BASIC VAPOR POWER CYCLES

Ranjan Ganguly

Objectives

- Identify the key performance parameters of a vapor power cycle
- Analyze vapor power cycles in which the working fluid is alternately vaporized and condensed.
- Investigate ways to modify the basic Rankine vapor power cycle to increase the cycle thermal efficiency
- Analyze the reheat and regenerative vapor power cycles
- Study the heat balance diagram of a vapor power cycle

Key performance parameters

- Thermal efficiency: $\eta_{th} = W_{net}/Q_{in}$
- Work Ratio: $r_w = W_{net}/W_T$
- Specific Steam Consumption:

  $SSC = \dot{m}/\dot{W}$; $SSC = 1/(\text{sp. work output})$ [kg/kJ]
- Second Law Efficiency:

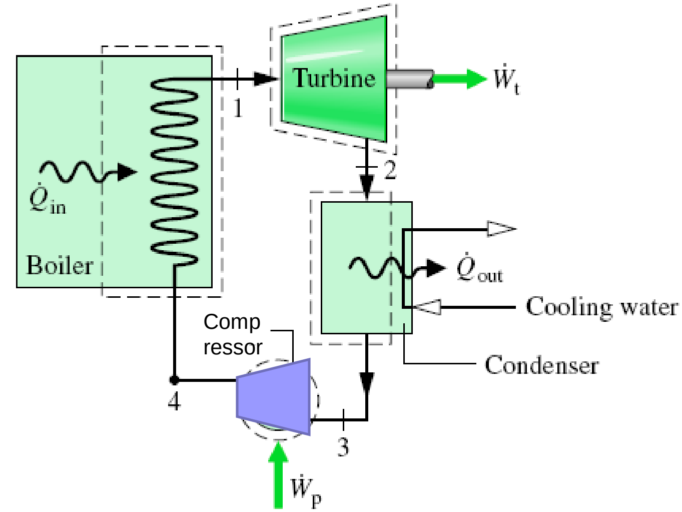
  $\eta_{II} = W_{net}/\text{Eexergy input} \approx \eta/\eta_{Carnot}$

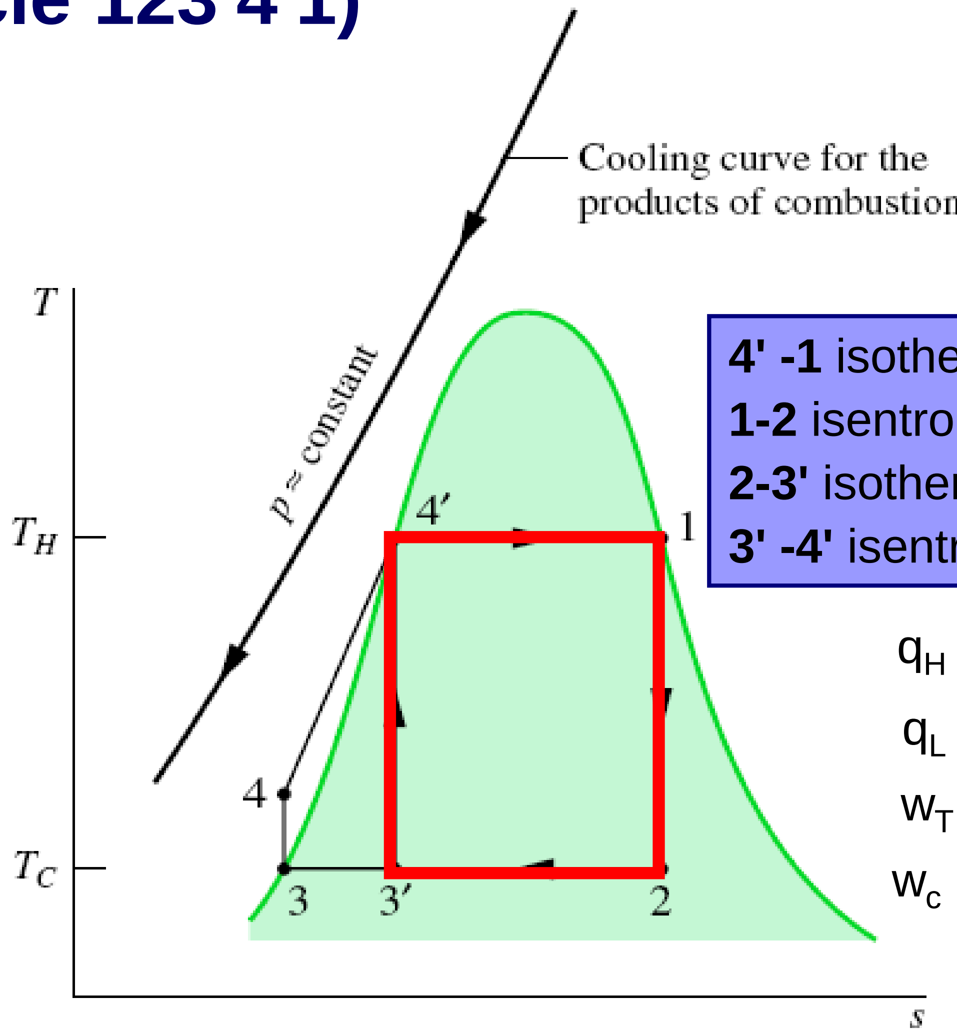
Why is work ratio important?

	Ideal cycle		Actual cycle $\eta_T = \eta_P = 0.9$	
	A	B	A'	B'
Q_H	100	100	100	100
W_T	90	40	81	36
W_p	60	10	66.7	11.1
W_{net}	30	30	14.3	24.9
η	0.3	0.3	0.143	0.249
r_w	0.33	0.75		

Higher work ratio implies less deterioration of the cycle performance under practical irreversibilities

THE CARNOT VAPOR CYCLE (Cycle 123'4'1)





4' -1 isothermal heat addition in a boiler
1-2 isentropic expansion in a turbine
2-3' isothermal heat rejection in condenser
3' -4' isentropic compression in compressor

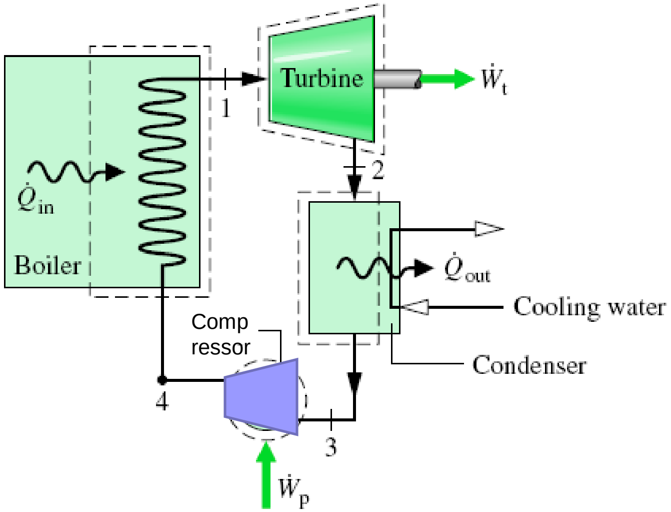
$$q_H = (h_1 - h_2)$$
$$q_L = (h_2 - h_{3'})$$
$$w_T = (h_1 - h_2)$$
$$w_c = (h_{4'} - h_{3'})$$

