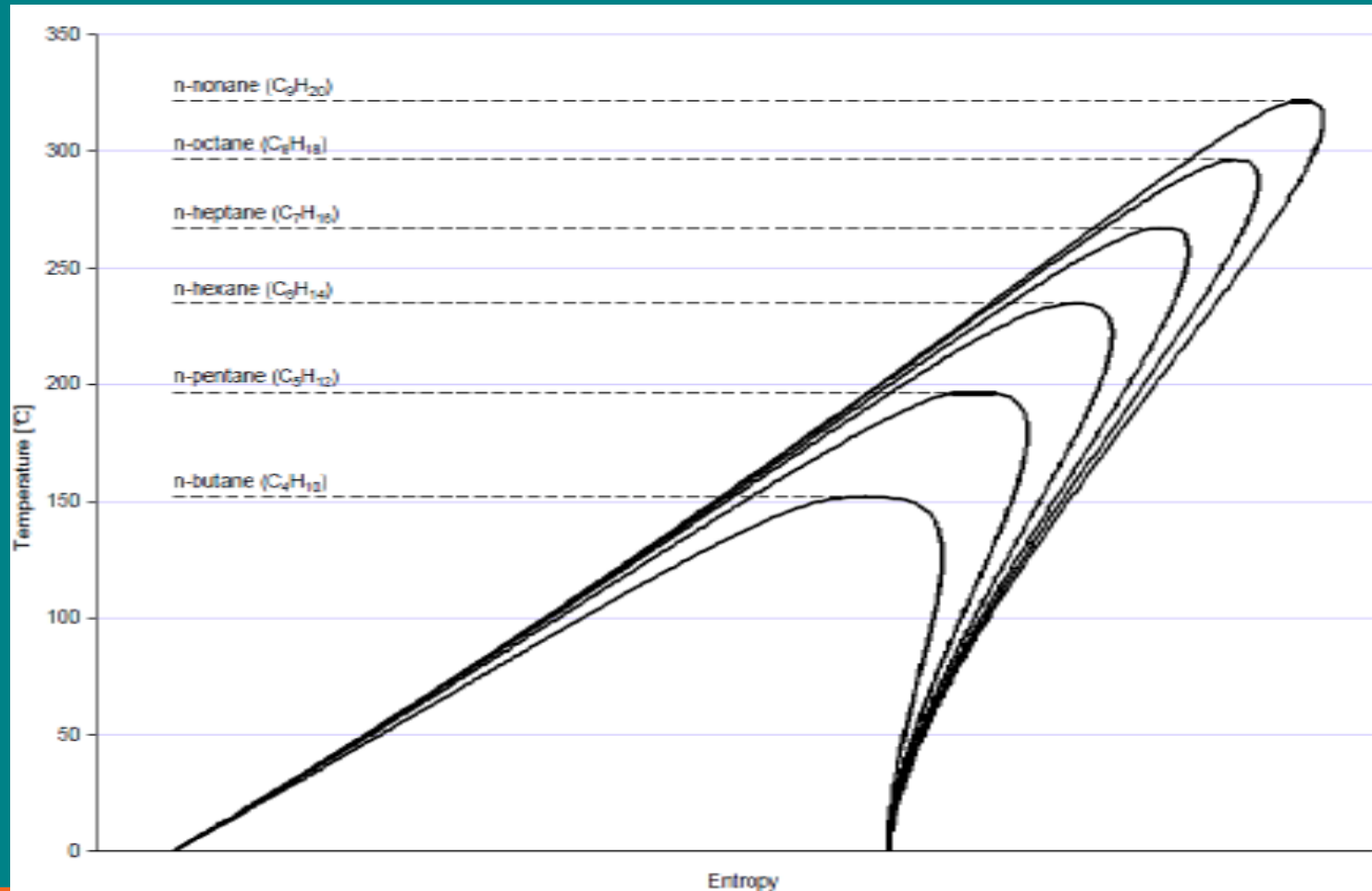
Working fluids

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 μCHP, 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. 25–30 °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%

