STEAM PLANT

The harnessing of steam power ushered in the industrial revolution. It began with **Thomas Newcomen** (Dartmouth) in the early 1700's. Early developments were very slow and Newcomen's design was used in England for nearly 100 years.

Newcomen's engine could be better described as a 'vacuum' engine. The vacuum was created by condensing steam.

The engine however, was extremely inefficient, and where coal had to be brought from a distance it was expensive to run.

James Watt (1769) brought about a major increase in power and efficiency with his developments. Watt re-designed the engine so that condensation occurred outside of the cylinder. This meant that the cylinder did not lose heat during each stroke. It also allowed the use of pressurised boilers thus obtaining power on the up-stroke as well as the down-stroke.

The beam engine gave way to the reciprocating steam engine which was refined to a high degree. Double and triple expansion steam engines were common and there was scarcely a demand for mechanical energy which steam could not meet.

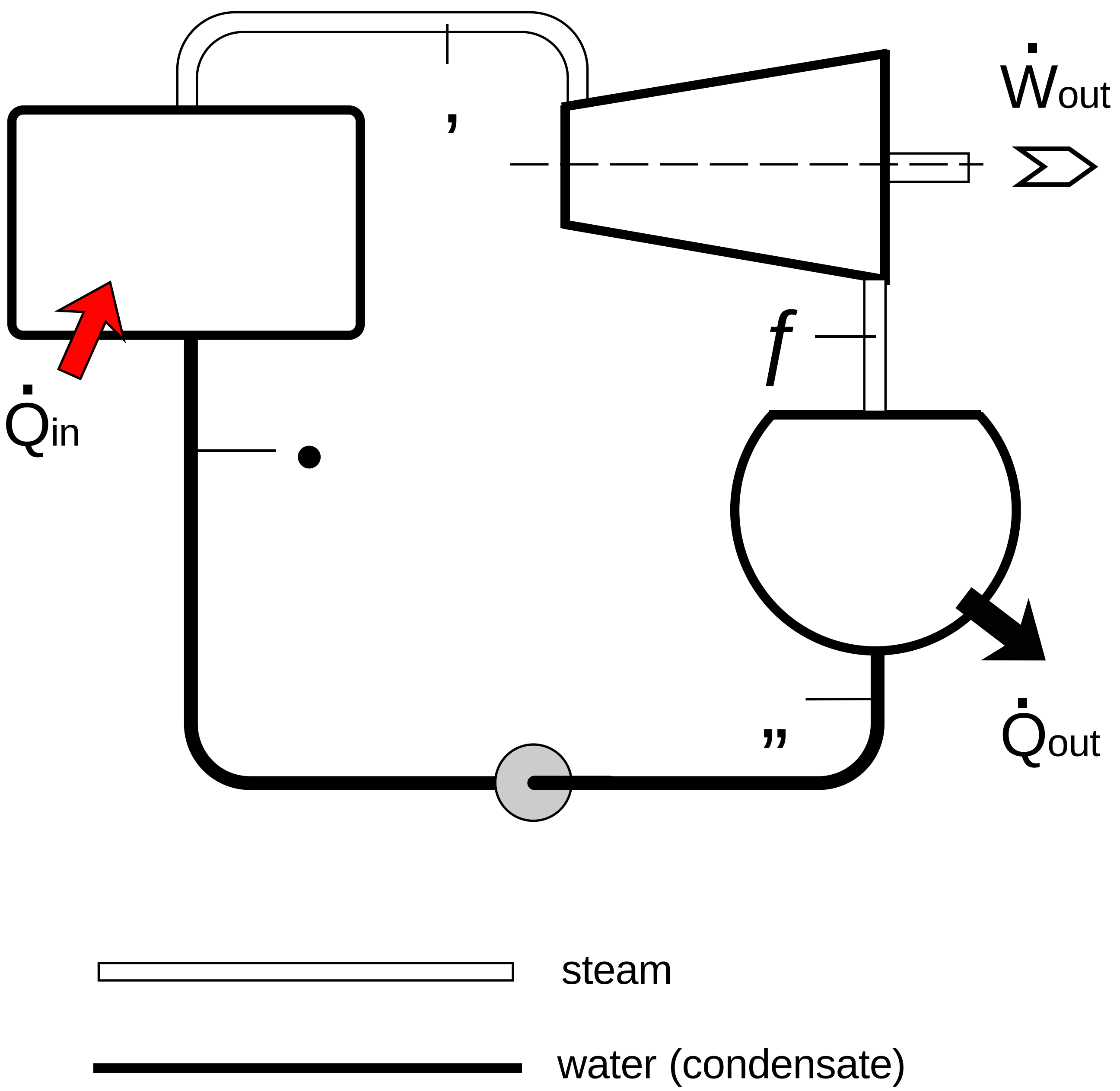
However, reciprocating steam engines were complicated, and hence not always reliable. In 1884 **Charles Parsons** produced the first steam turbine. With Michael Faraday's earlier discovery of electromagnetic induction (1831) the widespread use of electricity had begun. The two technologies came together and with the National grid, progressively eliminated the need for factories to have their own steam plant.

Today, mechanical power production using steam is almost wholly confined to electricity generation.

BASIC STEAM PLANT

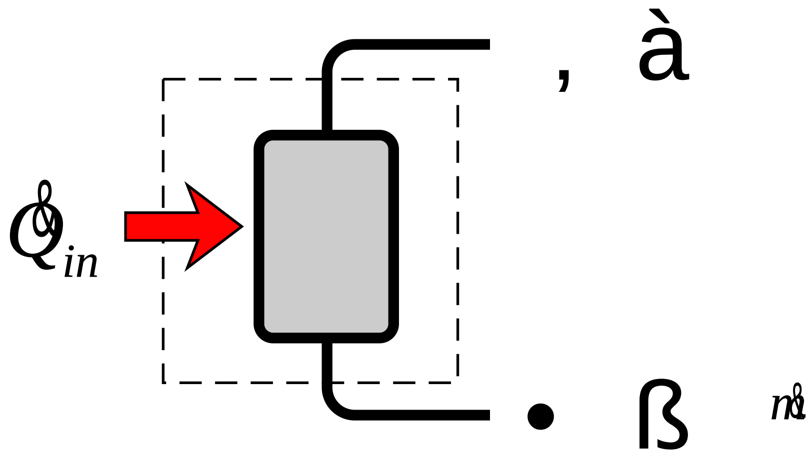
Basic Steam Plant consists of a:

1 ® 2: Steam generator (or Boiler)
2 ® 3: Steam Turbine
3 ® 4: Condenser
4 ® 1: Feed pump.



