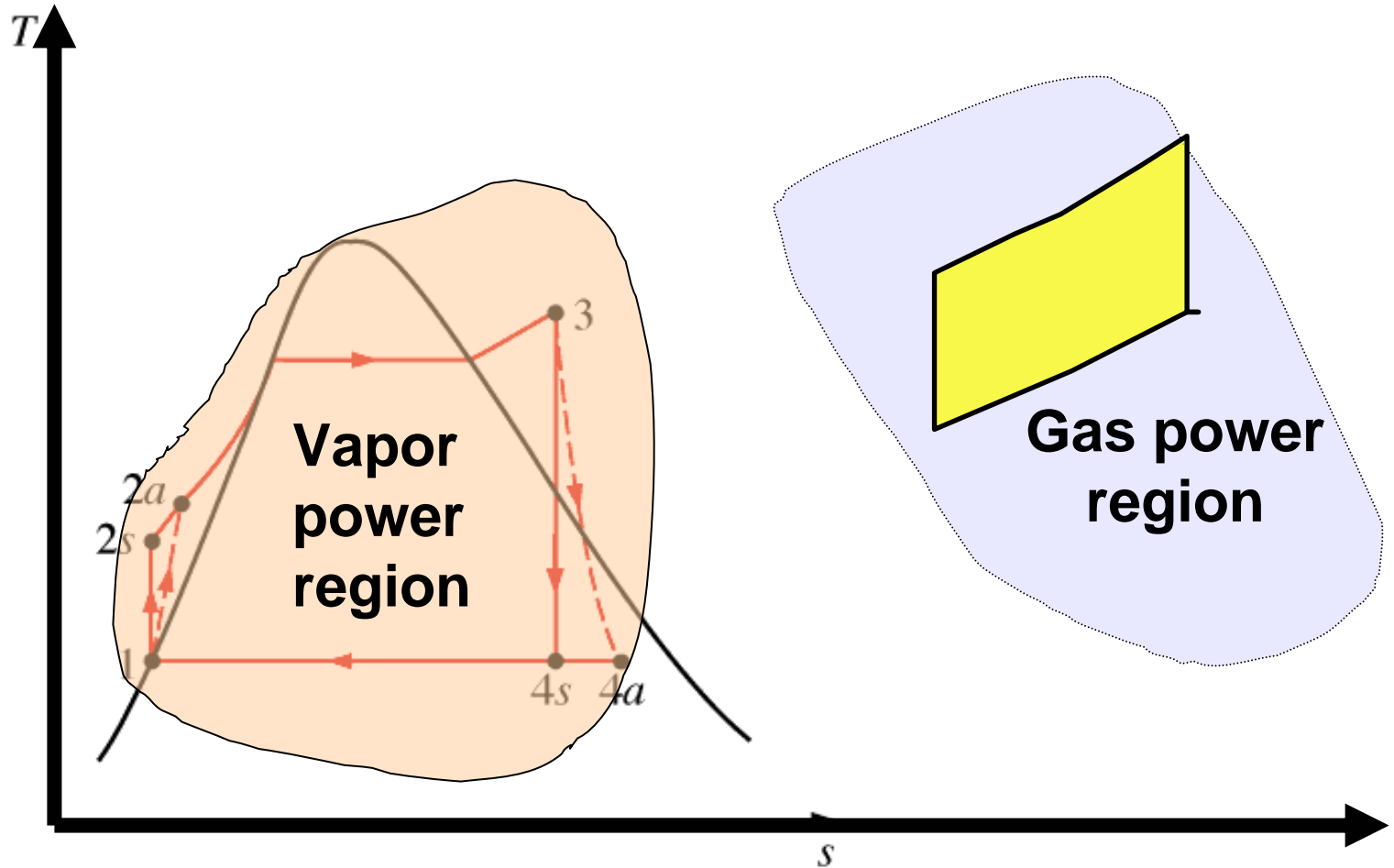


Vapor and combined power cycles

Introduction

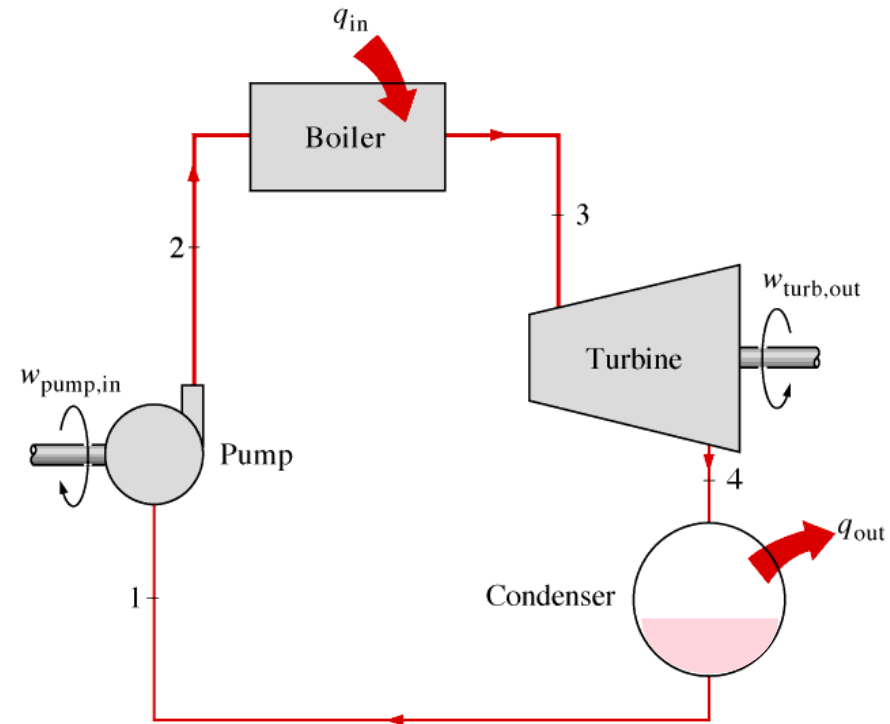
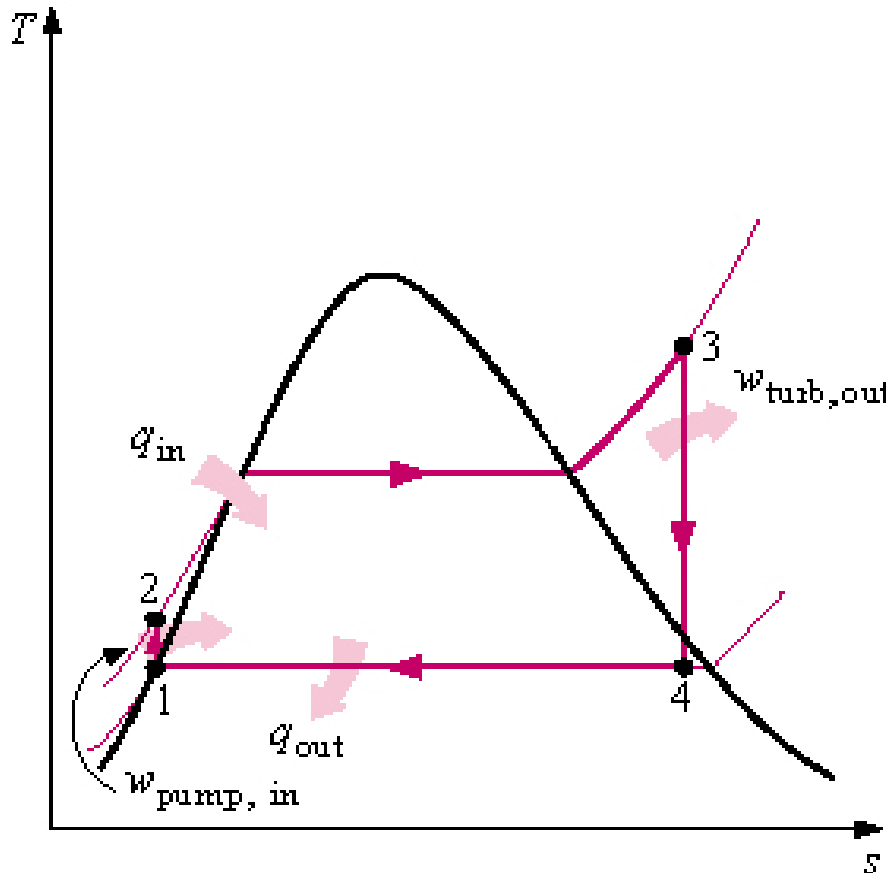


- In gas power cycles, the working fluid remains a gas throughout the cycle.
- In vapor power cycles, the working fluid is water vapor.

Rankine Cycle: The Ideal Cycle for Vapor Power Cycles

1→2 Isentropic compression in a pump

2→3 Constant pressure heat addition in a boiler (steam generator)