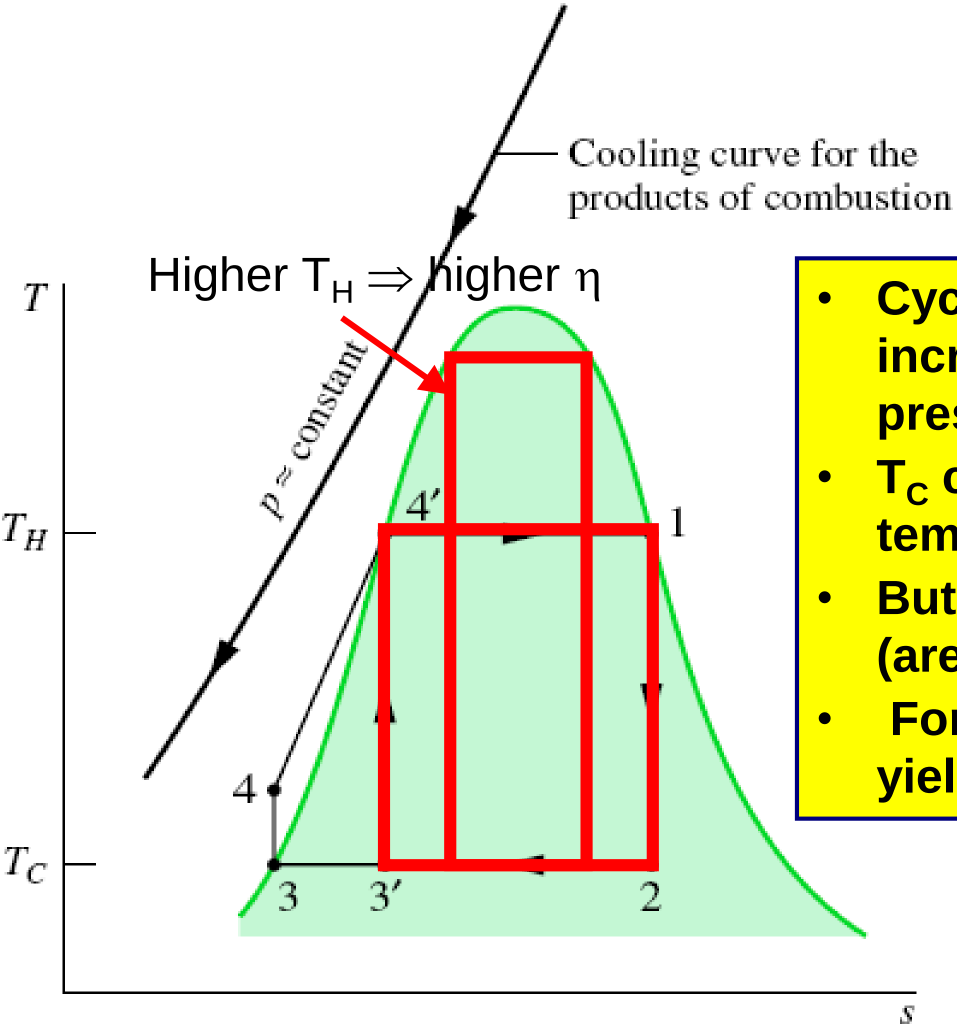
$$\eta = \frac{w_T - w_c}{q_H}; \; r_w = \frac{w_T - w_c}{w_T}$$
$$SSC = \frac{1}{w_T - w_c}; \; \eta_{II} = 1.0$$

Also $\eta = 1 - \frac{T_C}{T_H}$

***T-s* diagram of Carnot vapor cycles**

THE CARNOT VAPOR CYCLE (Cycle 123'4'1)





- **Cycle efficiency would increase if T_H is increased (say, by operating at higher boiler pressure).**
- **T_C cannot be reduced below ambient temperature**
- **But that reduces the specific work output (area of the cycle in T-s diagram)**
- **For a given set of T_H and T_C, Carnot cycle yields the maximum efficiency**

Why is Carnot cycle not practicable?

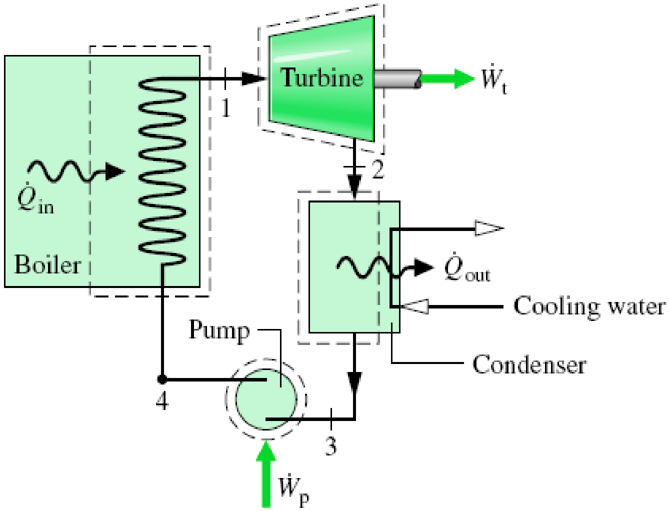
Thermodynamic perspective

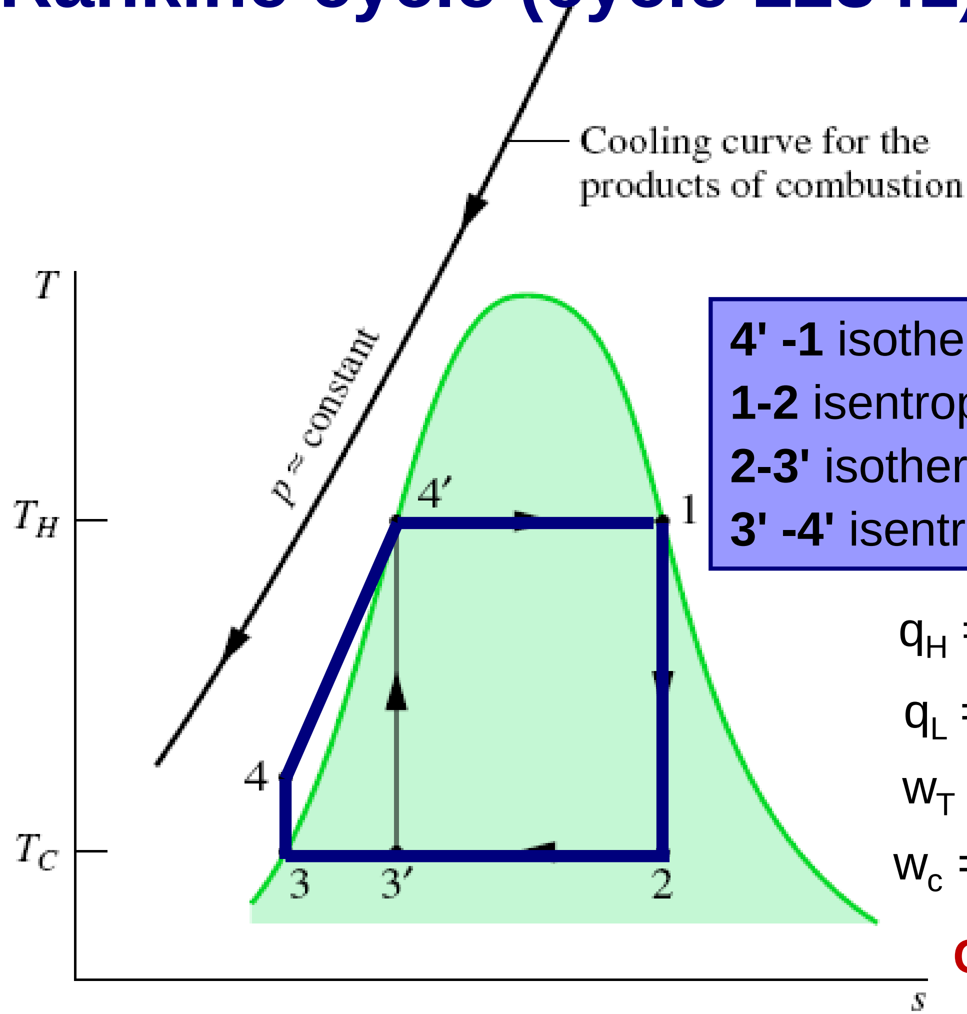
- Maximum temperature theoretically limited by T_{crit}, which, for water, is much below T_{met}
- Specific work output decreases drastically at higher pressure
- Work ratio is poor (making it vulnerable to practical irreversibilities)