Steam Generator or Boiler

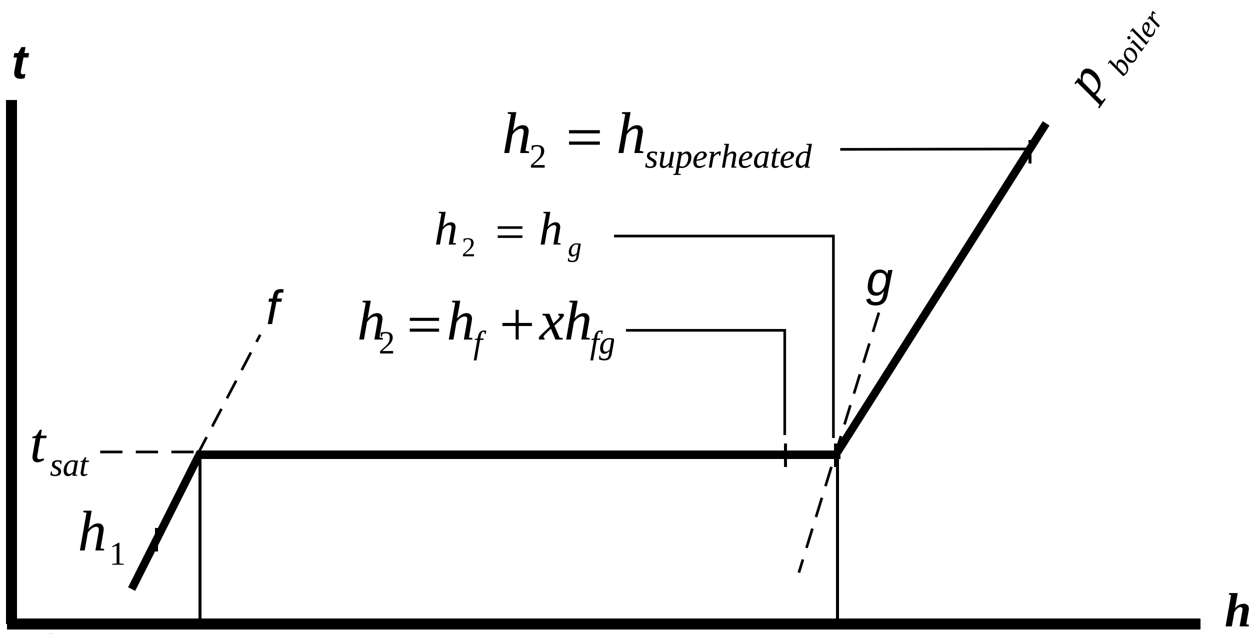
The purpose of the boiler is to convert water (pumped into it under pressure) to steam. The steam may emerge wet, dry saturated, or superheated depending on the boiler design.



We may analyse the boiler as a steady state open system using the SSFEE:

$$\dot{Q}_{in} = \dot{m}(h_2 - h_1)$$

h₁ is the specific enthalpy of sub-cooled water.
(ie at a temperature <u>*below*</u> its saturation temperature).
It can be found from 'sub-cooled' tables, but saturated values (at the same temperature) are usually sufficiently accurate.



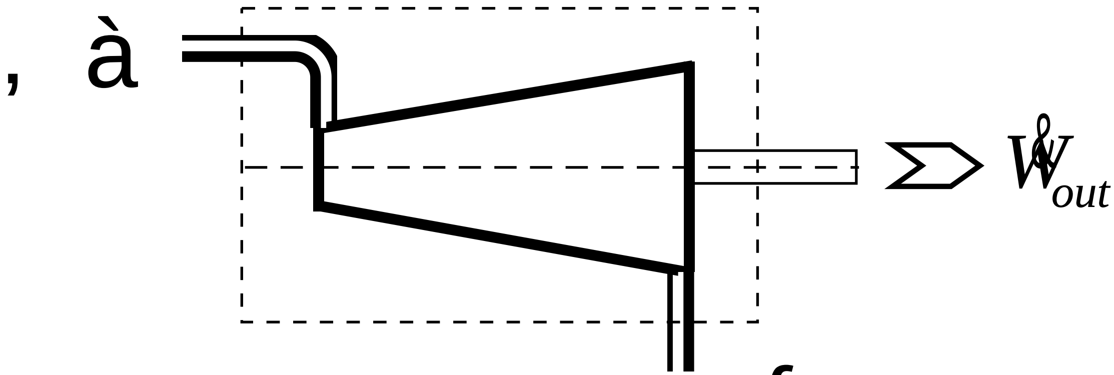
Notes on Boilers

1. The heat transfer rate to the water/steam is normally less than the rate at which energy is released inside the boiler (typically by combustion). We may therefore define a boiler efficiency as:

$$\eta_{boiler} = \frac{\dot{m}(h_2 - h_1)}{\dot{m}_{fuel} \times LCV}$$

Turbine

A steam turbine operates in a similar way to a gas turbine. The same basic performance and efficiency equations are used except that steam cannot be treated as a perfect gas.