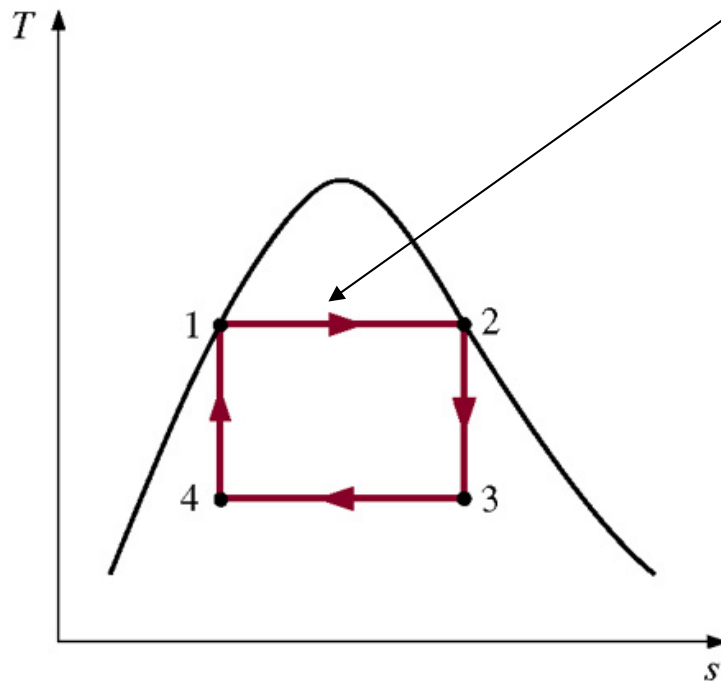


3→4 Isentropic expansion in a turbine

4→1 Constant pressure heat rejection in a condenser (water or dry air cooling)

Why do not we use the Carnot Vapor Cycle as an ideal cycle for the vapor power cycle?

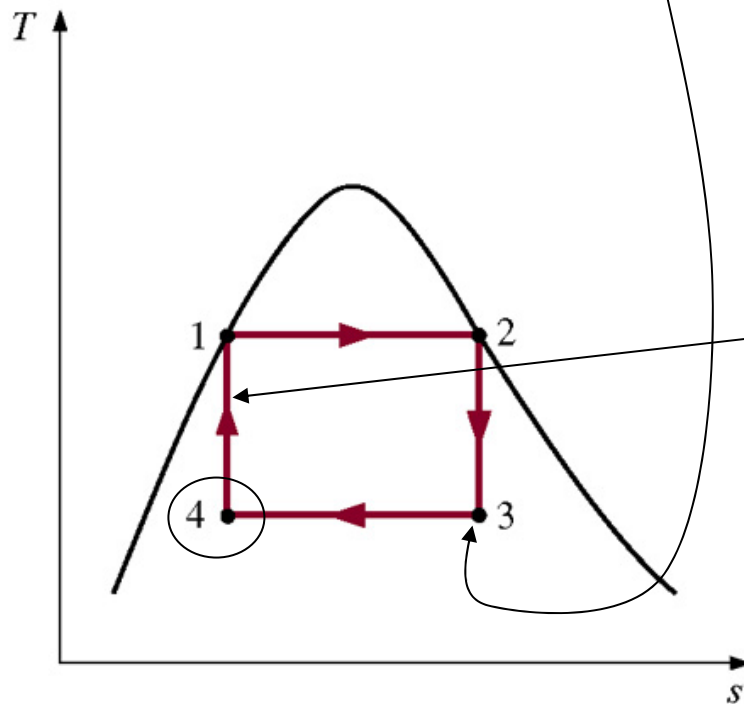
Carnot cycle is **NOT** a suitable model for power cycles due to several impracticalities associated with this cycle:



(a)

Isothermal heat transfer from or to a two-phase system limits the maximum temperature that can be used in the cycle (374°C water critical temperature). Limiting the maximum temperature in the cycle also limits the thermal efficiency.

It is not easy to control the condensation process so precisely as to end up with the *desired quality* at condenser exit.



(a)

It is not practical to design a compressor that will handle *two phases*.

Thermal Efficiency of the Ideal Rankine Cycle

All four processes that make up the Rankine cycle can be analyzed as steady-flow processes. *Thermal efficiency* of the ideal Rankine cycle is determined from

$$\eta_{th} = \frac{W_{net}}{q_{in}} = \frac{W_{turb,out} - W_{pump,in}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

The boiler and the condenser do not involve any work, and the pump and the turbine are assumed to be isentropic, thus,

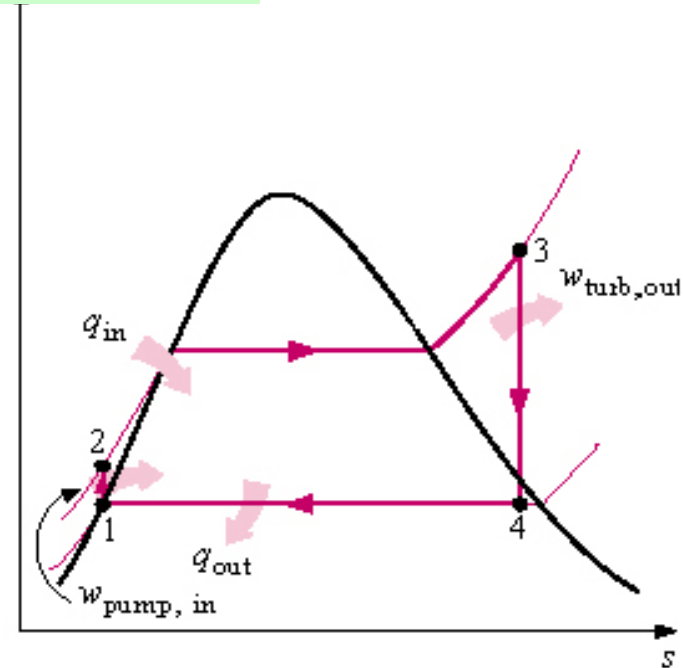
$$\text{Pump } (q = 0) : w_{pump,in} = h_2 - h_1 = v(P_2 - P_1)$$

