Sustainable Power Generation MJ2405

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Steam Cycles

Steam cycles & steam power plants
– *historical notes & development timeline*

Thermodynamic properties of water and steam
– *tables and diagrams*

Types of cycle arrangements & main components
- *Efficiency improvements*

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Reading material on steam cycles

Many books can be used!
Any chapter on water/steam properties and Rankine Cycles can serve fine.

The main suggested sources:

Advanced Energy Systems (Khartchenko&Kharchenko), *CRC Press 2014* – (chapter 3): sections 3.1 to 3.6.

Energy Conversion – *free e-book by courtesy of the University of Tulsa*, Kenneth C. Weston, 2000 – (chapter 4)
http://www.personal.utulsa.edu/~kenneth-weston/

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På Svenska:

Energiteknik -Del 2; Henrik Alvarez, *Studentlitteratur 2006* – delar av kapitel 5 & kapitel 9.

Tillämpad termodynamik; Ingvar Ekroth, Eric Granryd; *Studentlitteratur 2006* – kapitel 7 & 8

Ancient History

Already the early humans learned how to boil water and found out that power can be extracted from the steam flow!

First documented steam power device by:

Heron of Alexandria, around year 60 A.D.

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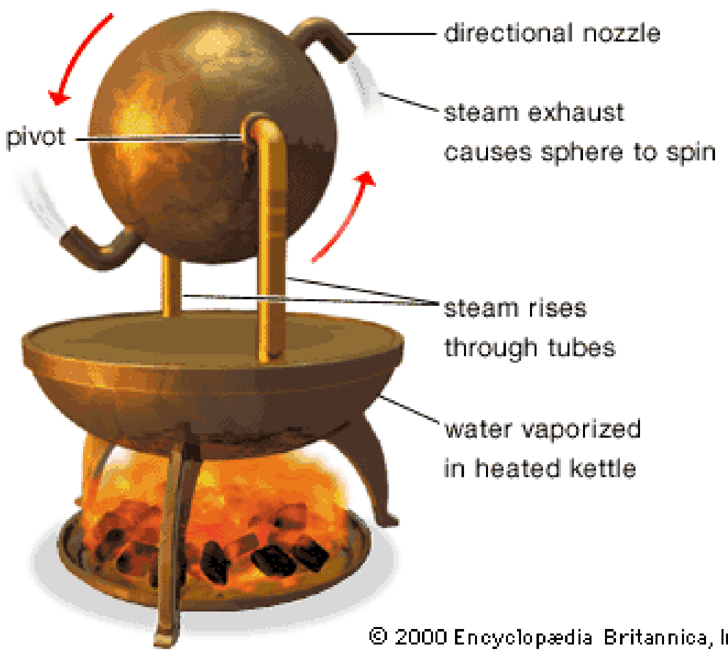
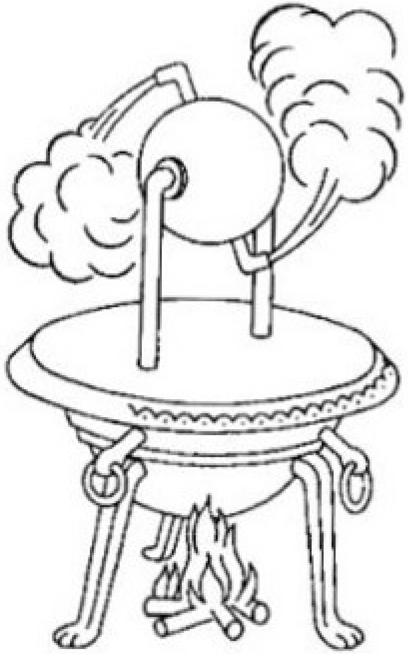
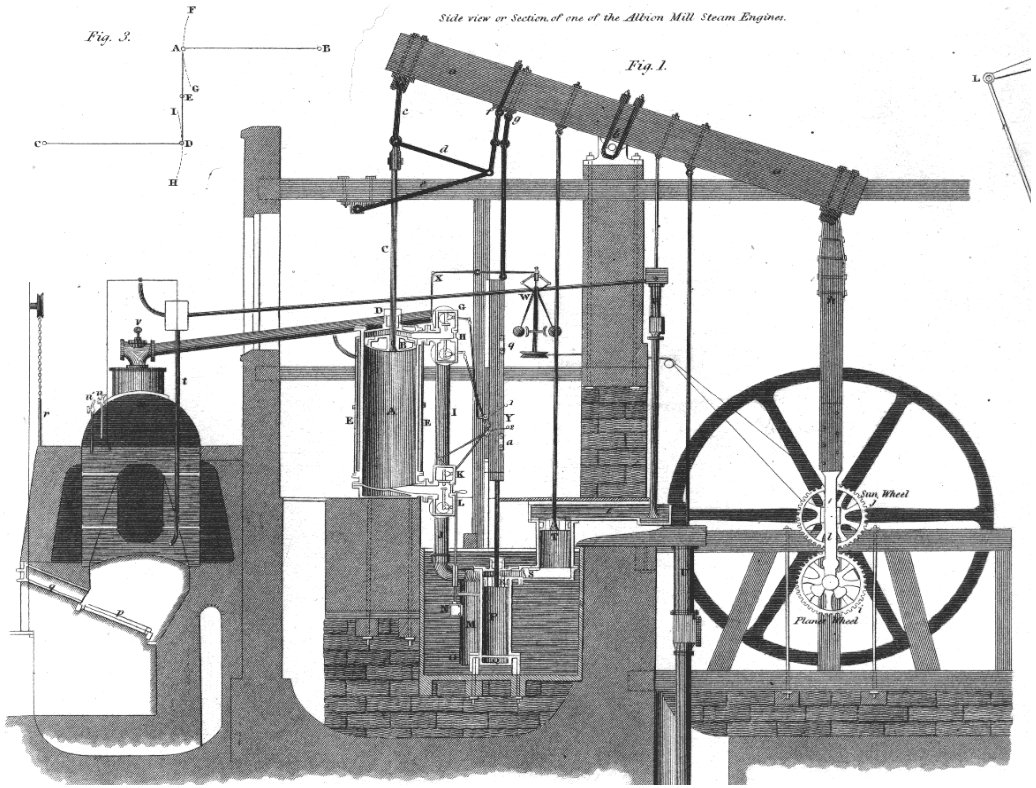