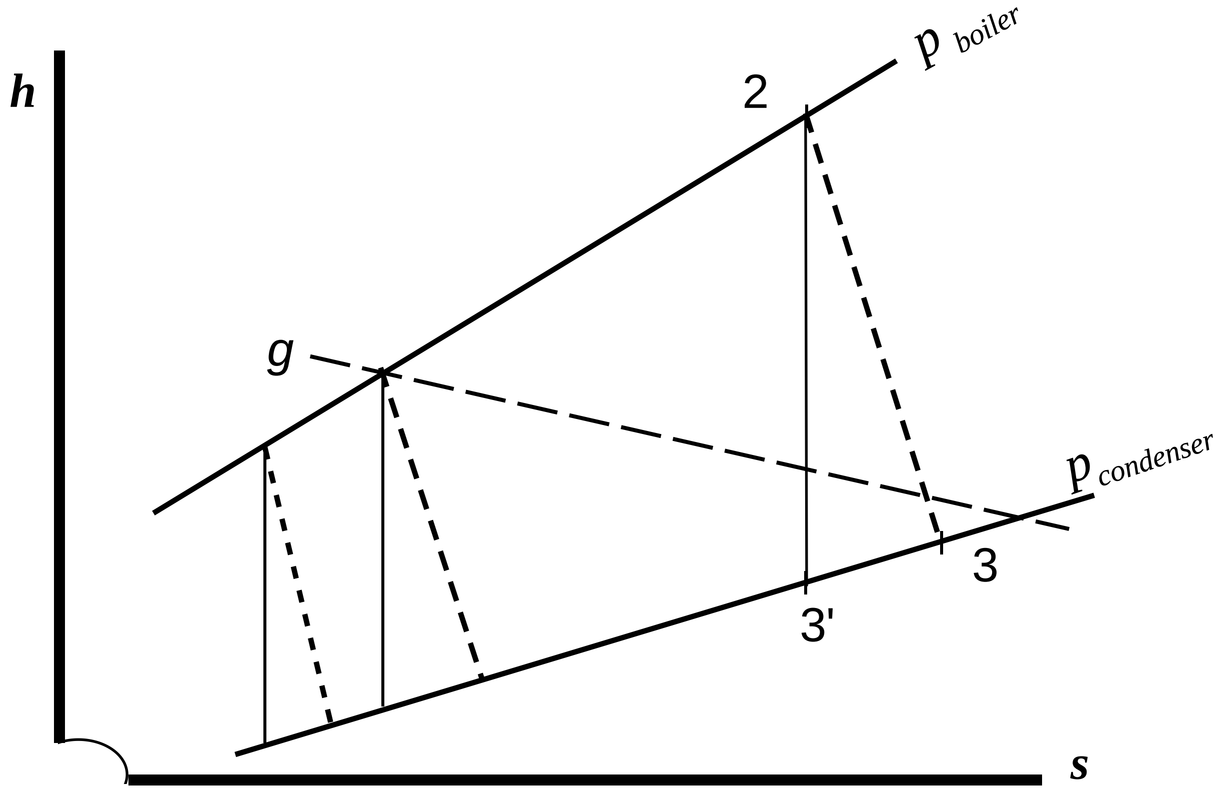


$$\dot{W}_{out} = \dot{m}(h_2 - h_3)$$

and $$\eta_{isen} = \frac{\dot{W}_{out}}{\dot{W}_{isen}} = \frac{\dot{m}(h_2 - h_3)}{\dot{m}(h_2 - h_{3isen})}$$

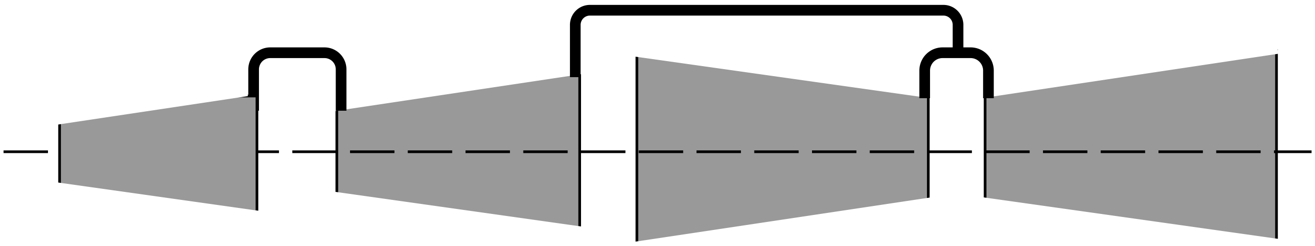
or $$\eta_{isen} = \frac{h_2 - h_3}{h_2 - h_{3'}}$$

As with a gas turbine the thermodynamic process may be shown on a T-s chart, or more usefully on an h-s chart



Notes on Turbines

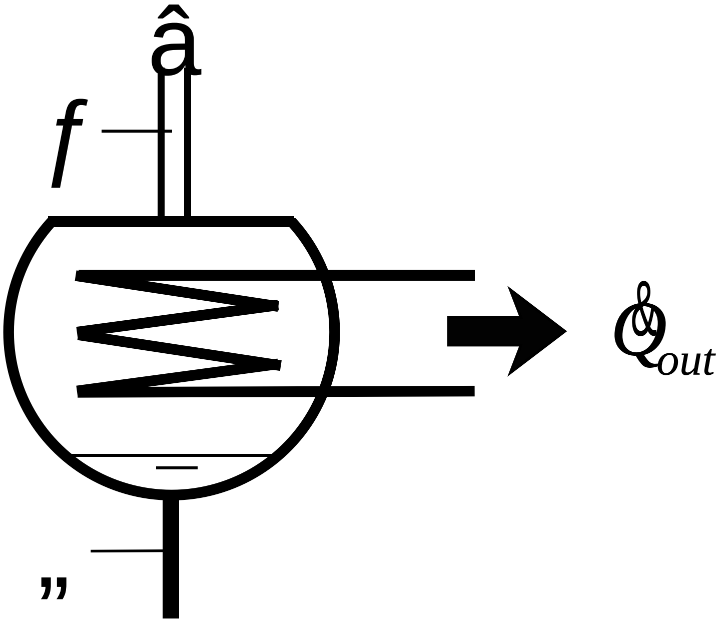
1. Steam turbines are usually staged owing to the fact that the specific volume of steam increases considerably as its pressure falls. A typical large steam turbine will be divided into high, intermediate and low pressure stages. The LP stage may be split.



Condenser

The condenser brings the exhaust steam into contact with a cool medium (usually cold water) in order to remove heat and condense it back to water known as condensate.

Thermodynamically it behaves in the same way as the boiler, but in reverse.



$$\dot{Q}_{out} = \dot{m}\left(h_3 - h_4\right)$$

Notes:

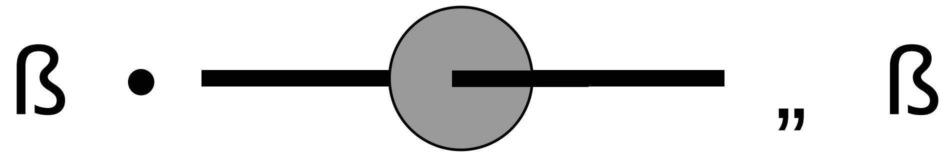
1. The cooling water temperature would be typically in the range 10°C to 30°C depending on the source. Condensing temperatures are therefore in the range 25°C to 45°C.
This means condensing pressures in the range 3 to 8 kPa, ie well below atmospheric pressure. This gives rise to problems with air leakage into condensers, which has to be counteracted by the use of vacuum pumps.