Practical perspective

- Poor quality of steam at the turbine exhaust (LPT blade erosion takes place)
- Cannot stop condensation at 3′
- Difficulty in wet vapor (mixture of water and vapor) compression

These difficulties are overcome in a Rankine cycle (cycle 12341)





4' -1 isothermal heat addition in a boiler
1-2 isentropic expansion in a turbine
2-3' isothermal heat rejection in condenser
3' -4' isentropic compression in pump

$q_H = (h_1 - h_2)$

$q_L = (h_2 - h_3)$

$w_T = (h_1 - h_2)$

$w_c = (h_4 - h_3)$

$$\eta = \frac{w_T - w_c}{q_H}; \; r_w = \frac{w_T - w_c}{w_T}$$

$$SSC = \frac{1}{w_T - w_c}; \; \eta_{II} = \frac{\eta}{\eta_{Carnot}}$$

Cycle efficiency less than η_{Carnot}

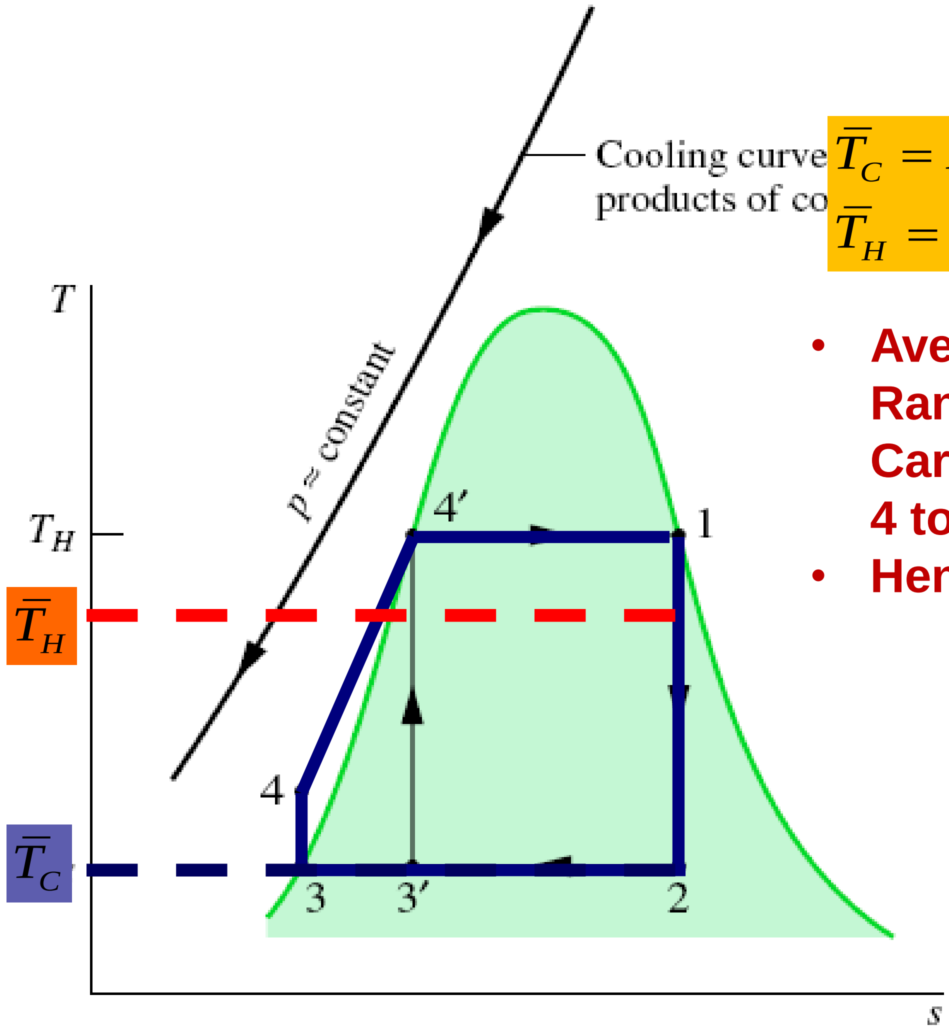
***T-s* diagram of Rankine cycles (without superheat)**

Cycle Efficiency of non-Carnot cycles

$$\eta = 1 - \frac{\bar{T}_C}{\bar{T}_H}$$

$\bar{T}_C$ = Average temperature of heat rejection

$\bar{T}_H$ = Average temperature of heat addition



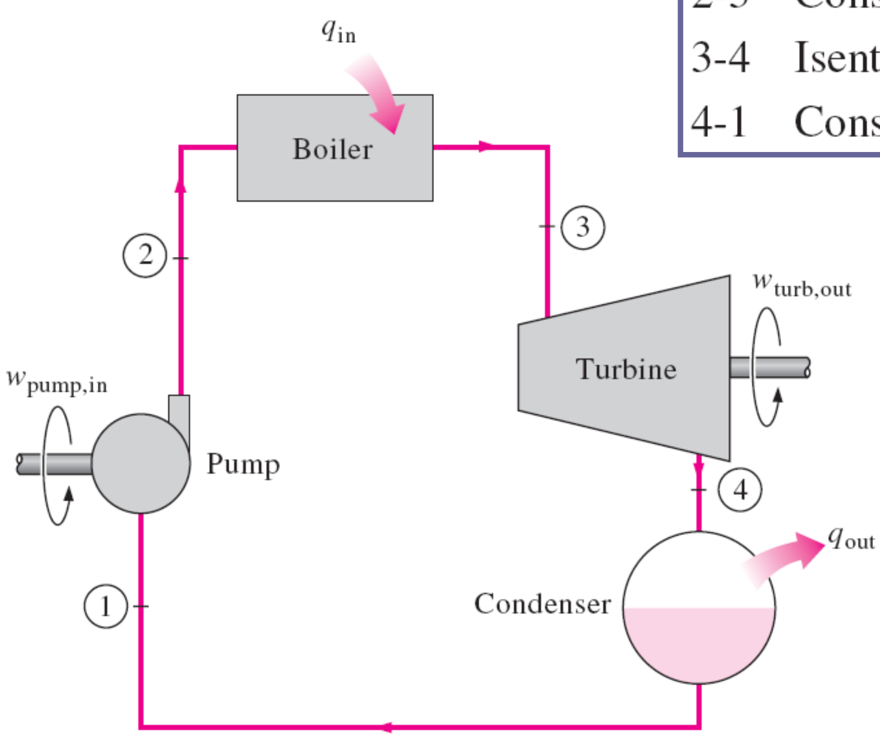
- Average temperature of heat addition of Rankine Cycle is lower than that of Carnot Cycle, because the heating from 4 to 4′ takes place at lower temperature.
- Hence cycle efficiency less than η_{Carnot}