$$\text{where } h_1 = h_f @ P_1 \text{ and } v \cong v_1 = v_f @ P_1$$

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

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

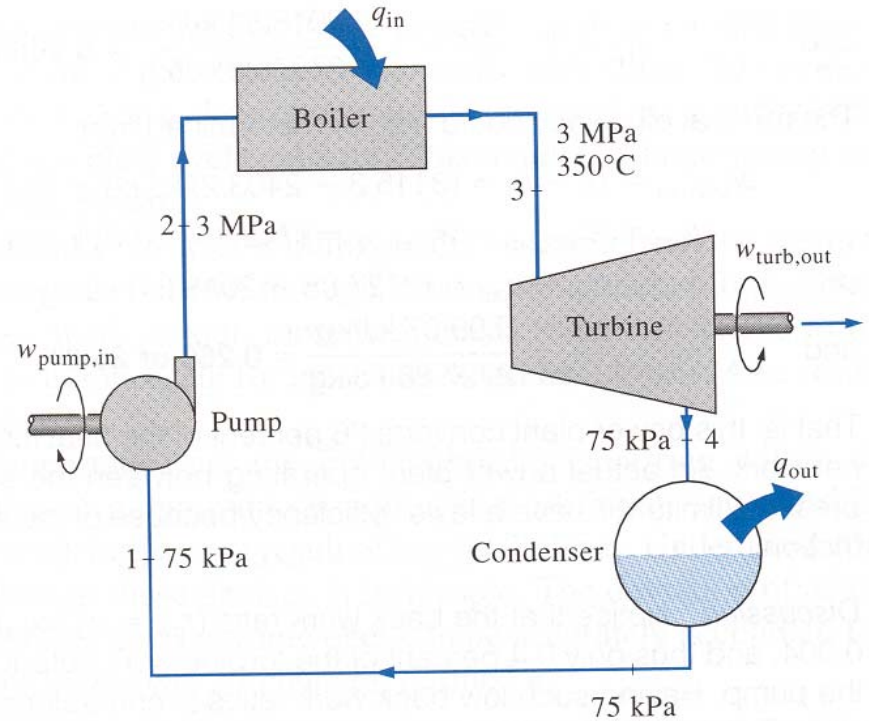
$$\text{Condenser } (w = 0) : q_{out} = h_4 - h_1$$