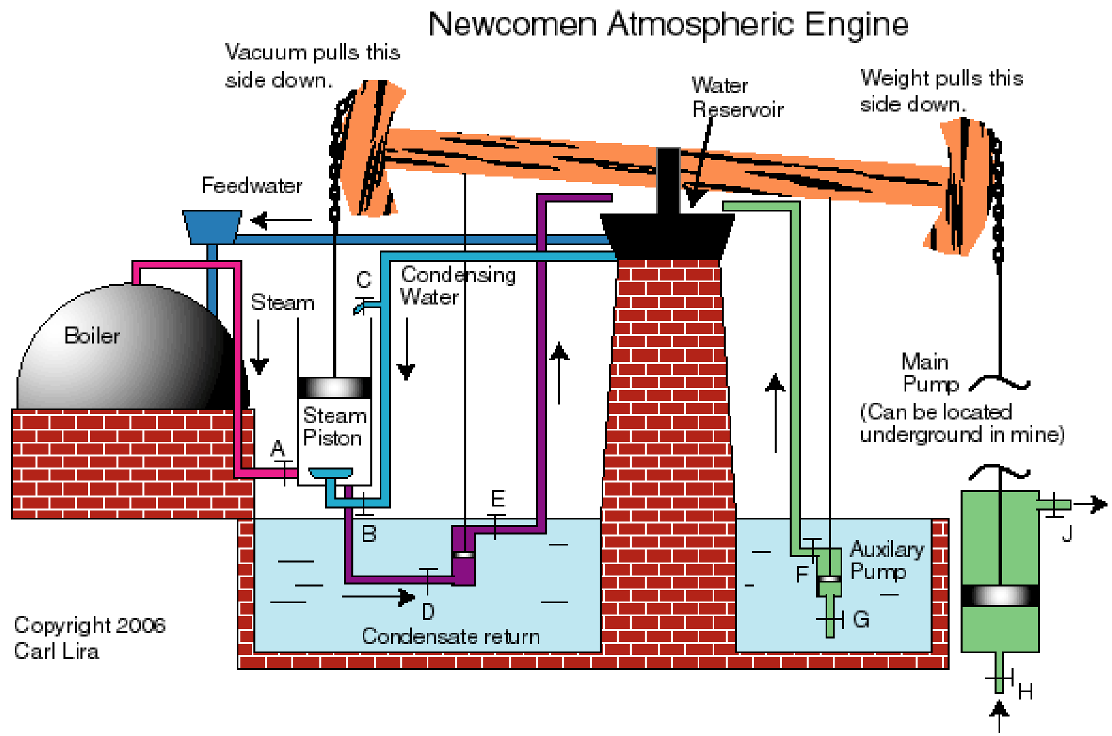


The industrial revolution

Year 1690: Steam piston/cylinder patented by Denis Papin.
Year 1698: First patent of a steam pump by Thomas Savery.



The first large industrial steam engine by Thomas Newcomen, around year 1700…

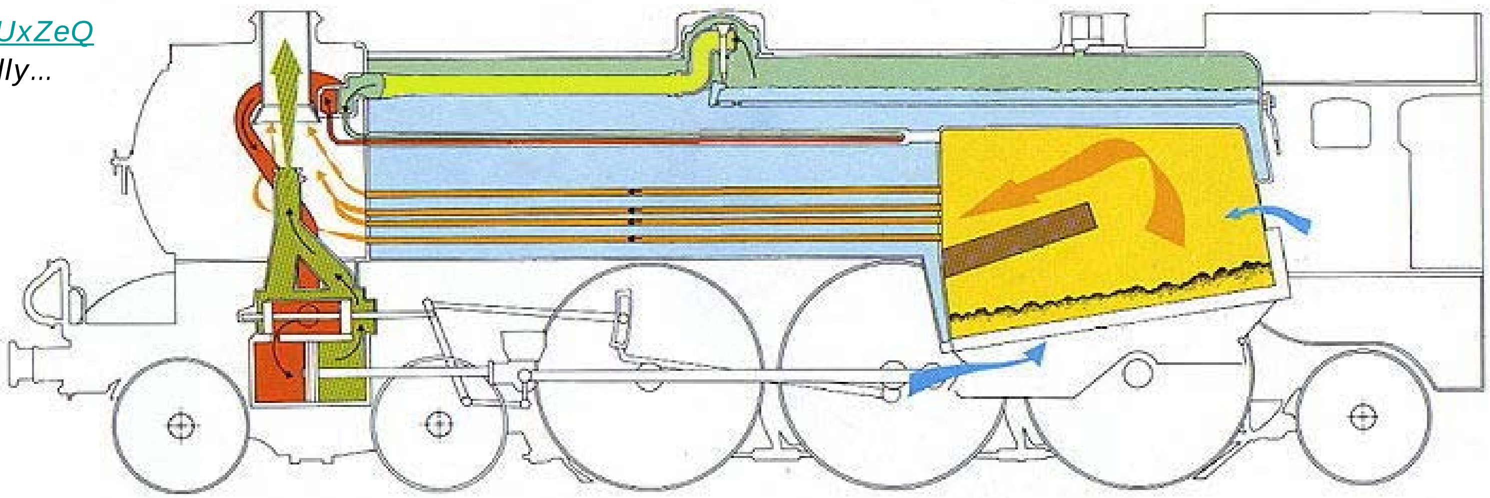


Historical Applications

- The industrial development was initiated with the steam engine
- Steam traction (locomotives and ships) and steam-engine drives (pumps, looms, presses, tooling machines, etc.) were completely ruling the industrial landscape until the 1920's
- First thermal power plant – a coal-fired steam-engine driven, with overall efficiency of about 6% (*Edison Electric Light Station – one in London and one in New York, year 1882*)
- Modern application – advanced steam cycles for power production using steam turbines, whatever the source of heat, ranging from small-scale units and up to 1000+ MW per unit
- The fundamental steam cycle today remains the same!

Simple steam boiler (closed vessel):
The Steam Locomotive

To appreciate the work of those who brought us where we stand today – check this video!!: https://www.youtube.com/watch?v=hRsYIiUxZeQ
...and also other similar stuff now available digitally...



Self-pressurized sealed water container, producing saturated steam.

Steam is drawn from the boiler and released after expansion, thus the available water is gradually used, so it needs to be replenished (refilled) after a certain time of operation.