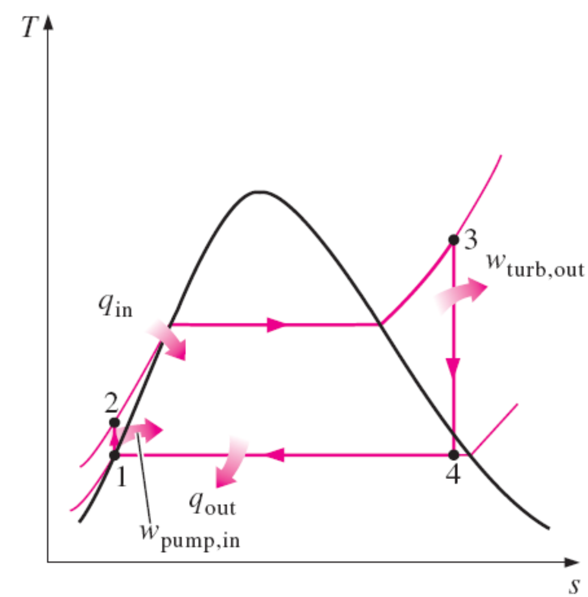
T-s **diagram of Rankine cycles (without superheat)**

RANKINE CYCLE WITH SUPERHEAT

Many of the impracticalities associated with the Carnot cycle can be eliminated by superheating the steam in the boiler and condensing it completely in the condenser. The cycle that results is the **Rankine cycle**, which is the ideal cycle for vapor power plants. The ideal Rankine cycle does not involve any internal irreversibilities.

1-2	Isentropic compression in a pump
2-3	Constant pressure heat addition in a boiler
3-4	Isentropic expansion in a turbine
4-1	Constant pressure heat rejection in a condenser

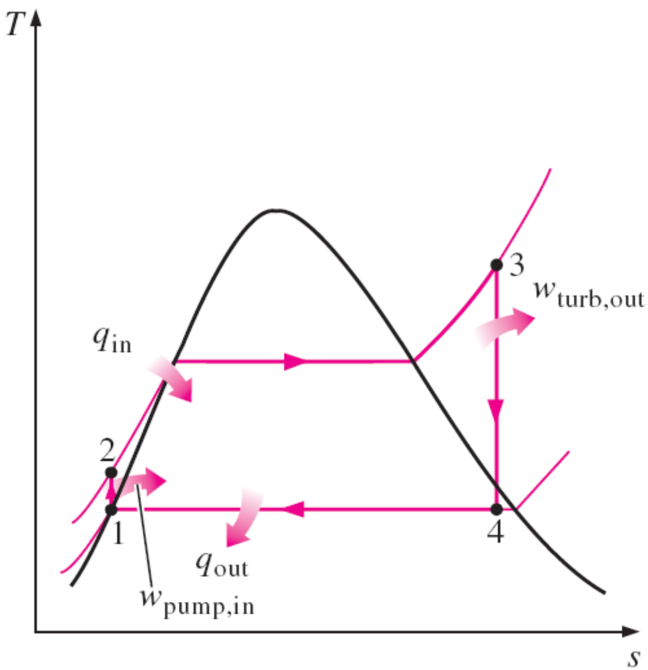




The simple ideal Rankine cycle.

Assignment: Draw p-v and h-s diagrams of the Rankine Cycle

Energy Analysis of the ideal Rankine Cycle



Steady-flow energy equation

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \qquad \text{(kJ/kg)}$$

Pump ($q = 0$): $$w_{pump,in} = h_2 - h_1$$

$$w_{pump,in} = v(P_2 - P_1)$$

$$h_1 = h_{f\,@\,P_1} \quad \text{and} \quad v \cong v_1 = v_{f\,@\,P_1}$$

Boiler ($w = 0$): $$q_{in} = h_3 - h_2$$

Turbine ($q = 0$): $$w_{turb,out} = h_3 - h_4$$

Condenser ($w = 0$): $$q_{out} = h_4 - h_1$$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

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

The efficiency of power plants in is often expressed in terms of **heat rate**, which is the amount of heat supplied, in kCal, to generate 1 kWh of electricity.

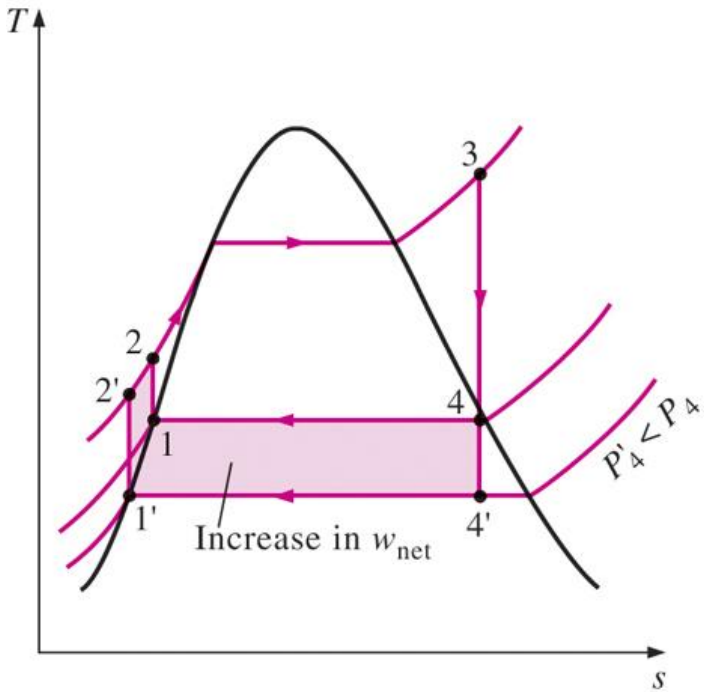
Heat Rate = 860/ η_{th}

The thermal efficiency can be interpreted as the ratio of the area enclosed by the cycle on a *T-s* diagram to the area under the heat-addition process.

HOW CAN WE INCREASE THE EFFICIENCY OF THE RANKINE CYCLE?

1. ***Increase the average temperature at which heat is transferred to the working fluid in the boiler,***
2. ***Decrease the average temperature at which heat is rejected from the working fluid in the condenser.***

Lowering the Condenser Pressure (*Lowers* $T_{low,avg}$)

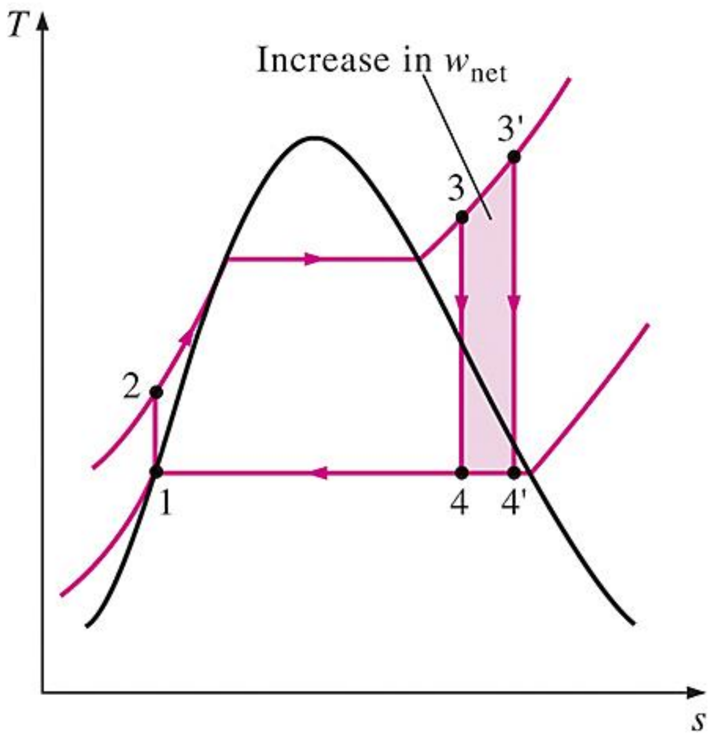


The effect of lowering the condenser pressure on the ideal Rankine cycle.