2. The condensate will normally leave the condenser as a saturated liquid at the saturation temperature

Feed pump

The feed pump is needed to pump water back into the boiler. In order to do this it has to raise the pressure to at least boiler pressure.

It requires mechanical energy to achieve this, but in comparison to the energy produced by the turbine the amount required is very small, and can normally be ignored in plant efficiency calculations.



To find the actual power requirements of the feed pump we use the SSFEE.

$$
\begin{aligned}
-\dot{W}_{fp} &= \dot{m}\left(h_1 - h_4\right) \\
&= \dot{m}\left[\left(u_1 + p_1 v_1\right)\right] - \left[\left(u_4 + p_4 v_4\right)\right]
\end{aligned}
$$

Since the water temperature will not change significantly, and also since water is virtually incompressible:

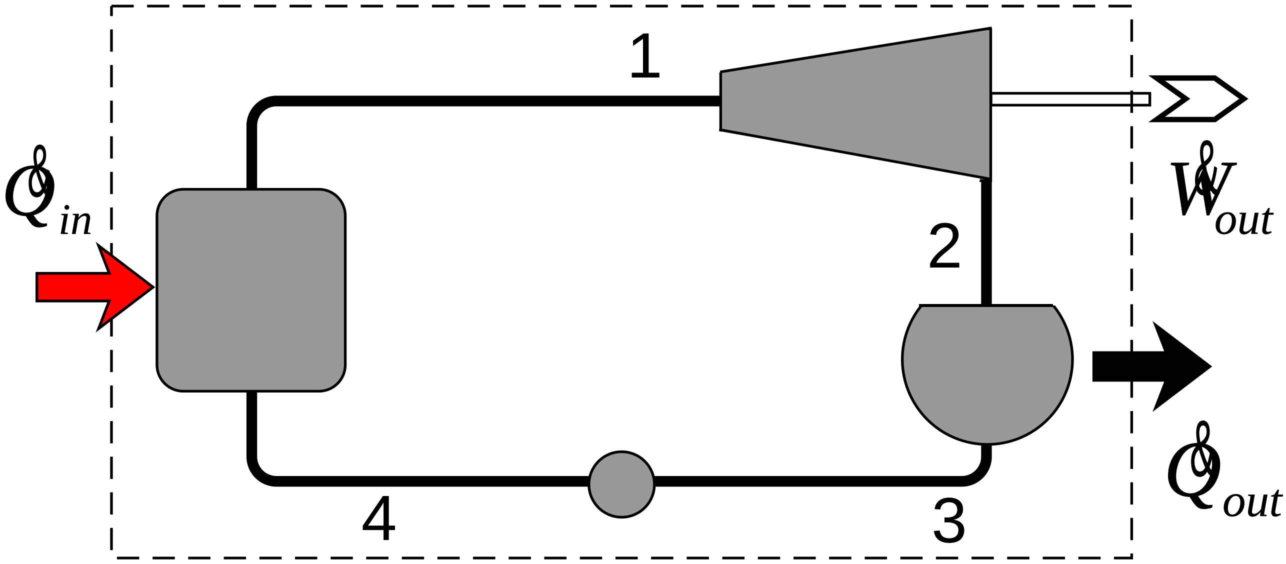
$$u_1 = u_4 \text{ and } v_1 = v_4$$

$$\therefore \quad \dot{W}_{fp} = \dot{m} v_1 \left(p_4 - p_1\right)$$

$$\frac{\dot{W}_{fp}}{\dot{m}} = \Delta h = 0.001 \times \left(2 \times 10^6\right) = 2 \ kJ/kg$$

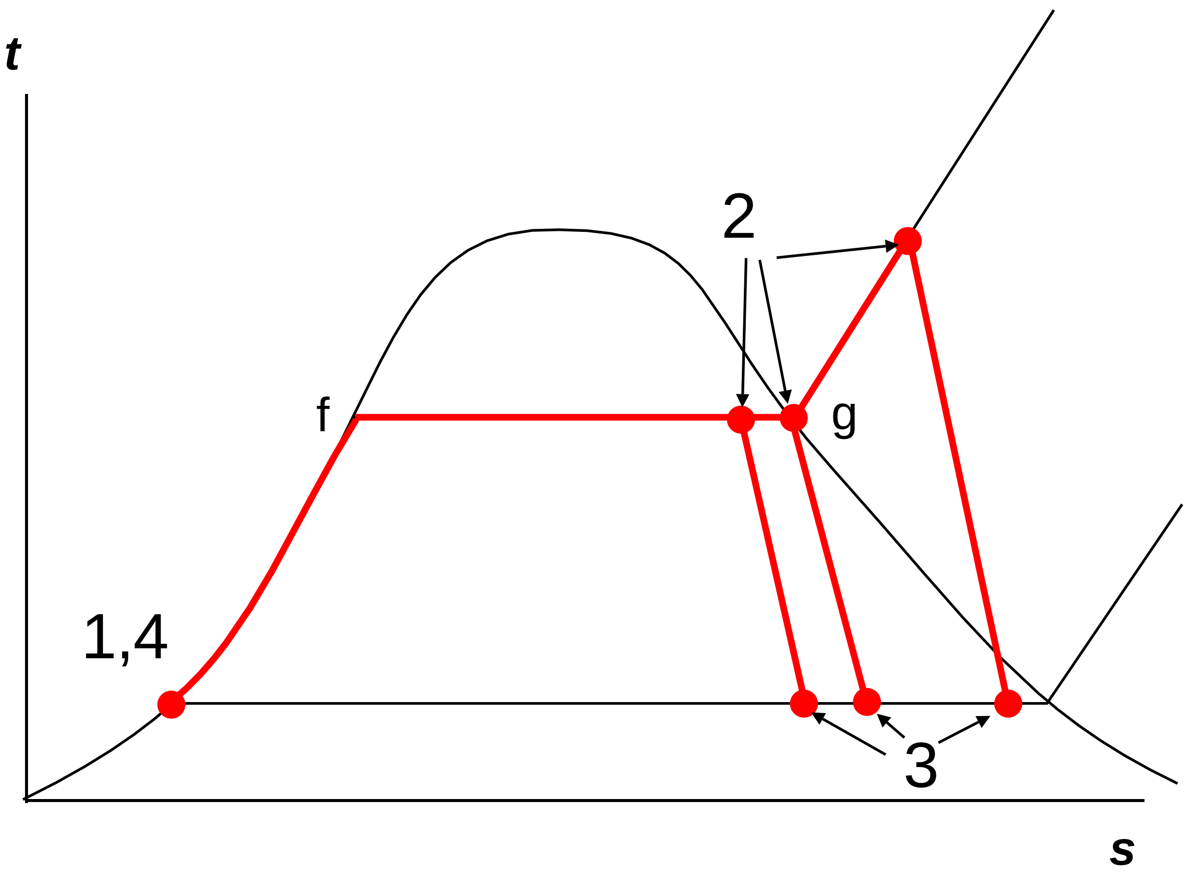
This compares with a specific enthalpy change across the turbine of ~ 1000 kJ/kg, ie negligible.