Modern steam boiler:
The continuous cycle (circulating system)

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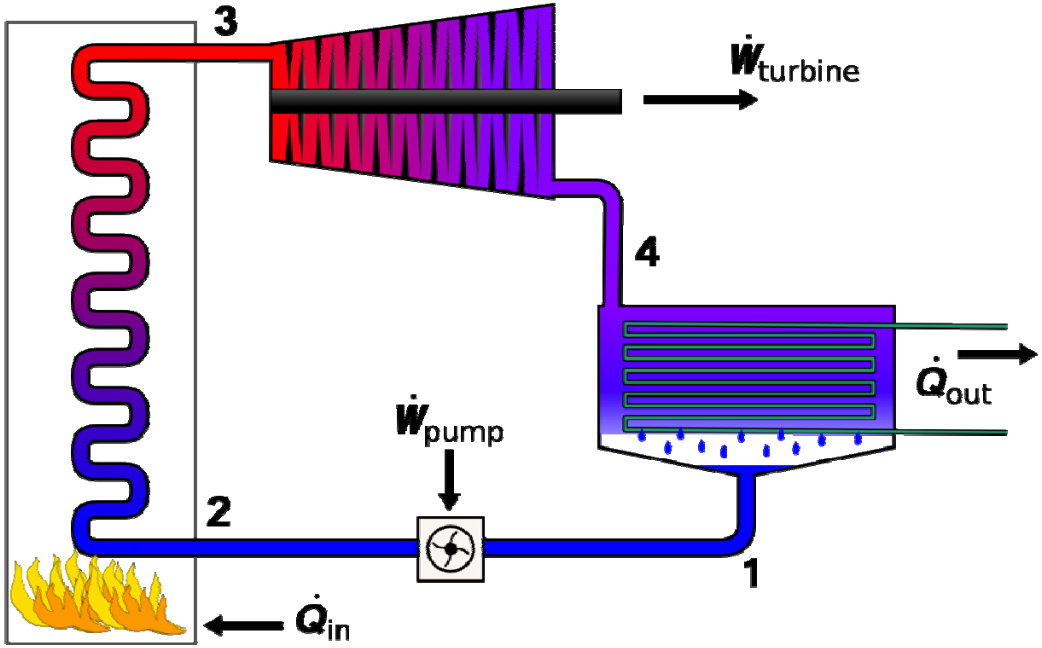
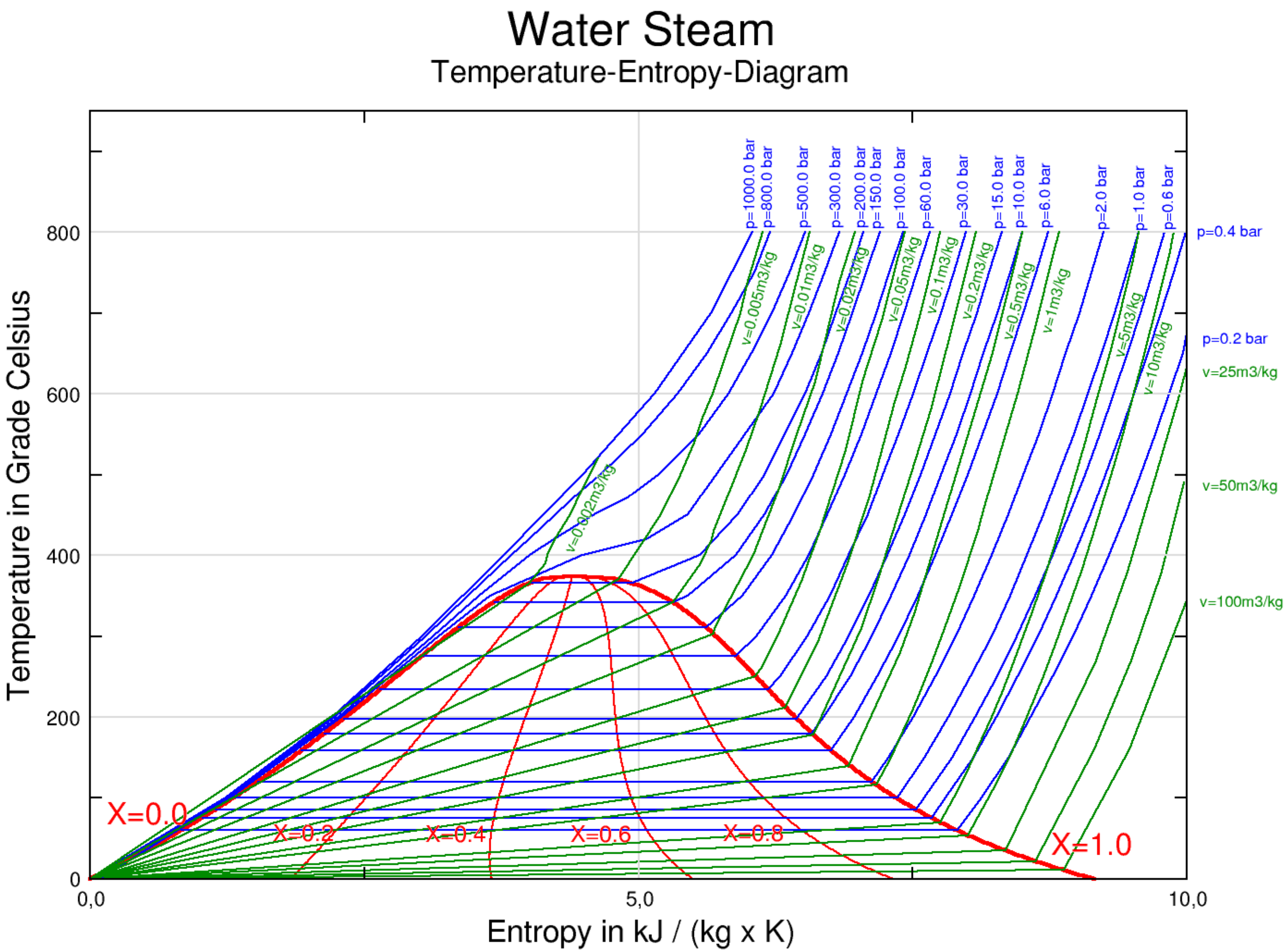


The steam boiler is an open-circuit vessel, where the boiling pressure is defined by the circulating pump.

The water/steam fluid is in constant circulation, repeatedly undergoing phase change from liquid to vapor inside the boiler, and back into liquid in the condenser after the expansion process.

Property diagrams for water / steam



The temperature-entropy (T-S) diagram is very useful for the visualization of thermal processes in any thermodynamic cycle.

Remember that in the double-phase zone (inside the bell-shaped dome) where water boils into steam, the temperature and the pressure lines are merged together.

Therefore, in a T-S diagram the process of water boiling (or steam condensation) at constant pressure and thus at a constant temperature goes along the same horizontal line.

At 1 bar pressure, water boils at 100 degrees and freezes at 0, this is how Anders Celsius (a Swedish scientist in Uppsala) defined the centigrade temperature scale in 1742.