To take advantage of the increased efficiencies at low pressures, the condensers of steam power plants usually operate well below the atmospheric pressure. There is a lower limit to this pressure depending on the temperature of the cooling medium

Side effect: Lowering the condenser pressure increases the moisture content of the steam at the final stages of the turbine.

Superheating the Steam to High Temperatures (Increases $T_{high,avg}$)



The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.

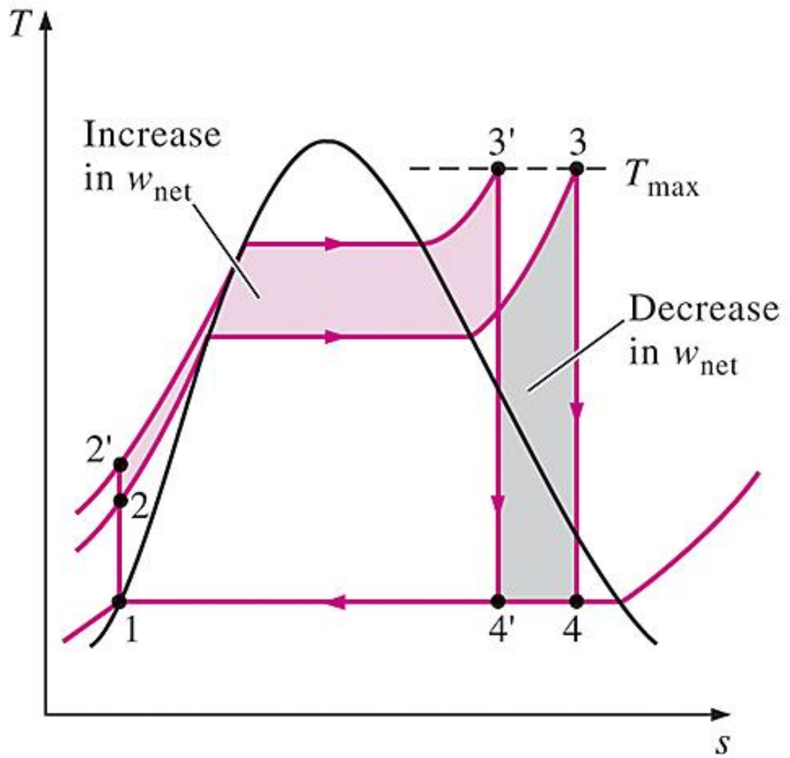
Both the net work and heat input increase as a result of superheating the steam to a higher temperature. The overall effect is an increase in thermal efficiency since the average temperature at which heat is added increases.

Superheating to higher temperatures decreases the moisture content of the steam at the turbine exit, which is desirable.

The temperature is limited by metallurgical considerations. Presently the highest steam temperature allowed at the turbine inlet is about 620°C.

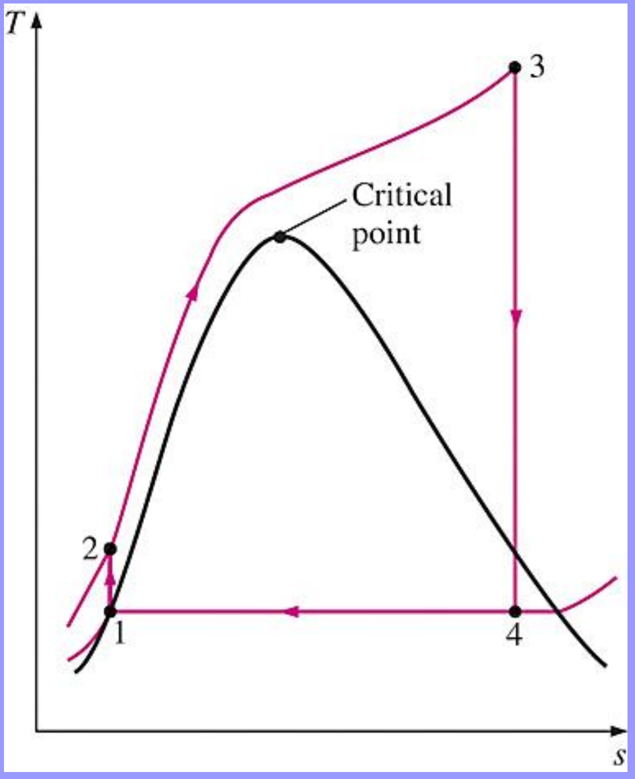
Increasing the Boiler Pressure (Increases $T_{high,avg}$)

For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases. This side effect can be corrected by reheating the steam.



The effect of increasing the boiler pressure on the ideal Rankine cycle.

Today many modern steam power plants operate at supercritical pressures (*P* > 22.06 MPa) and have thermal efficiencies of about 40% for fossil-fuel plants and 34% for nuclear plants.



A supercritical Rankine cycle.

THE IDEAL REHEAT RANKINE CYCLE

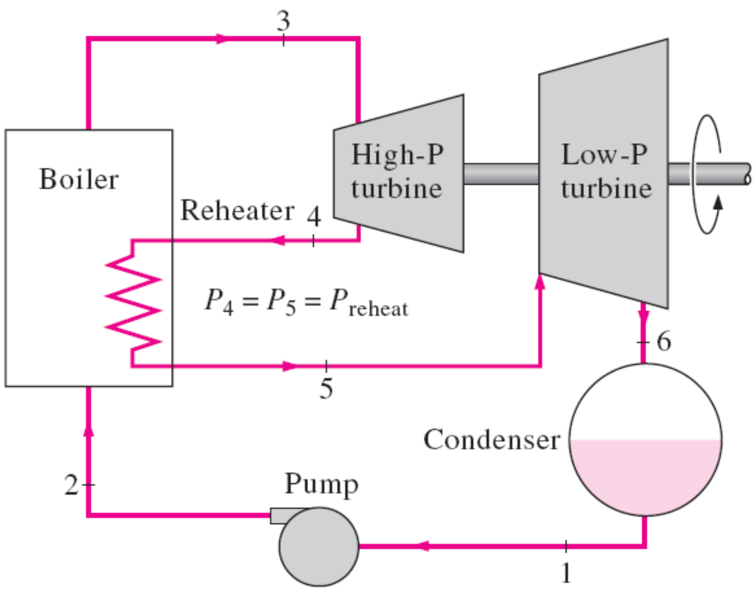
How can we take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine?

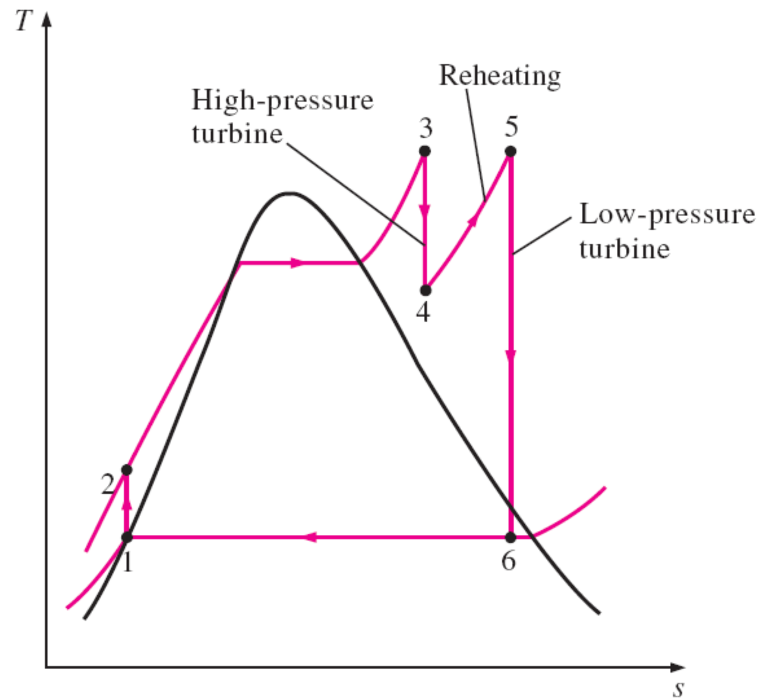
1. Superheat the steam to very high temperatures. It is limited metallurgically.
2. Expand the steam in the turbine in two stages, and reheat it in between (**reheat**)