Example

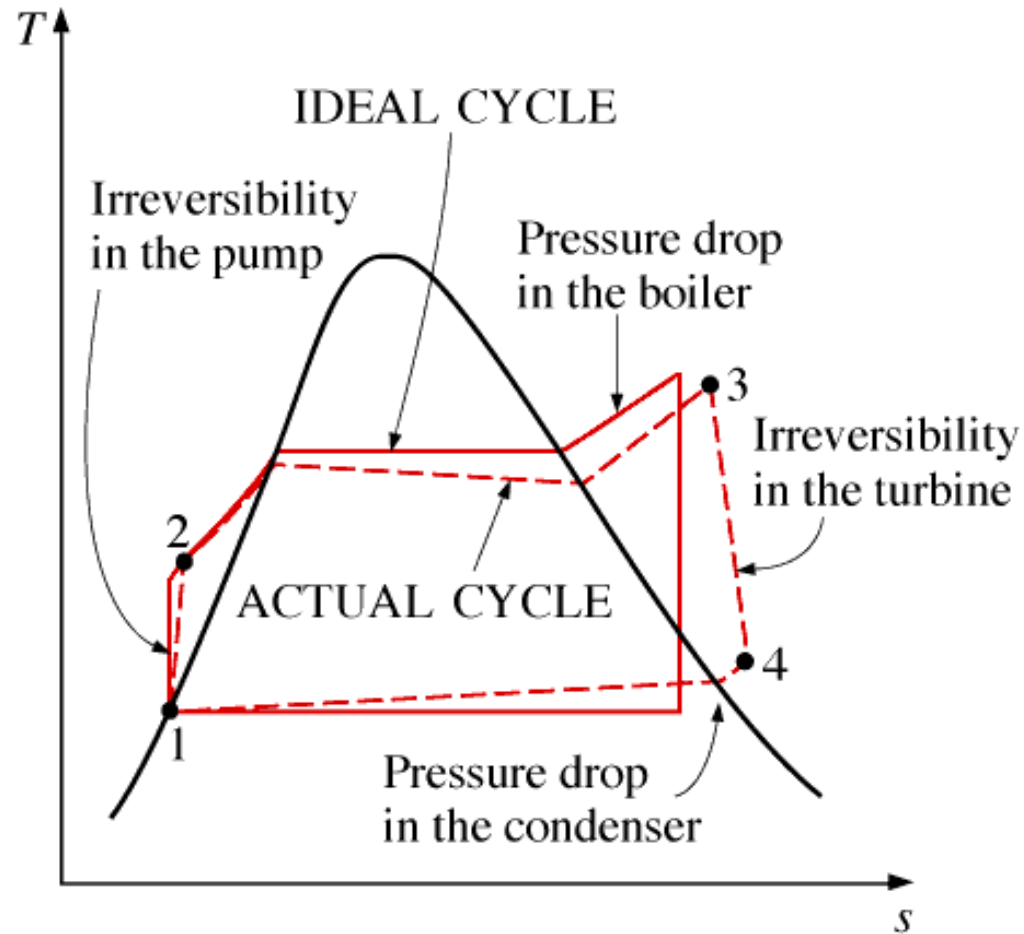
The Simple Ideal Rankine Cycle

Consider a steam power plant operates on the simple ideal Rankine cycle. The steam enters the turbine at 3MPa and 350°C and is condensed in the condenser at a pressure of 75 kPa. Determine the thermal efficiency of this cycle.



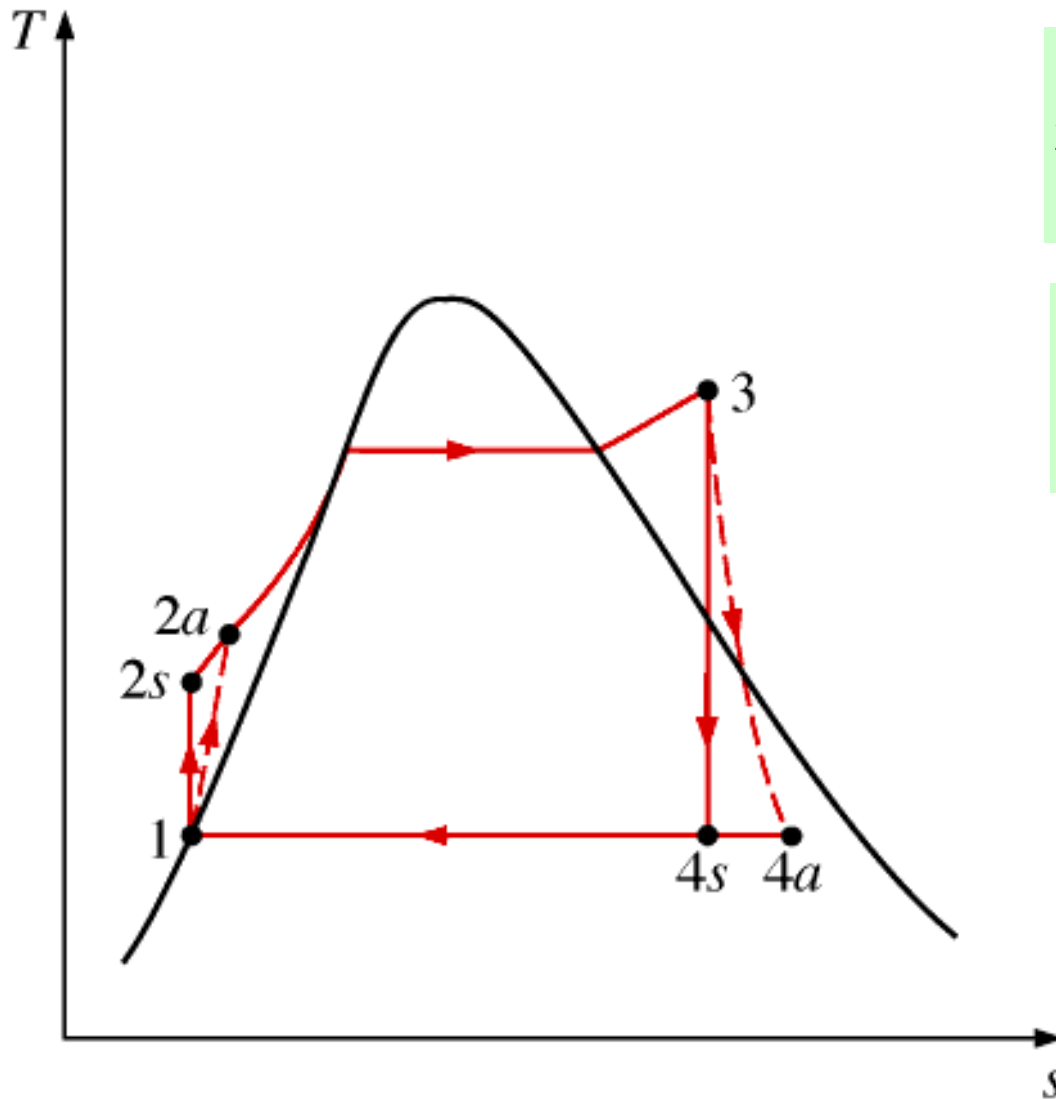
8-11 Deviation of Actual Vapor Power Cycle from Idealized Ones

- The irreversibilities occurring within the pump and the turbine.
- Fluid friction causes pressure drops in the boiler, the condenser, and the piping between various components.
- Heat loss from the steam to the surroundings.
- Heat losses occur at the bearings between the moving parts as a result of friction.
- Steam that leaks out during the cycle and air that leaks into the condenser.
- Power consumed by the auxiliary equipment such as fans that supply air to the furnace.