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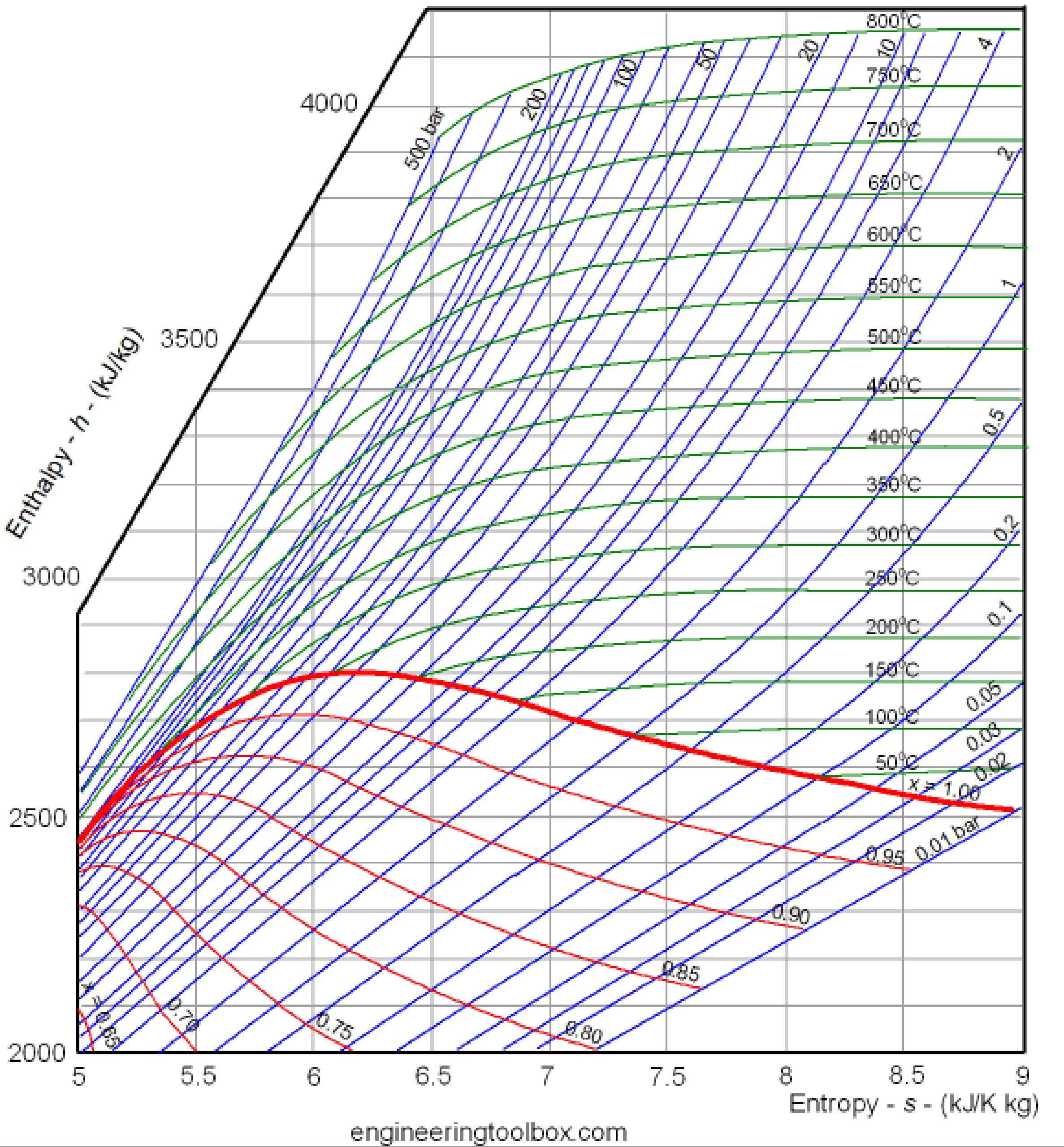
Mollier Diagram (h-s diagram)

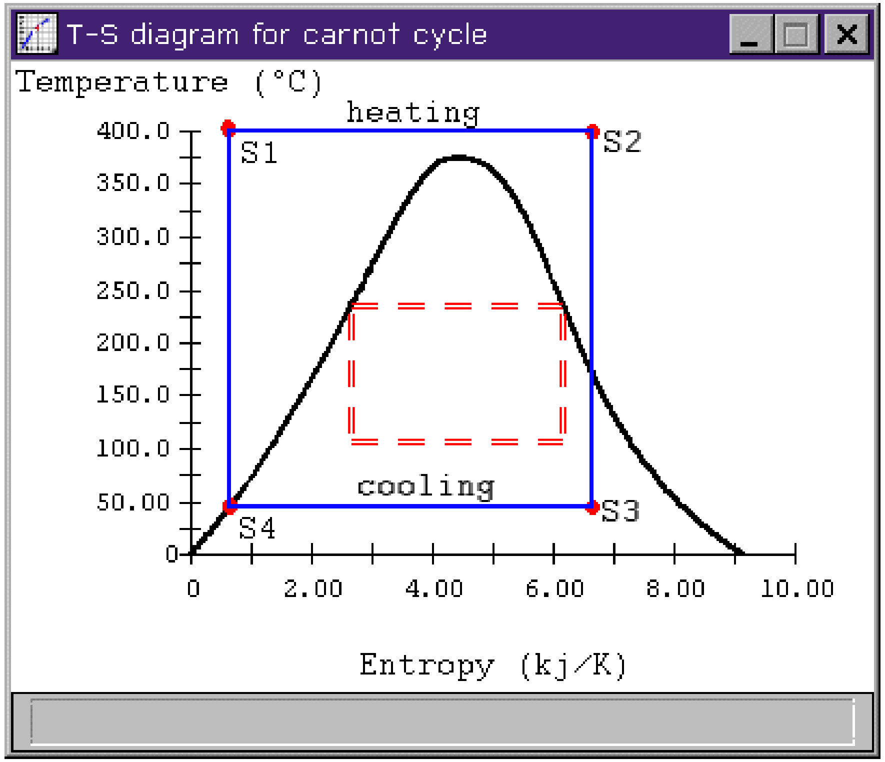


The enthalpy-entropy diagram is most applicable for steam processes.

Steam is **not a perfect gas**, neither is any gas near phase-change conditions, so steam enthalpy values cannot be simplified!
We rather use diagrams or tabulated enthalpy values (or software tools) where the steam enthalpy has been calculated via complex polynomials.

The Mollier diagram zooms into the region around the **saturated vapor line** (right end of the double-phase dome towards superheated steam) so it's very handy to be used for expansion calculations in a turbine.

Approaching the Carnot cycle



- Isothermal heating and cooling;
- Isoentropic compression and expansion;
- Hence, a square shape in the T-S diagram.

Impossible to be implemented in reality!