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

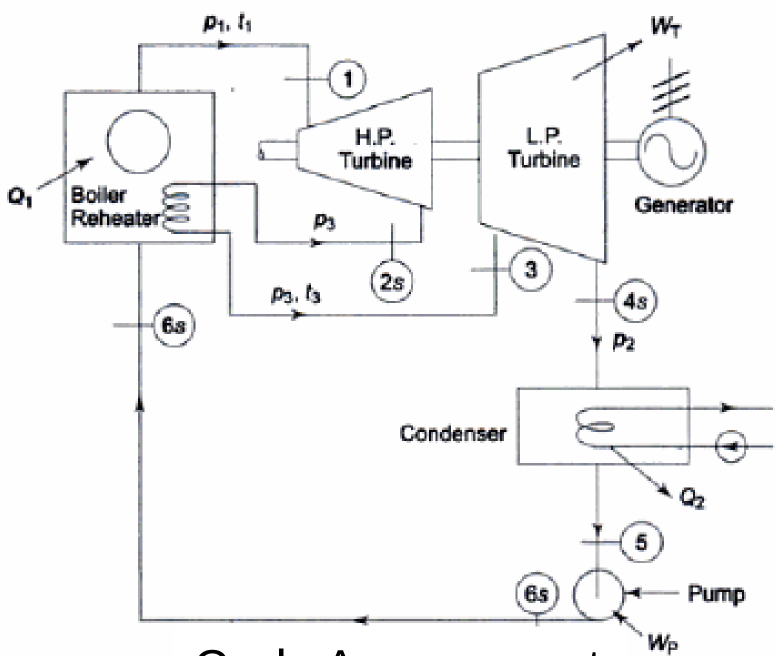
$$w_{\text{turb,out}} = w_{\text{turb,I}} + w_{\text{turb,II}} = (h_3 - h_4) + (h_5 - h_6)$$

The ideal reheat Rankine cycle.