THE KOLA SUPERDEEP BOREHOLE: THE DEEPEST HOLE ON EARTH
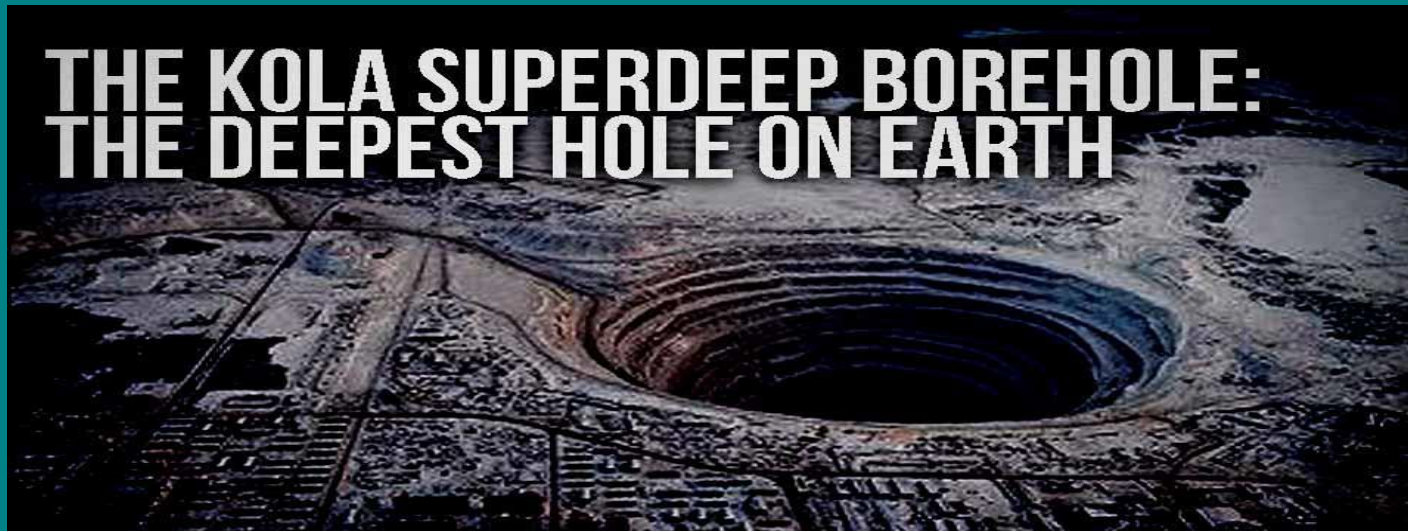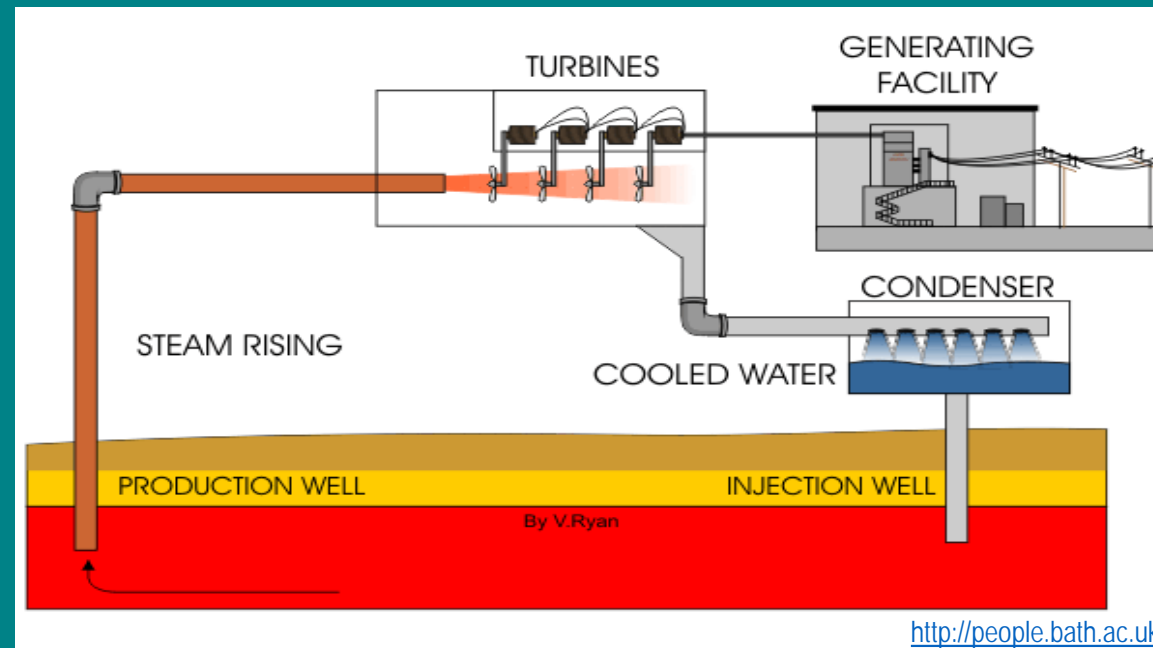
Geothermal plants