However, it can be attempted by a cycle situated fully inside a double-phase zone, e.g. by any vapor cycle!
(see the dashed lines in the figure)

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Fundamental Steam Cycle

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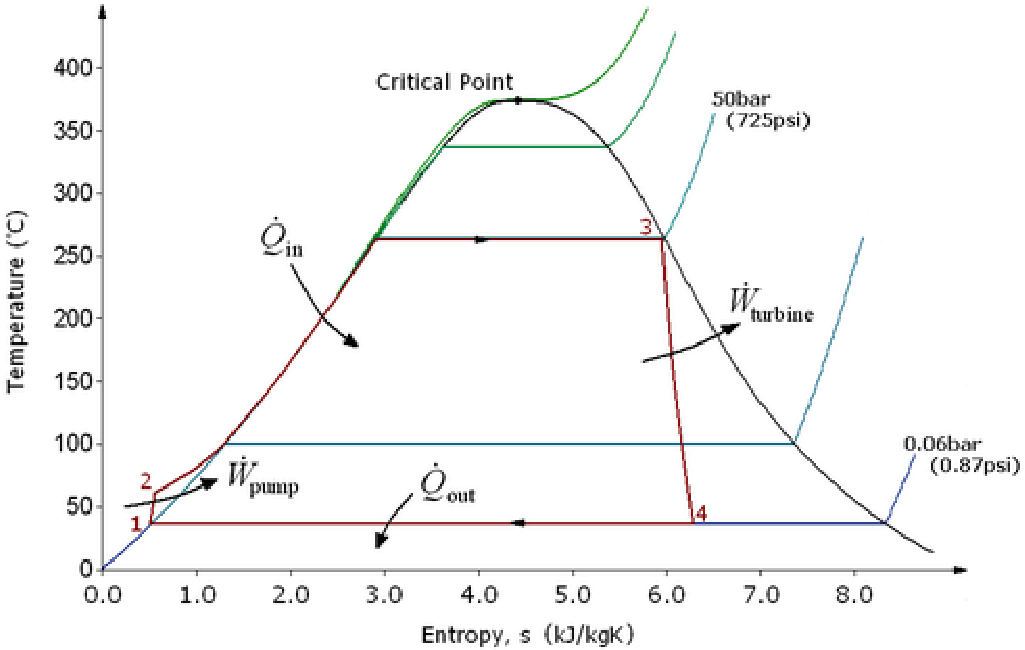
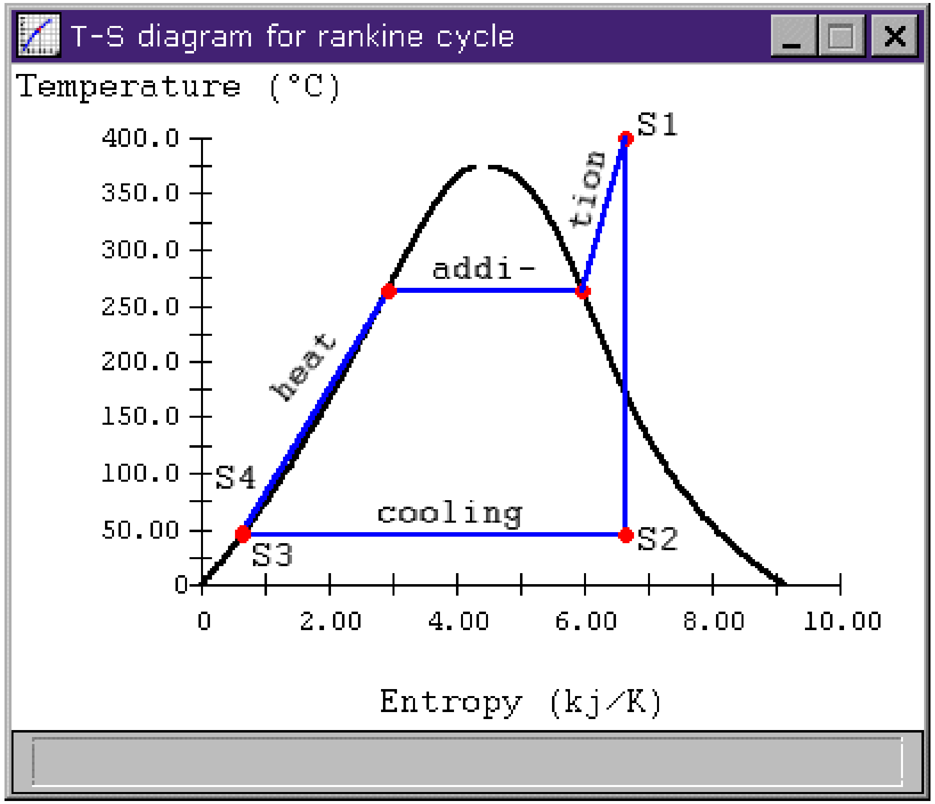


Practically, it is easier to condense the steam all the way down to water (4→1) and then pump it up as liquid (1→2), instead of the troublesome process of wet vapor compression.

A water pump instead of a vapor compressor: Losing the Carnot potential but gaining robustness and bringing down the parasitic load to nearly zero!

The expansion can still work with saturated steam, unless…

Steam cycle with Superheat = Rankine cycle!