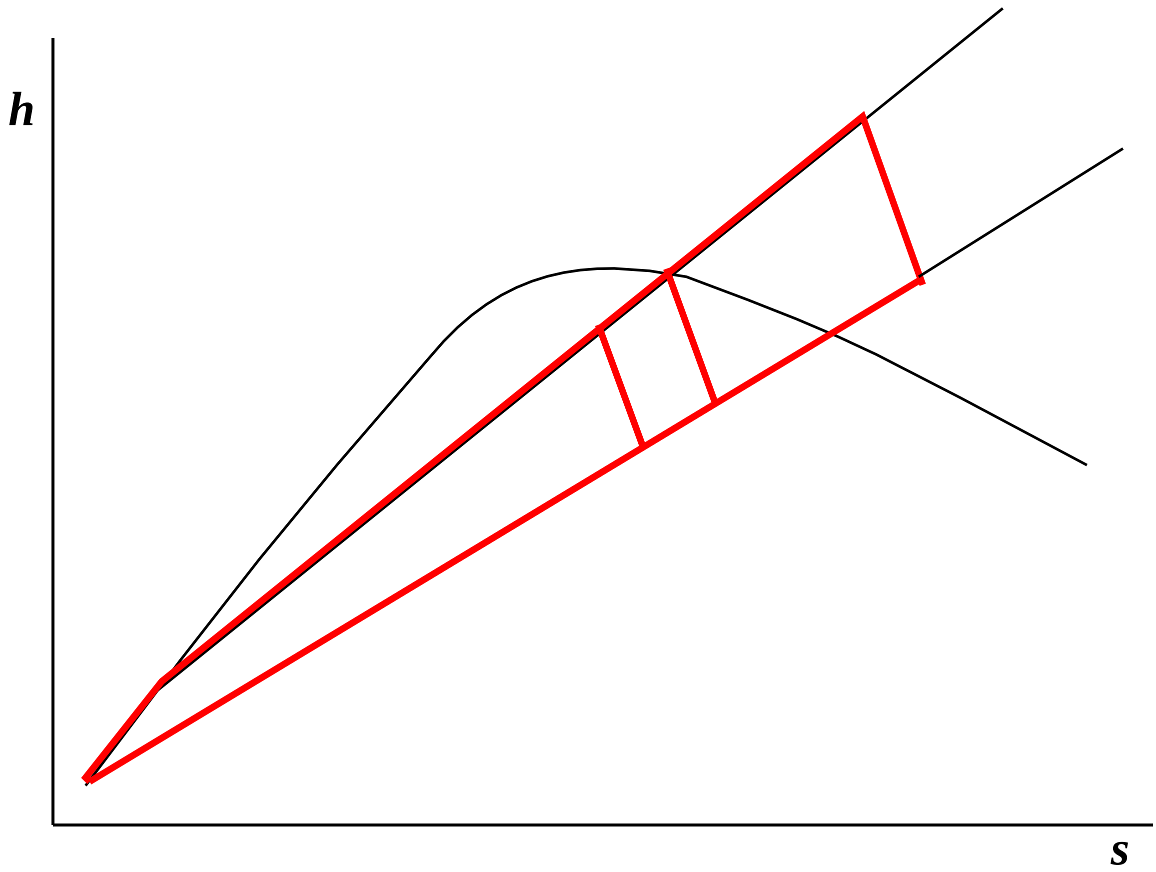
Steam Plant as a complete system



As a heat engine:- $\dot{Q}_{in} = \dot{W}_{out} + \dot{Q}_{out}$

Cycle (h_2£h_g: Rankine Cycle; $h_2>h_g$ Superheated Rankine Cycle)





Cycle thermal efficiency (neglecting feed pump power):