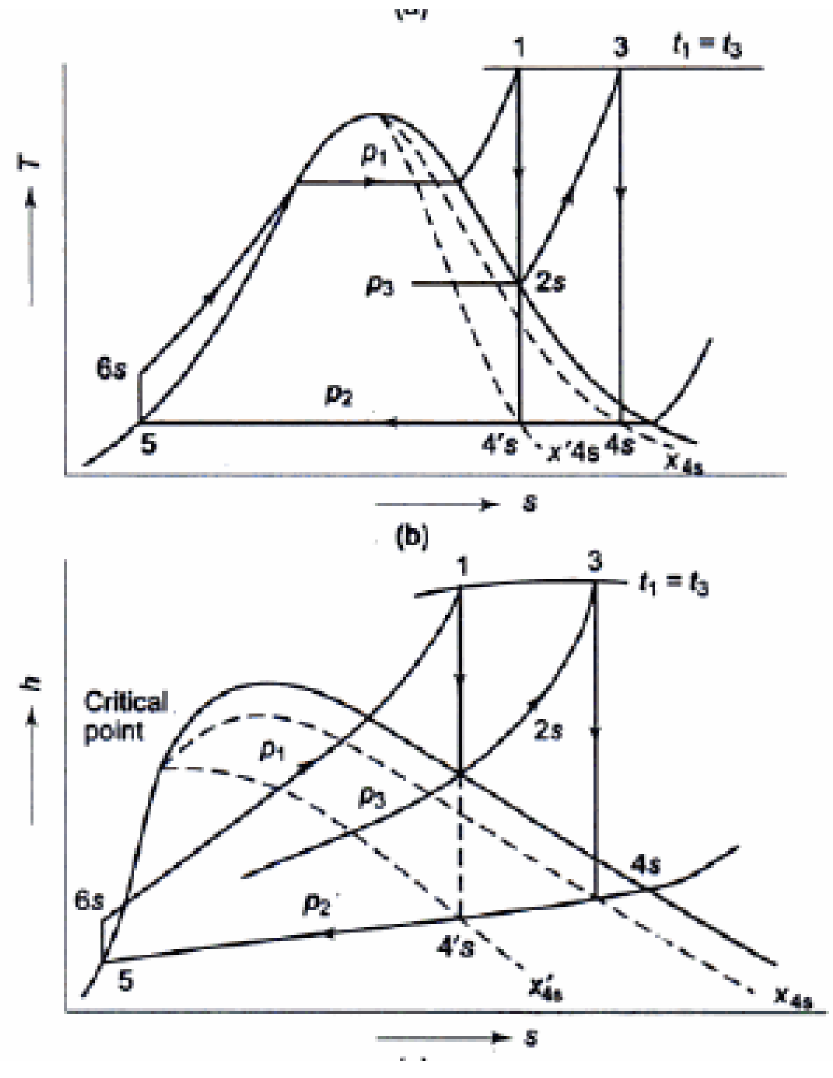




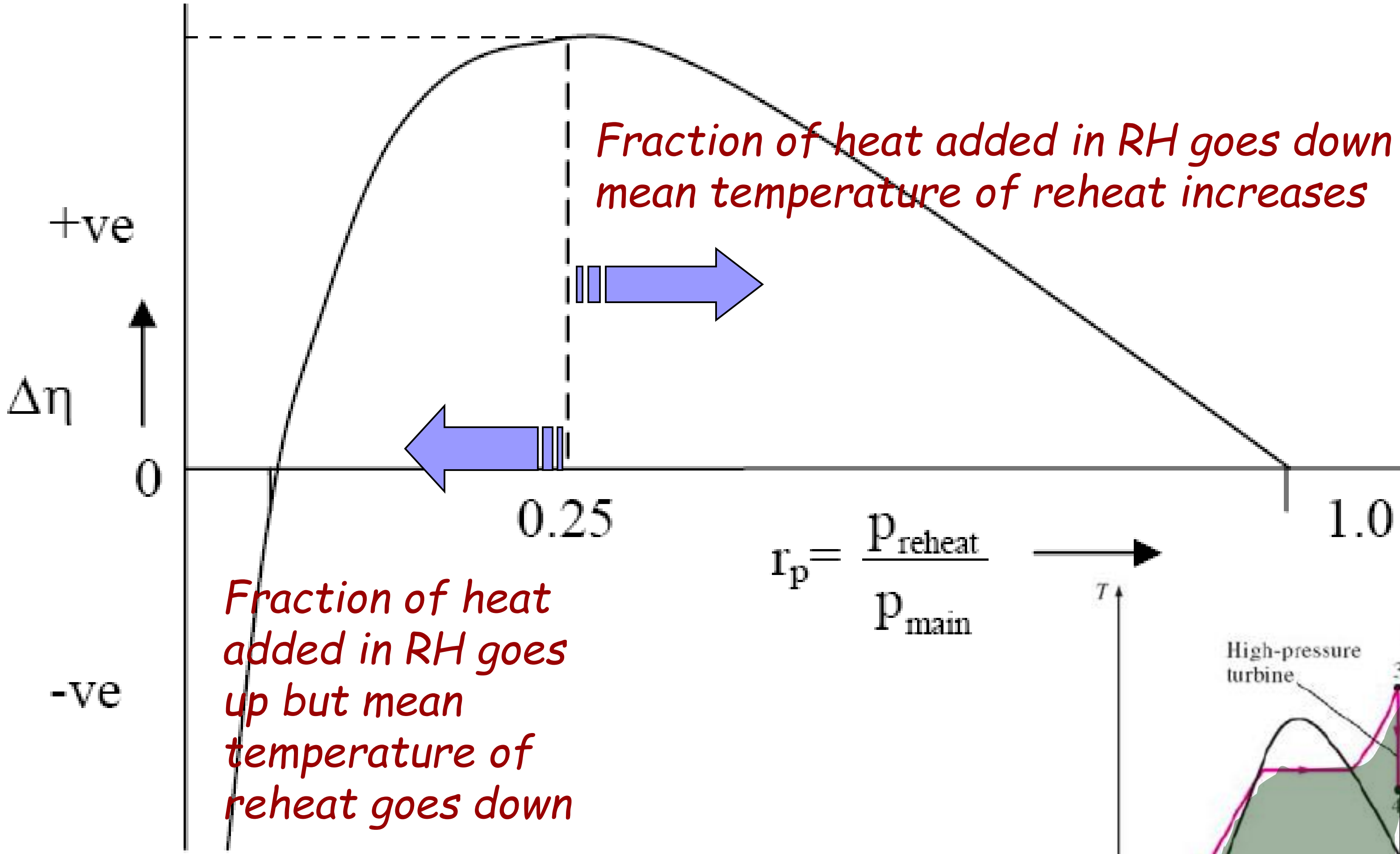
T-s and h-s diagrams of a Reheat Cycle

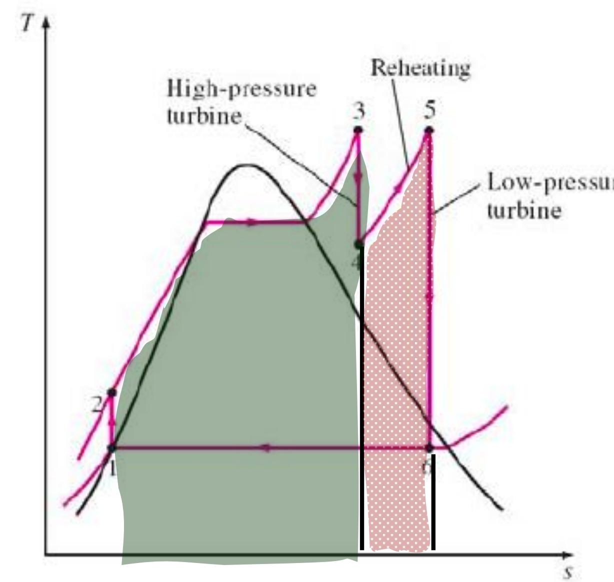


Cycle Arrangement



Effect of reheating on efficiency

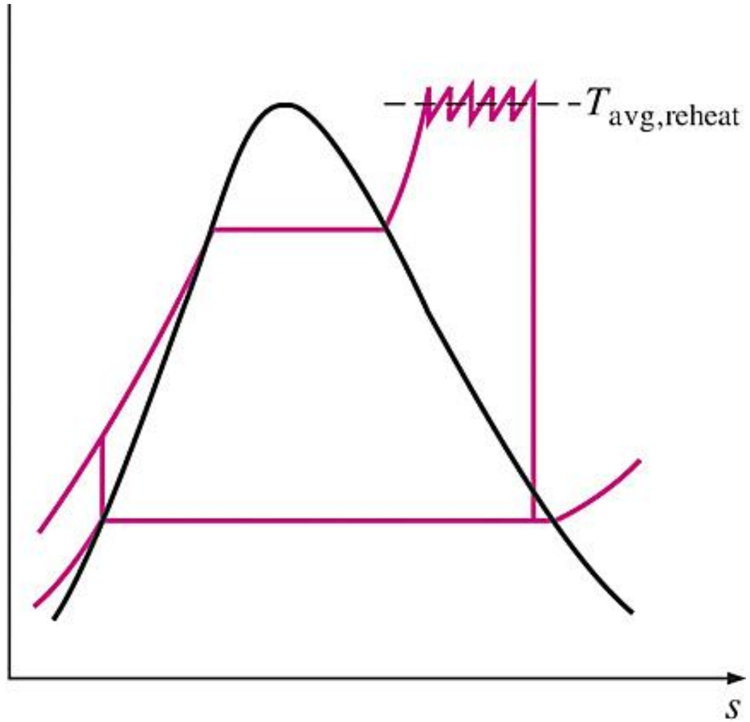




The optimum reheat pressure is about one-fourth of the maximum cycle pressure.

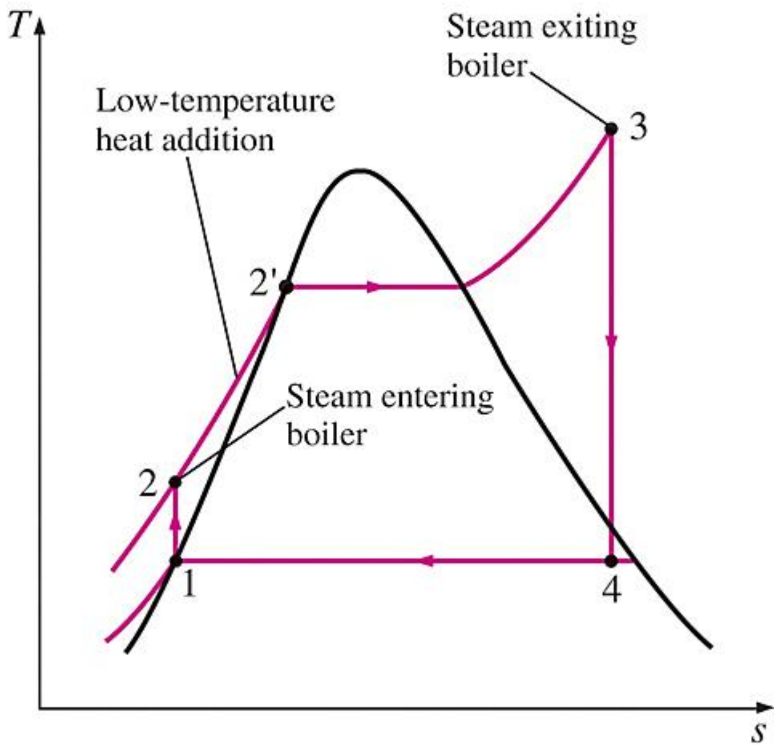
Effect of reheating on efficiency

- Single reheat in a modern power plant improves the cycle efficiency by 4 to 5% by increasing the average temperature at which heat is transferred to the steam.
- The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages.
- The use of more than two reheat stages is not practical. The theoretical improvement in efficiency from the second reheat is about half of that which results from a single reheat.
- The reheat temperatures are very close or slightly more than the main steam temperature.



Progressive reheating

The ideal regenerative Rankine cycle



The first part of the heat-addition process in the boiler takes place at relatively low temperatures.

Heat is transferred to the working fluid during process 2-2 at a relatively low temperature. This lowers the average heat-addition temperature and thus the cycle efficiency.

In steam power plants, steam is extracted from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead. The device where the feedwater is heated by regeneration is called a **regenerator**, or a **feedwater heater (FWH)**.