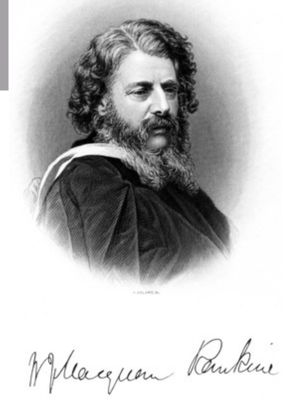


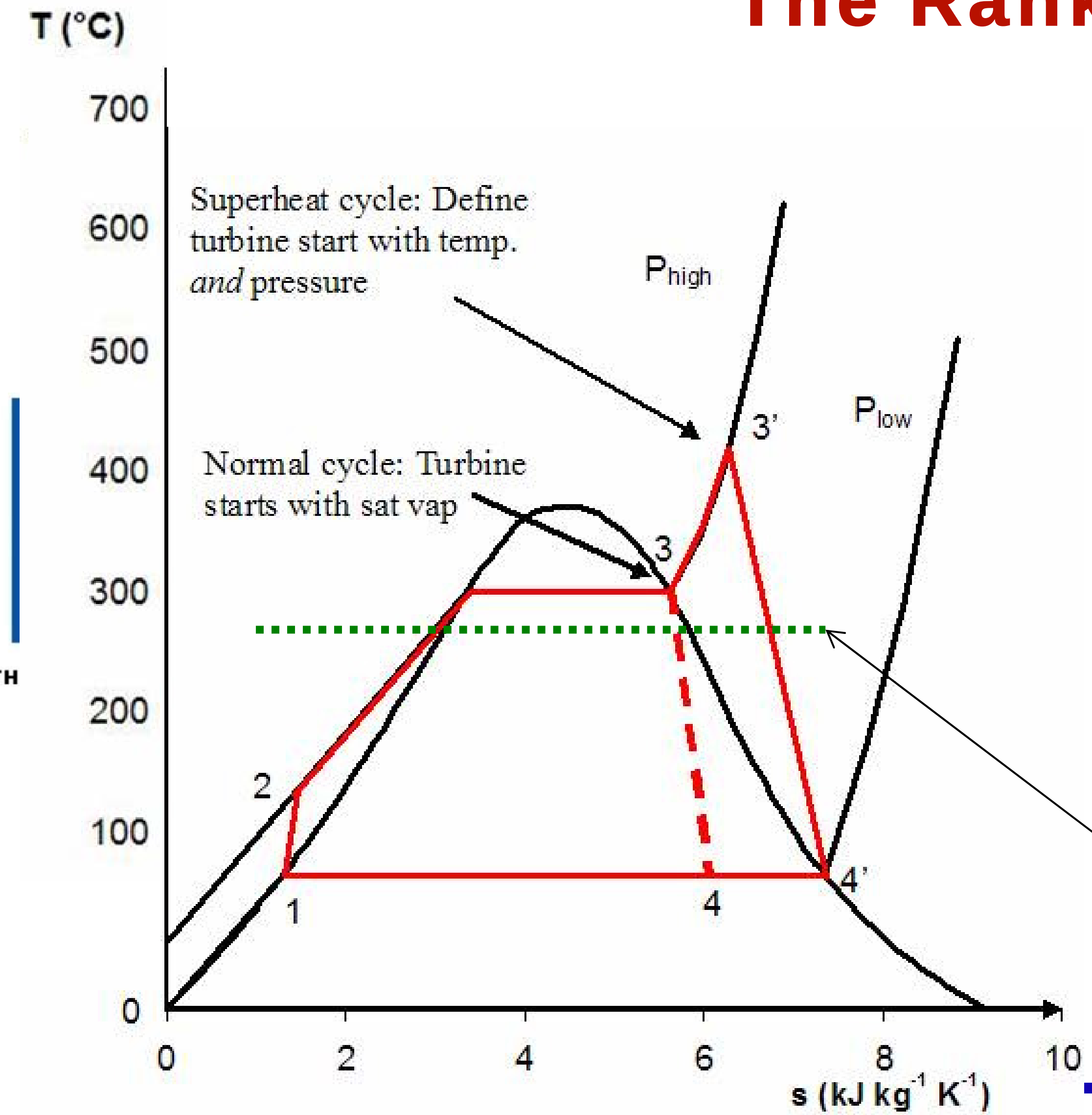
...unless the actual expansion device is damaged by water droplets in the saturated steam.

Thus: the steam is superheated before expansion in a turbine. The expansion should ideally end at the saturated vapor line and avoid entering inside the wet (double-phase) zone.

Looking at the figure here, the goal would be to superheat more (moving point S1 further up and right) until point S2 (end of expansion) falls on the saturation line or only slightly penetrates into the wet zone.

The Rankine Cycle





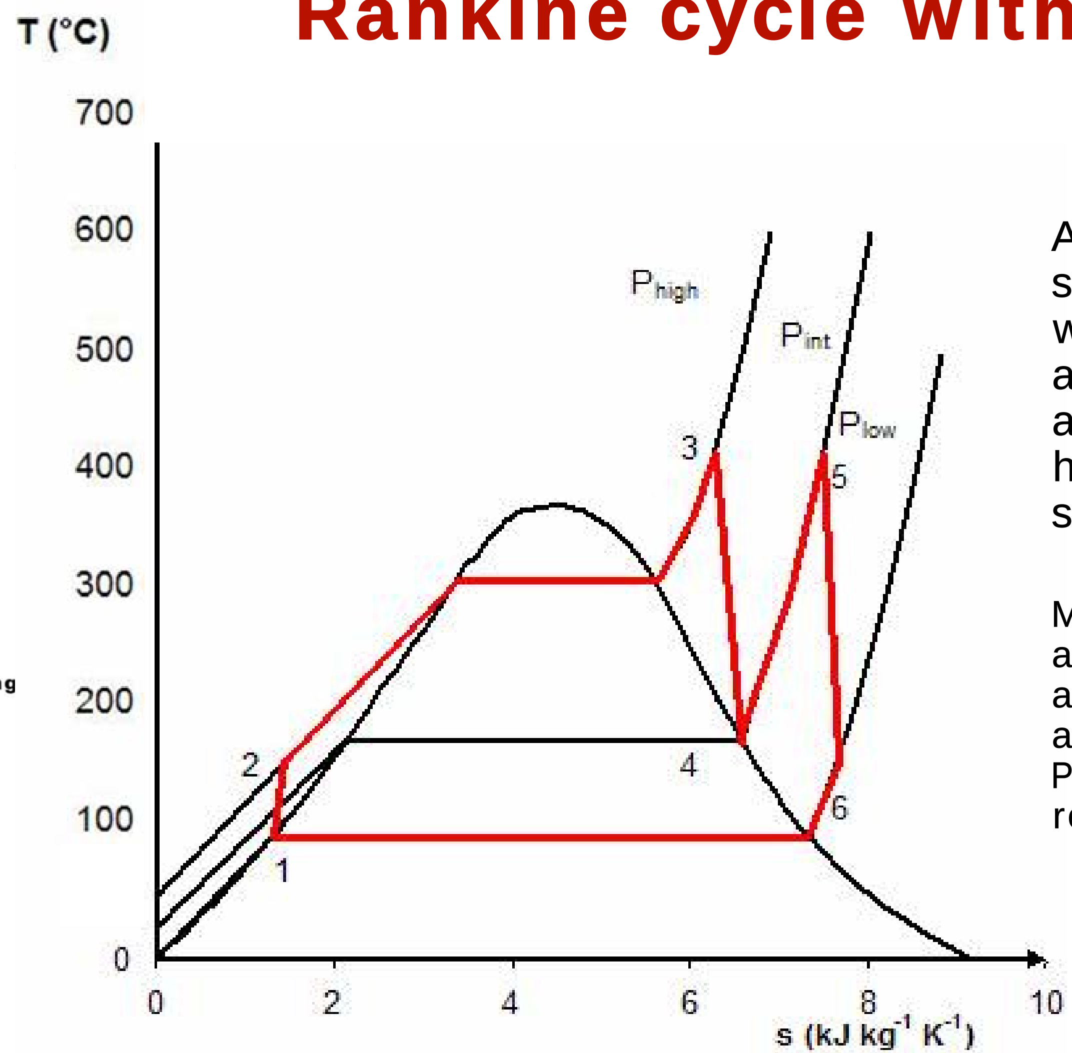
Superheating also helps to **increase the average temperature of heat addition to the cycle**, therefore raising its efficiency!!