- 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

Crust
0 - 70 km

Mantle
70 - 2891 km

Outer Core
2391 - 5150 km

Innre Core
2391 - 6731 km
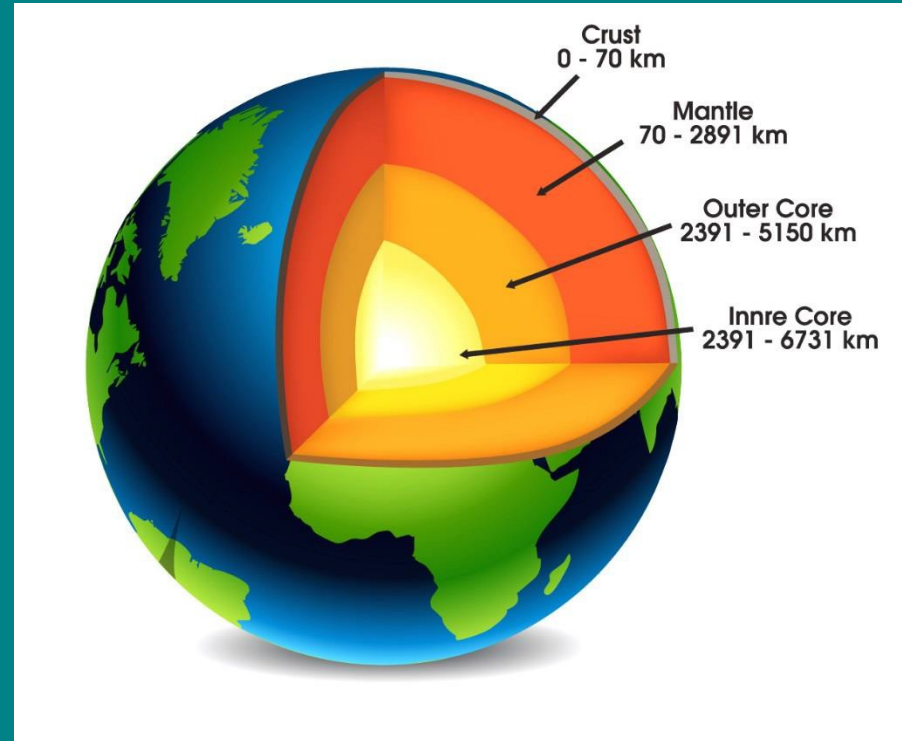
Dry steam power plant

- 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?