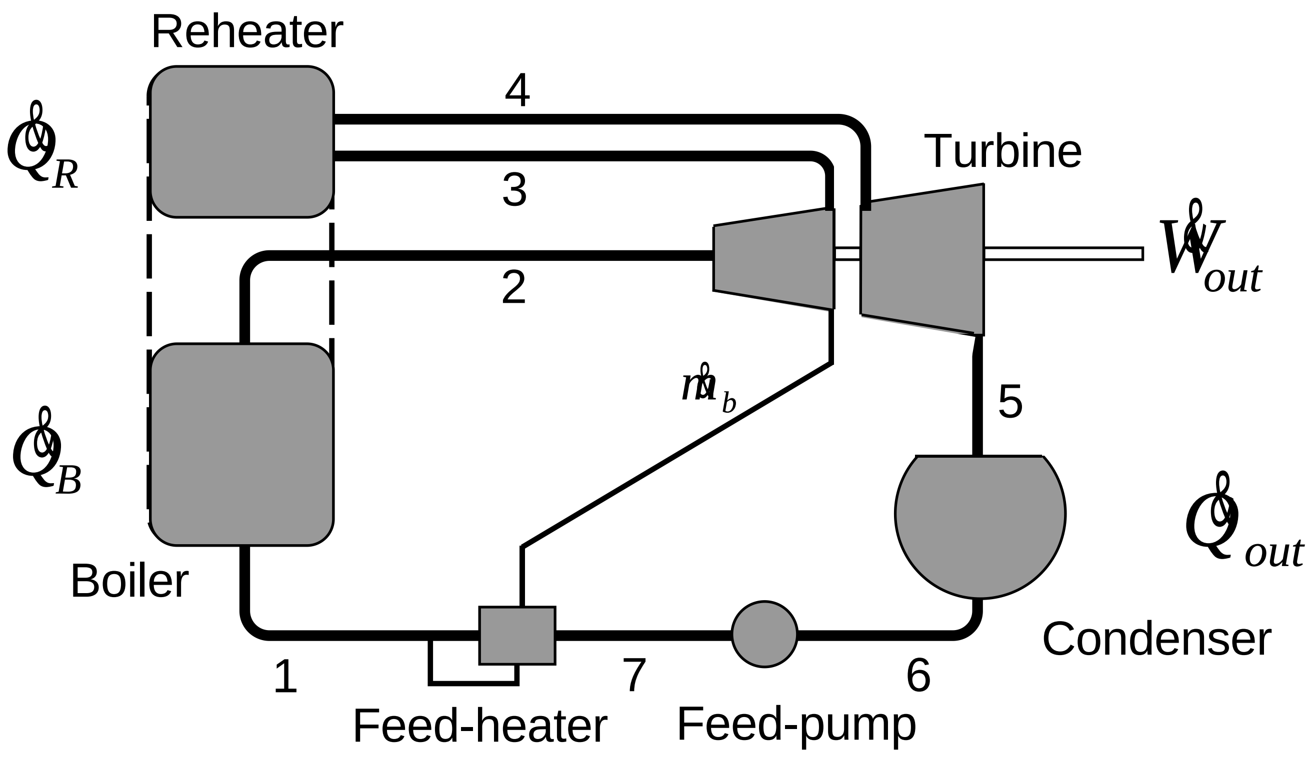
$$\eta_{th} = \frac{\dot{W}_t}{\dot{Q}_{in}} = \frac{\dot{m}(h_2 - h_3)}{\dot{m}(h_2 - h_1)}$$

ie $$\eta_{th} = \frac{(h_2 - h_3)}{(h_2 - h_1)}$$

ADVANCED STEAM PLANT

The cycle and overall thermal efficiency of steam plant can be improved by the inclusion of:

Feed-heating;
Reheat;
Heat recovery

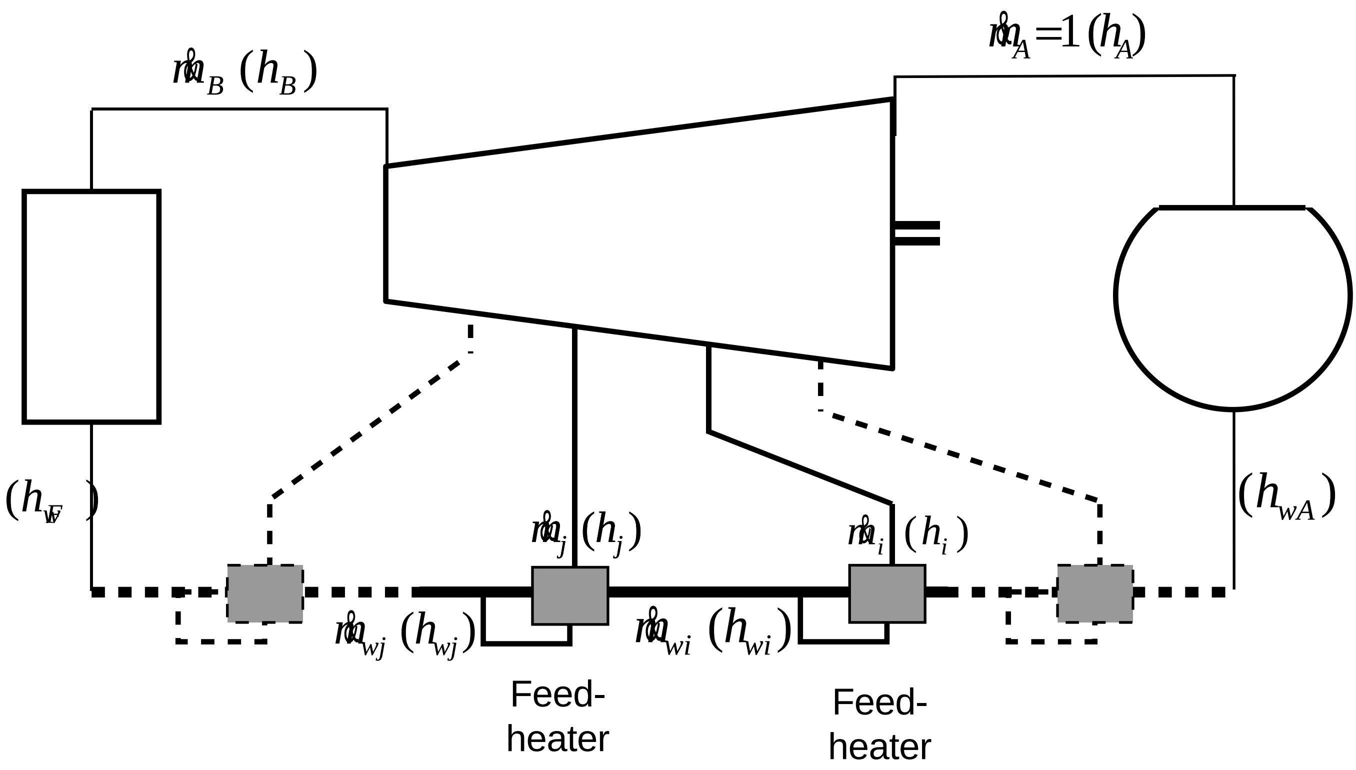


FEED HEATING

One feed-heater would raise the feed water temperature by a certain amount depending on the condition of the steam bled from the turbine used to increase the feed water temperature.

What if we added more feed heaters?
How should we use them?

Let us look at an indeterminate number of feed-heaters serving a steam plant. We shall focus on any two adjacent feed-heaters.