William John Macquorn Rankine – a Scottish engineer – described the merit of superheating and gave his name to the modern steam cycle. Rankine collaborated with Rudolf Clausius, William Thomson (Lord Kelvin), James Joule, etc., and participated in the definition of the absolute temperature scale around 1850, known as "degrees Rankine" in imperial units.

Any generic vapor cycle for power generation nowadays is designated as a "Rankine Cycle".

The average temperature of heat addition – used for defining the efficiency potential of the cycle – can be found by integration along the actual heat addition line and lies somewhat below the boiling (evaporation) temperature in this particular case.

Rankine cycle with Reheat



Adding a reheating step (a second superheat after partial expansion) would further increase the average temperature of heat addition to the cycle, plus again helping the expansion process to stay free of wet steam.

Multiple reheating steps (theoretically an infinite number of reheats) would attempt a quasi-isothermal heat addition, thus a quasi-Carnot cycle. Practically, only one or two reheating steps are justified.

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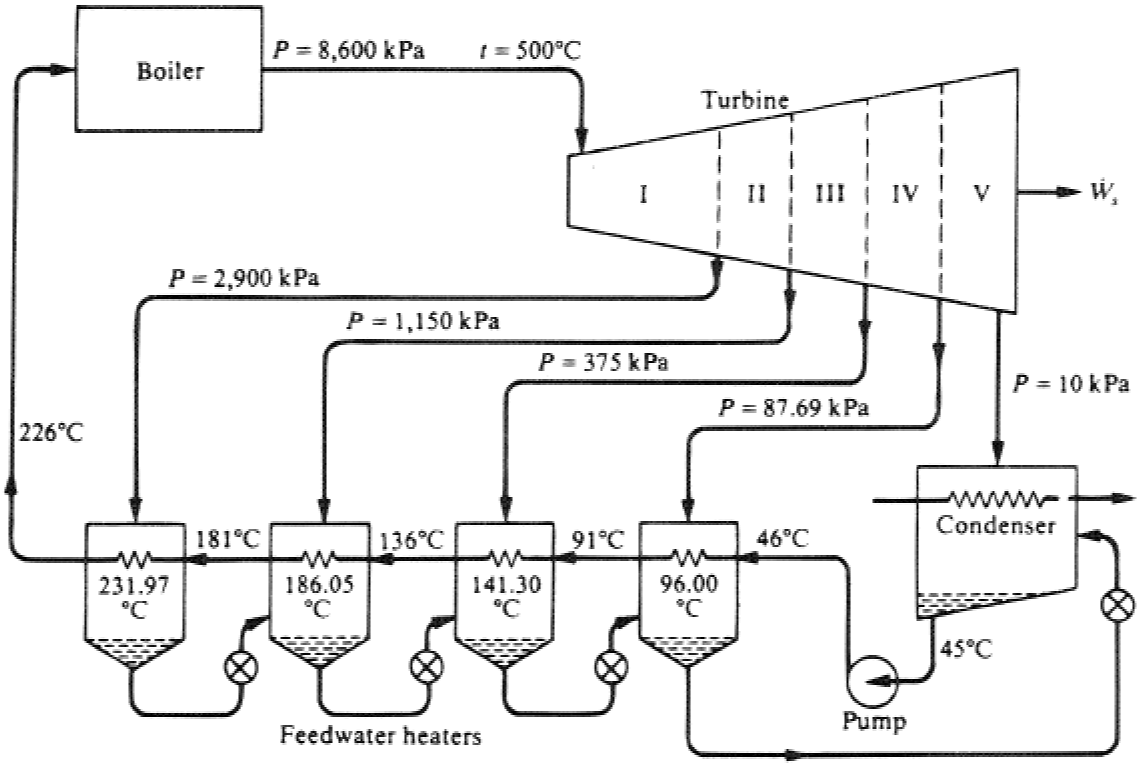
Feedwater Preheating

$T_{boiling}$ = 300 °C



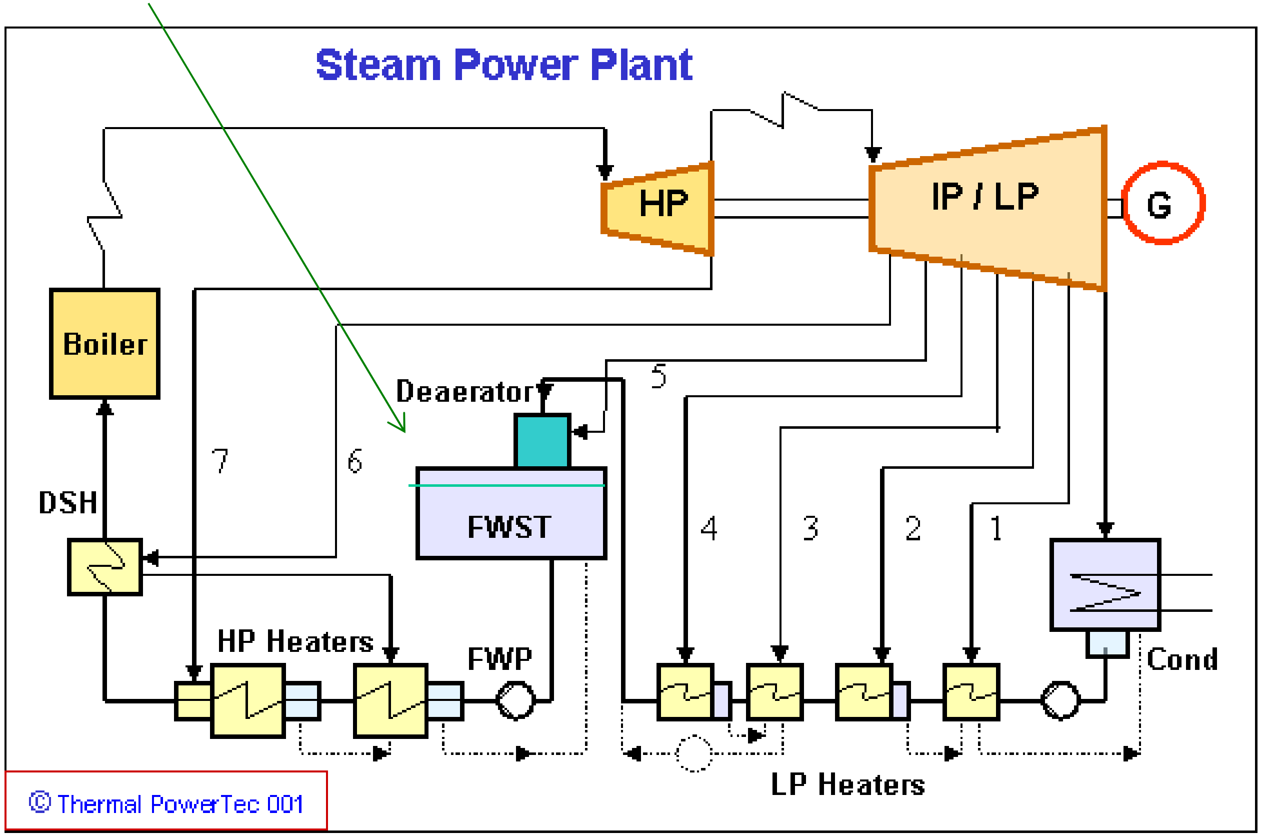
The merit of feedwater preheating can be comprehended only if we consider the entire steam cycle, including the steam boiler.