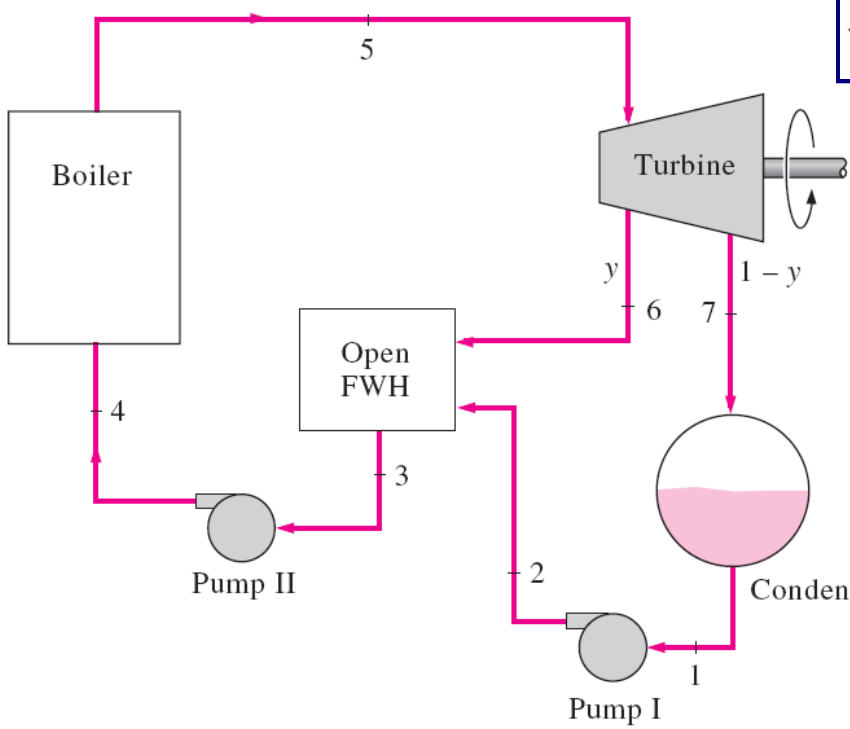
A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters).

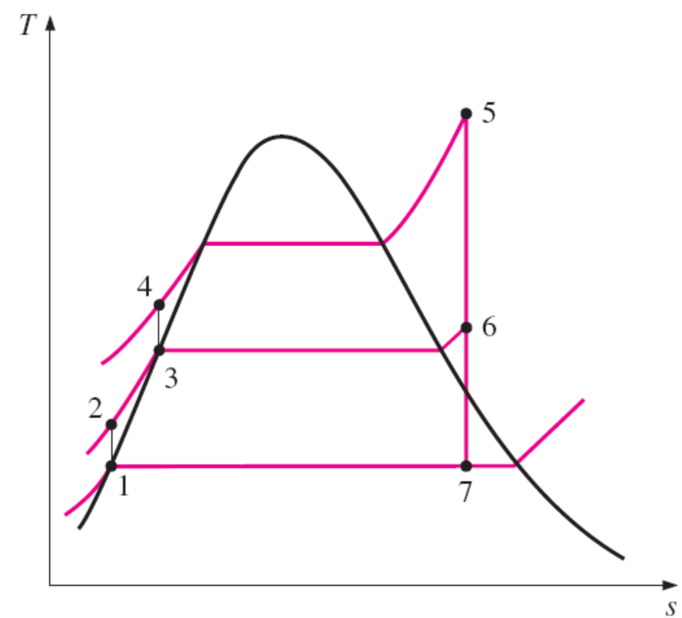
Open feedwater heaters

An **open** (or **direct-contact**) **feedwater heater** is basically a *mixing chamber,* where the steam extracted from the turbine mixes with the feedwater exiting the pump. Ideally, the mixture leaves the heater as a saturated liquid at the heater pressure.

$$q_{in} = h_5 - h_4$$
$$q_{out} = (1 - y)(h_7 - h_1)$$
$$w_{turb,out} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$
$$w_{pump,in} = (1 - y)w_{pump\ I,in} + w_{pump\ II,in}$$

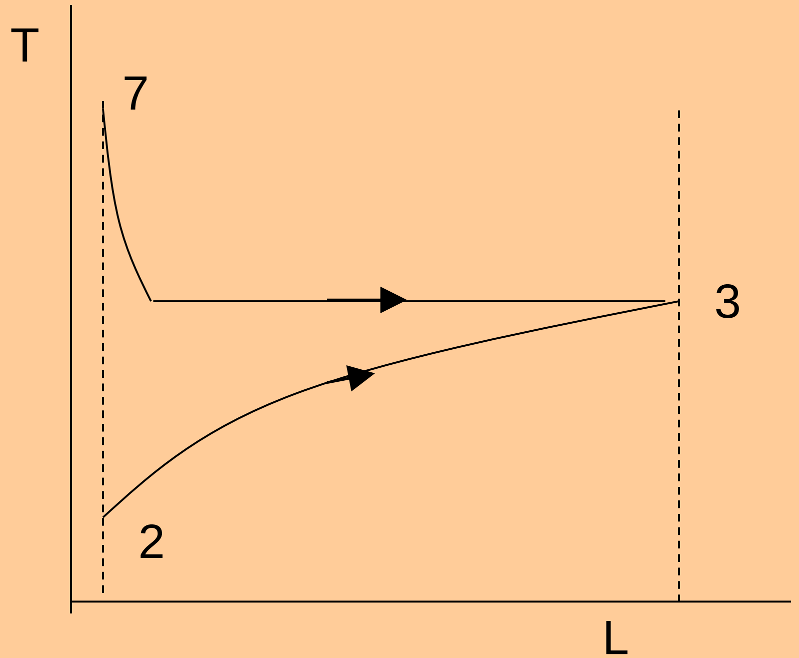
$$y = \dot{m}_6/\dot{m}_5 \qquad \text{(fraction of steam extracted)}$$
$$w_{pump\ I,in} = v_1(P_2 - P_1)$$
$$w_{pump\ II,in} = v_3(P_4 - P_3)$$



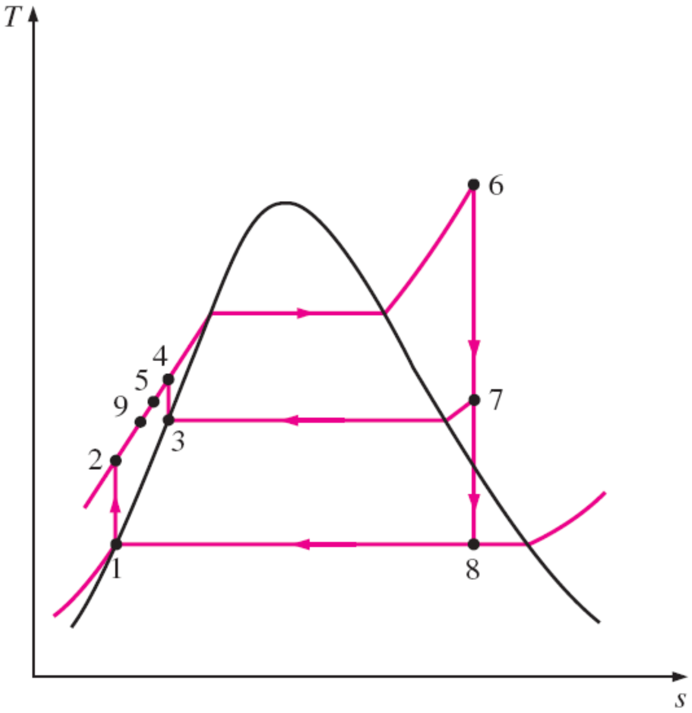


The ideal regenerative Rankine cycle with an open feedwater heater.

Temperature-length diagrams of deaerators



Terminal Temperature Difference = 0



Deaerator: the open type FW Heater