NB: the subscript 'w' denotes liquid <u>w</u>ater

An energy balance on feed-heater (j) gives:-

$$\dot{m}_j (h_j - h_{wj}) = \dot{m}_{wi} (h_{wj} - h_{wi}) \qquad \text{(i)}$$

ie, enthalpy lost by bled steam = enthalpy gained by incoming feed-water

A mass balance of feed-heater (j) gives:-

$$\dot{m}_{wj} = \dot{m}_{wi} + \dot{m}_j \qquad \text{(ii)}$$

from (i) $$\dot{m}_j = \dot{m}_{wi} \frac{(h_{wj} - h_{wi})}{(h_j - h_{wj})}$$

from (ii) $$\dot{m}_{wj} = \dot{m}_{wi} (1 + \frac{h_{wj} - h_{wi}}{h_j - h_{wj}})$$

or $$\frac{\dot{m}_{wj}}{\dot{m}_{wi}} = \gamma_j = 1 + \frac{h_{wj} - h_{wi}}{h_j - h_{wj}}$$

if $h_{wj} - h_{wi} = r_j$ ***(enthalpy rise of feed - water in 'j')***

and $h_j - h_{wj} = F_j$ ***(enthalpy Fall of bled steam into 'j')***

then $$\gamma_j = 1 + \frac{r_j}{F_j}$$

The mass flow into the turbine $(\dot{m}_B)$ may be written:-

$$\dot{m}_B = \frac{\dot{m}_B}{\dot{m}_{wj}} \times \frac{\dot{m}_{wj}}{\dot{m}_{wi}} \times \frac{\dot{m}_{wj}}{\dot{m}_{wh}} \times \times \times \frac{\dot{m}_{wa}}{1}$$

ie $\dot{m}_B$ = <u>product</u> of all the ratios $= \prod_{n=1}^{j} \gamma_j$

Now $$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{\dot{m}_A (h_A - h_{wA})}{\dot{m}_B (h_B - h_{wF})}$$

but $\dot{m}_A = 1$

$$\therefore \quad \eta_{th} = 1 - \frac{(h_A - h_{wA})}{\dot{m}_B (h_B - h_{wF})}$$

For given values of the enthalpies (ie the operating parameters of the plant have been established), the plant thermal efficiency is a maximum when $\dot{m}_B$ is a maximum.

ie when $\prod_{n=1}^{j} \gamma_j$ is a maximum.

The condition when this occurs can be deduced by considering any two adjacent feed-heaters (i & j).

let us assume that the total enthalpy rise in the feed water over <u>both</u> heaters is *R*. Then:

$$R = r_i + r_j \qquad \text{i.e. } r_j = R - r_i$$

so

$$\gamma_j = 1 + \frac{R - r_i}{F_j}$$

then

$$\gamma_i \gamma_j = (1 + \frac{r_i}{F_i})(1 + \frac{R - r_i}{F_j})$$

If we look at the cycle on a t-h or h-s chart it can be seen that the Fall in enthalpy of the bled steam for two adjacent feed-heaters is almost the same.

so $\quad F_i = F_j = F$

& $\quad \gamma_i \gamma_j = (1 + \frac{r_i}{F})(1 + \frac{R - r_i}{F})$

The maximum value of $\gamma_i \gamma_j$ ***is given when*** $\frac{\partial(\gamma_i \gamma_j)}{\partial r_i} = 0$

$$(1 + \frac{r_i}{F})(-\frac{1}{F}) + (1 + \frac{R - r_i}{F})(\frac{1}{F}) = 0$$

ie when $R = 2r_i$ ***or*** $r_i = \frac{1}{2} R$

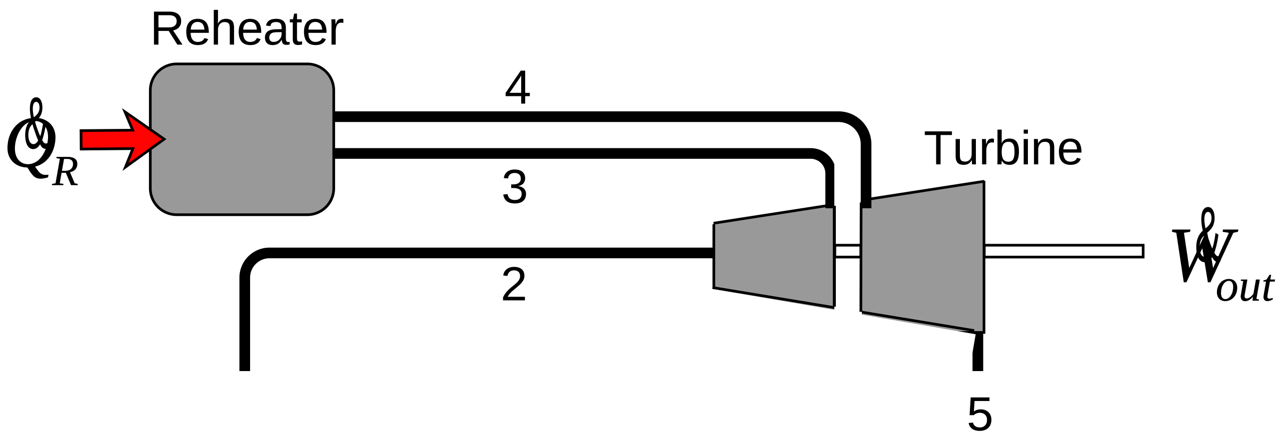
ie the enthalpy rise in the feed-water passing through two adjacent feed-heaters should be equal to obtain the maximum value of the product $g_i g_j$.