Sacrificing a small mass flow of steam extracted (bled) from the turbine and using its latent heat of condensation for preheating the cold feedwater coming from the steam condenser.

Work is lost when steam is extracted instead of expanded to the end, however, much more **fuel energy is saved in the boiler** when we send there hot (preheated) water ready to start boiling, instead of cold feedwater directly from condenser.

Complex modern steam cycles

FeedWater Storage Tank, also serving as an open preheater and deaerator!

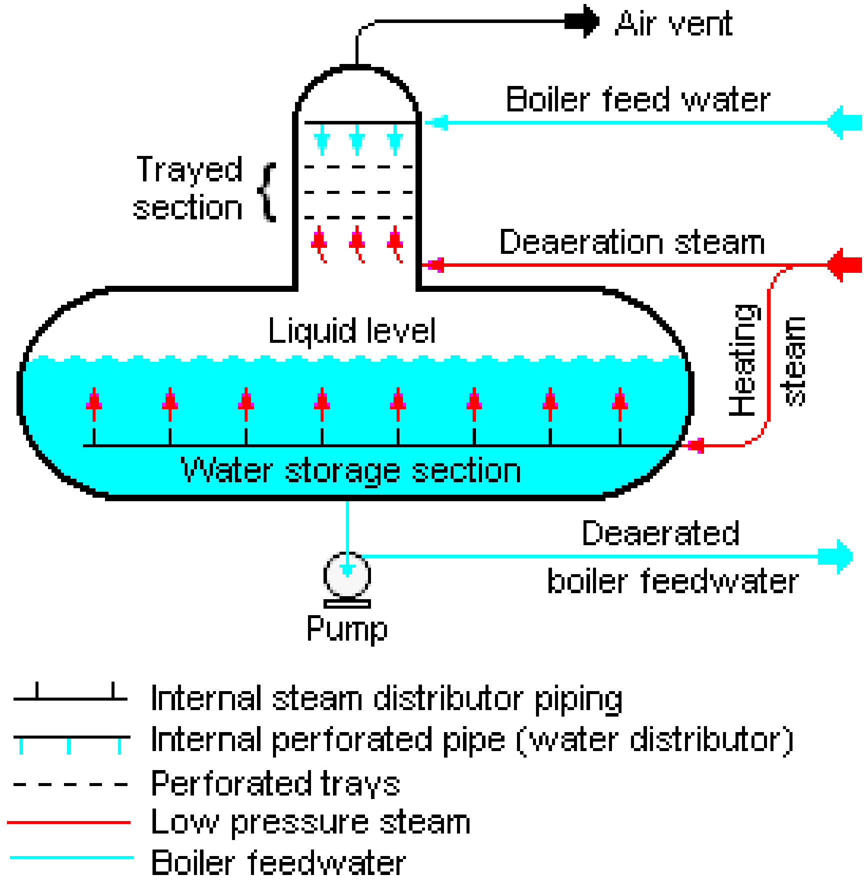


The typical steam cycle for electricity production nowadays (depending on size and complexity) would have one or two reheat stages thus dividing the turbine into high-pressure (HP) section, middle or intermediate pressure (MP) or (IP) and low pressure (LP) sections.

It would also use (if any) about 2 to 6 LP feedwater preheaters, a feedwater tank, and 1 to 4 HP feedwater preheaters.

The efficiency of the cycle is a function of the average temperature of heat addition, the condensation temperature, the internal losses in all components, the complexity of the feedwater circuit (number of preheaters), the possible leaks and parasitic loads by auxiliary components, etc.. There is a giant need for further improvements in all of these aspects.

Feedwater tank (deaerator)



The **feedwater tank (FWT)** is a vital component for the practical steam cycle. It has 3 main purposes:

- When the cycle is not operating, the FWT stores the working fluid (cold liquid water) for the system.
- When the cycle is operating, the FWT still holds most of the available water in saturated condition and buffers any small fluctuations in mass flow. It also works as a direct contact (mixing) preheater. The heating agent is steam, extracted from the turbine at the FWT pressure or supplied from the boiler after throttling. The heating steam is directly mixed with the water in the tank, keeping it constantly heated to saturated condition (slightly boiling) at the given pressure.
- Also, the FWT acts as a **deaerator**, where gases dissolved in the feedwater (primarily oxygen from air leaking into the condenser) are driven out during the preheating process and released to the atmosphere through an opening (air vent). Because of this, the FWT is also called ”open preheater”.

The typical pressure in the FWT is chosen somewhat higher than atmospheric, usually between 2 to 12 bar.

Cold start and operational challenges

- A large number of auxiliary components are necessary, lots of hardware, large footprint, miles of pipework, hundreds of valves, bypass lines, redundancy components, etc..
  There are many minor components usually not shown in the generalized steam cycle charts.

- Water/steam is the preferred and cheapest working fluid in large scales, but other fluids could be better for specific applications and for certain temperature range.
  Water needs to be treated (demineralized and degassed) to avoid scaling and corrosion.
  Mass losses (leakage from sealings or intentional blow-out of steam or water from deaerator or boiler) need to be recovered by a constant inflow of treated ”make-up water”.

- Cold start = slow and cumbersome process!
  Starting the cycle from cold condition involves slowly heating up the boiler, then sending steam to slowly heat up the turbine (larger components = slower heat-up rates, from several hours to several days), meanwhile initiating the condensation process by ”start-up ejectors” to devoid the condenser from air until it reaches its nominal conditions.
  Keeping the steam plant in idling mode or in ”hot reserve” would improve its flexibility and shorten the ramp-up time, but involves large expenses.

- Availability of a proper heat sink (cooling water) and maintaining the condenser in a good operating condition are crucial for the cycle performance.

- Partial loading is achieved by decreasing the mass flow of steam either by throttling valves or by a sliding boiler pressure, or a blend of those. The typical steam cycle quickly loses efficiency at deep part-load or in other off-design conditions, and is generally not flexible.
  It needs to be carefully designed for such operation if it would often be run at partial loading.

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