(a)

Irreversibilities in turbine and pump



(b)

$$\eta_{isen,pump} = \frac{w_{s,pump}}{w_{a,pump}} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

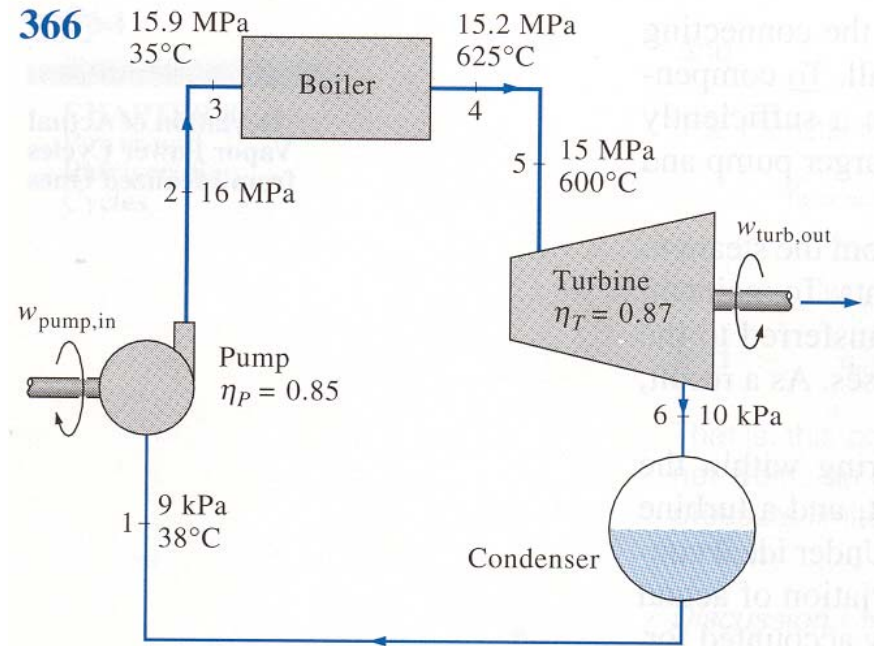
$$\eta_{isen,turb} = \frac{w_{a,turb}}{w_{s,turb}} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

Example

An Actual Steam Power Cycle

A steam power plant operates on the cycle shown in the figure at right if the isentropic efficiency of the turbine is 87 percent and the isentropic efficiency of the pump is 85 percent, determine

- the thermal efficiency of the cycle and
- the net power output of the plant for a mass flow rate of 15 kg/s.



Solve it your self !!

8-12 How Can We Increase the Efficiency of the Rankine Cycle?

The basic idea behind all the modifications to increase the thermal efficiency of the power cycle is the same:

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}; \quad \eta_{th} = \frac{W_{net}}{Q_{in}}$$

The average fluid temperature should be as high as possible during heat addition and as low as possible during heat rejection.

There are **three ways** of accomplishing this for the simple ideal Rankine cycle.

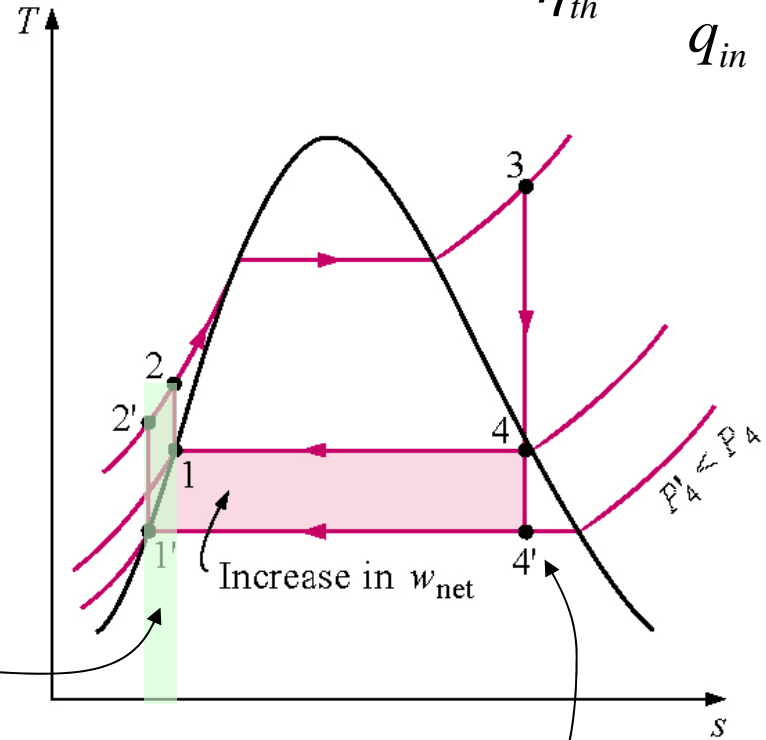
1. Lowering the Condenser Pressure

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H};$$

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

The colored area on the $T-s$ diagram represent the increase in net work output as a result of lowering the condenser pressure from P_4 to P_4' .