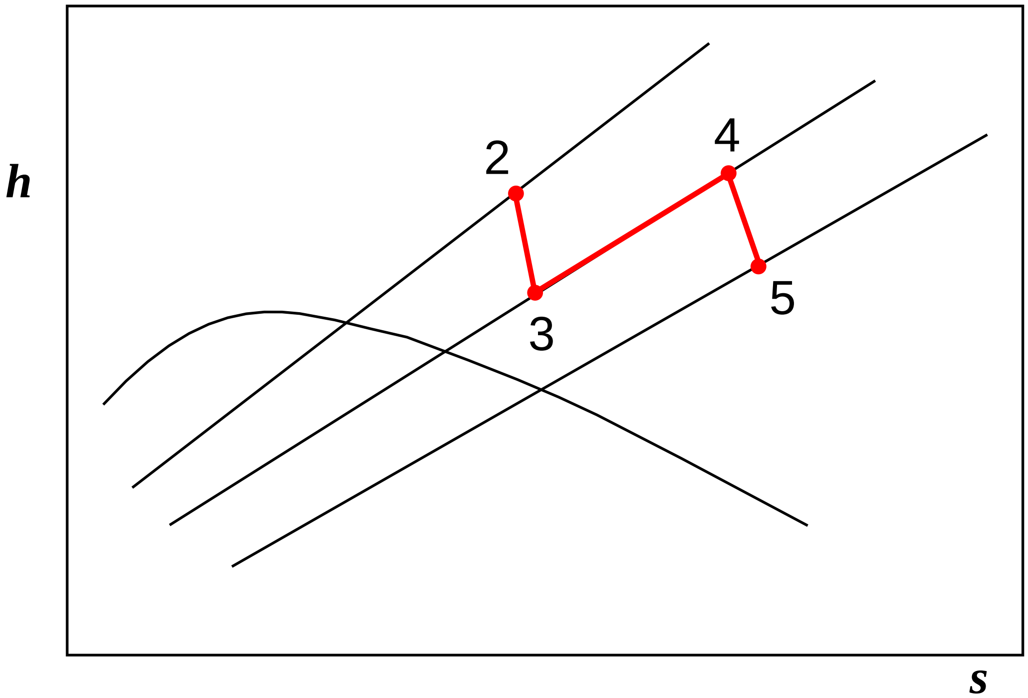
The analysis can be extended to any number of feed-heaters with the same result, i.e. equal enthalpy rises in the feed-heaters is the condition required to maximise the product and hence maximise the plant thermal efficiency.

Because the maxima is fairly flat the 'equal enthalpy rise' does not have to be precise.

If we plot the improvement in plant thermal efficiency against the number of feed-heaters it is found that beyond about 3 or 4 feed-heaters the increase in improvement does not justify the cost of the extra feed-heaters and plant complexity.

RE-HEAT

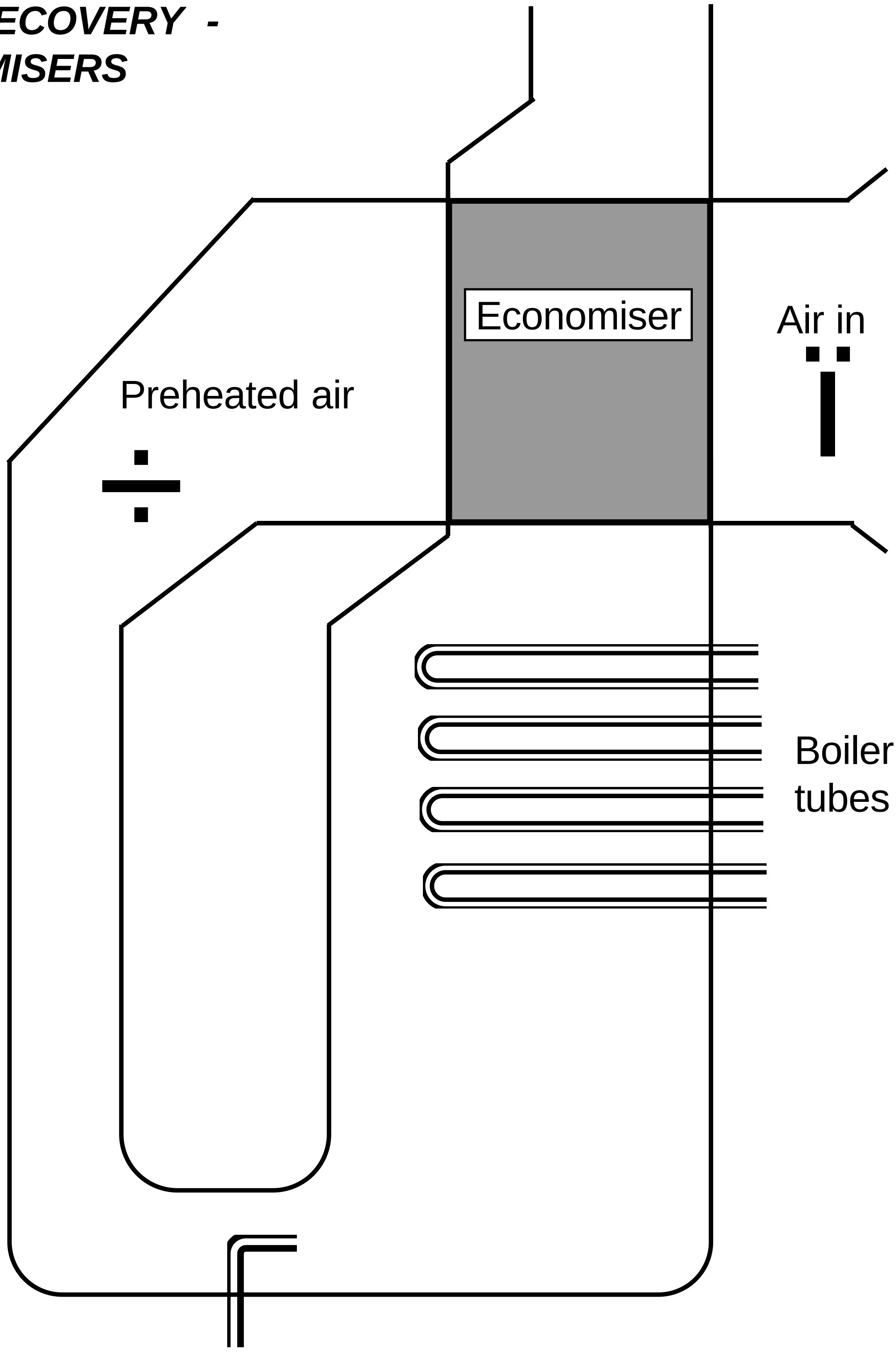




Re-heat:

1. Keeps the exhaust steam away from the saturation line
2. Allows additional heat to be supplied at high temperature
3. Usually only a small improvement in thermal efficiency

HEAT RECOVERY - ECONOMISERS



An economiser (air-to-air) preheats in-coming air using 'waste' heat in the flue gases