TURBINES

GENERATING FACILITY

STEAM RISING

CONDENSER

COOLED WATER

PRODUCTION WELL

INJECTION WELL

By V.Ryan

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

Flash steam power plant

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

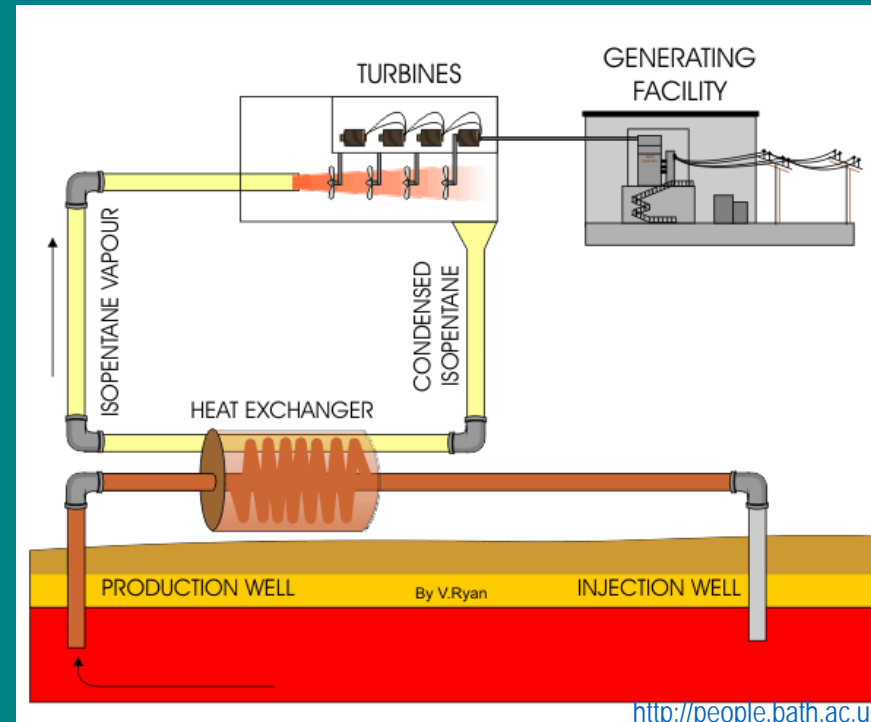What is missing?

http://people.bath.ac.uk/
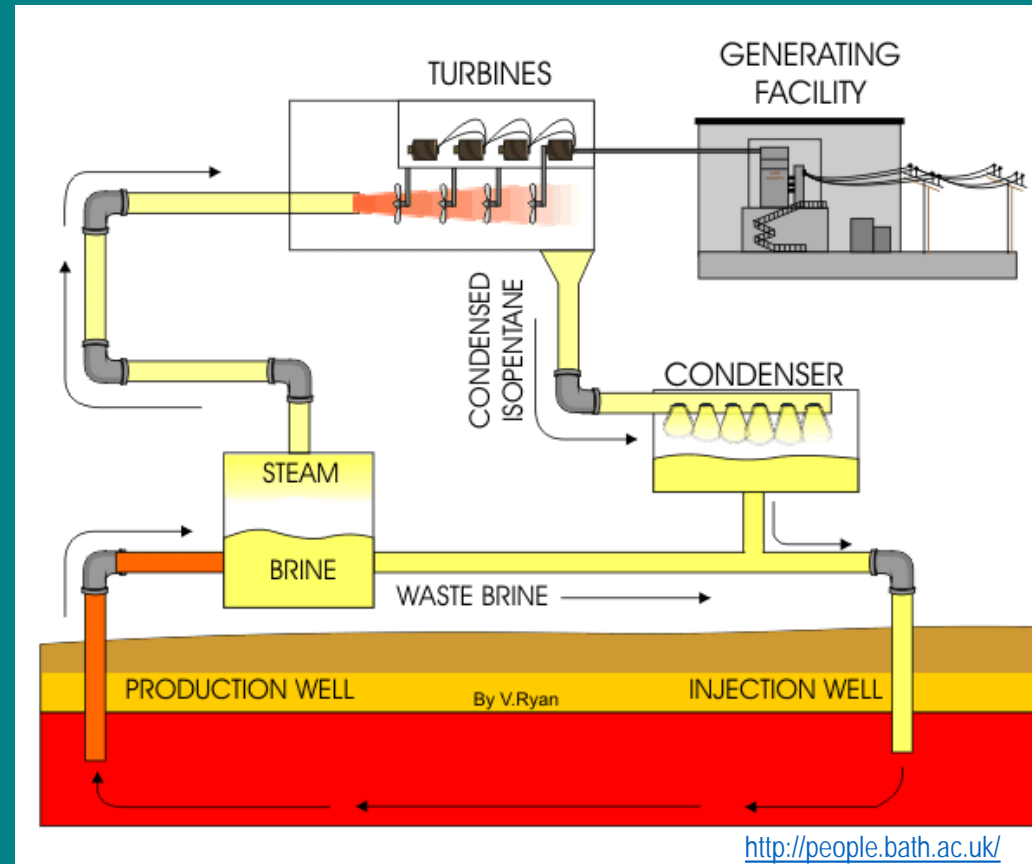
Binary power plant

- 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?

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

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-heater
   Is 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/