The heat requirement also increase (represented by the area under curve 2'-2), but this increase is very small.



The drawbacks are

(1) *air leak* into condenser and (2) increase of *moisture content at turbine exit.*)

2. Superheating the Steam to High Temperatures

The colored area on this diagram represents the increase in the net work.

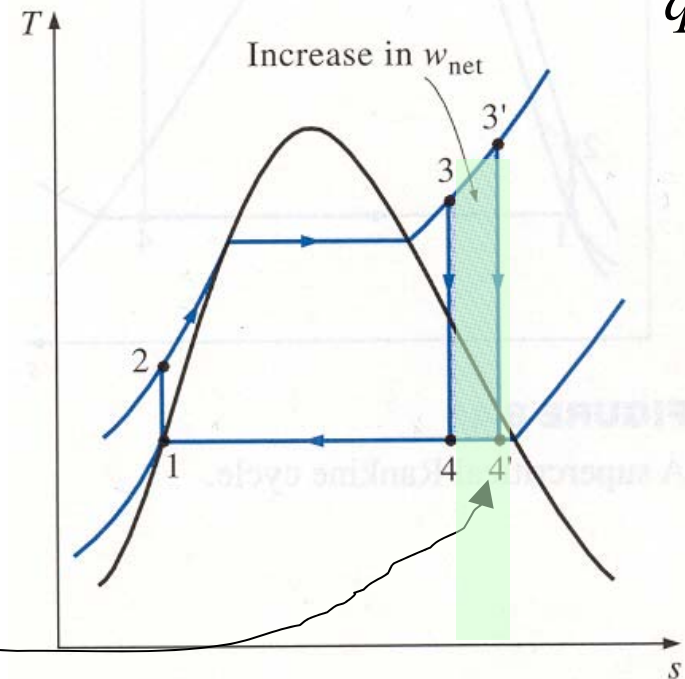
The total area under the process curve 3-3' represents the increase in the heat input.

The overall effect is an increase in thermal efficiency.

Positive: It decreases the moisture content of the steam at the turbine exit. That is quality increases.

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H};$$

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



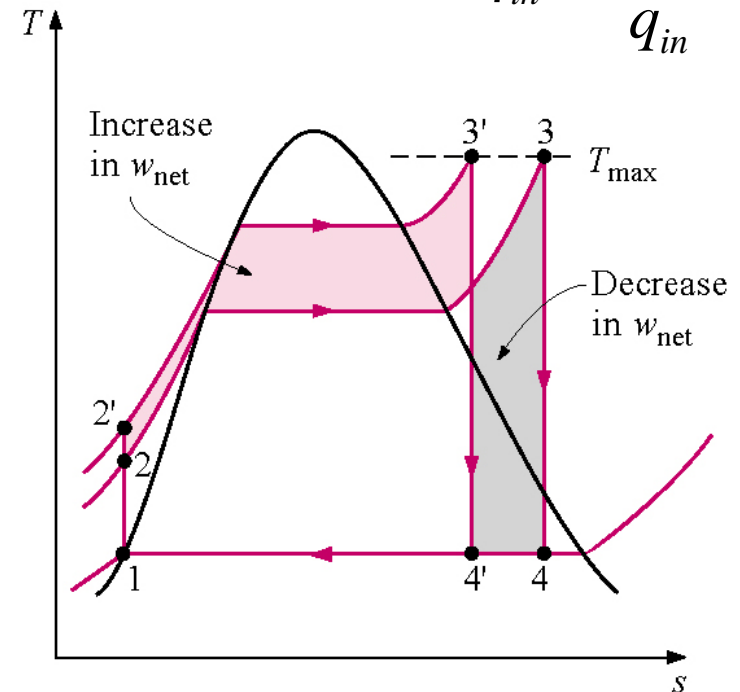
The temperature to which steam can be superheated is limited, however, by metallurgical considerations. Presently the highest steam temperature allowed is about **620°C**. **Ceramics!**

3. Increasing the Boiler Pressure

Another way of increasing the average temperature during the heat-addition process is to increase the operating pressure of the boiler, which automatically increase the temperature at which boiling takes place.

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H};$$

$$\eta_{th} = \frac{W_{net}}{q_{in}}$$

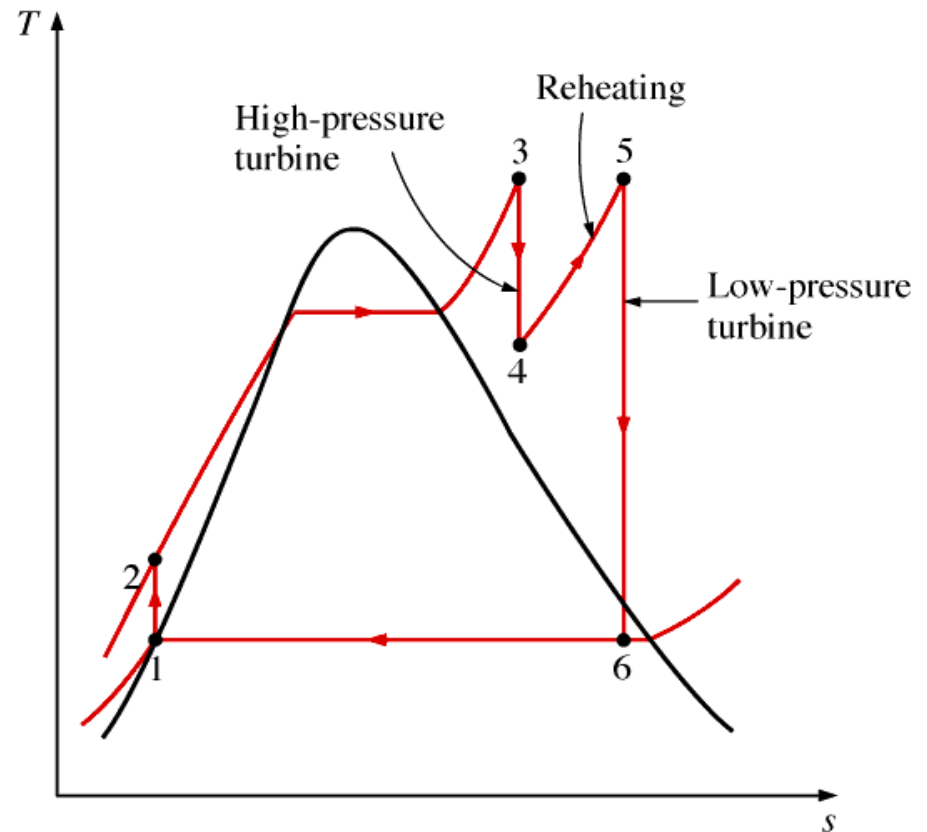
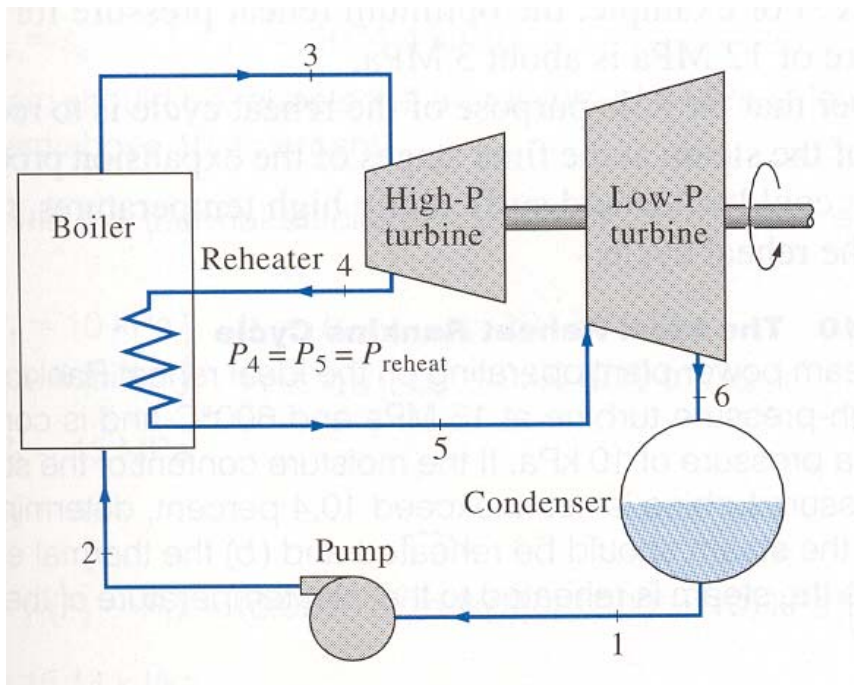


The drawbacks is increase of *moisture content at turbine exit.*)

This undesirable side effect can be corrected by *reheating* the steam as shown in the next slide:

8-13 The Ideal Reheat Rankine Cycle

Expand the steam in the turbine in two stages, and reheat it in between. This will increase the efficiency as well.



The T - s Diagram of Ideal Reheat Rankine Cycle

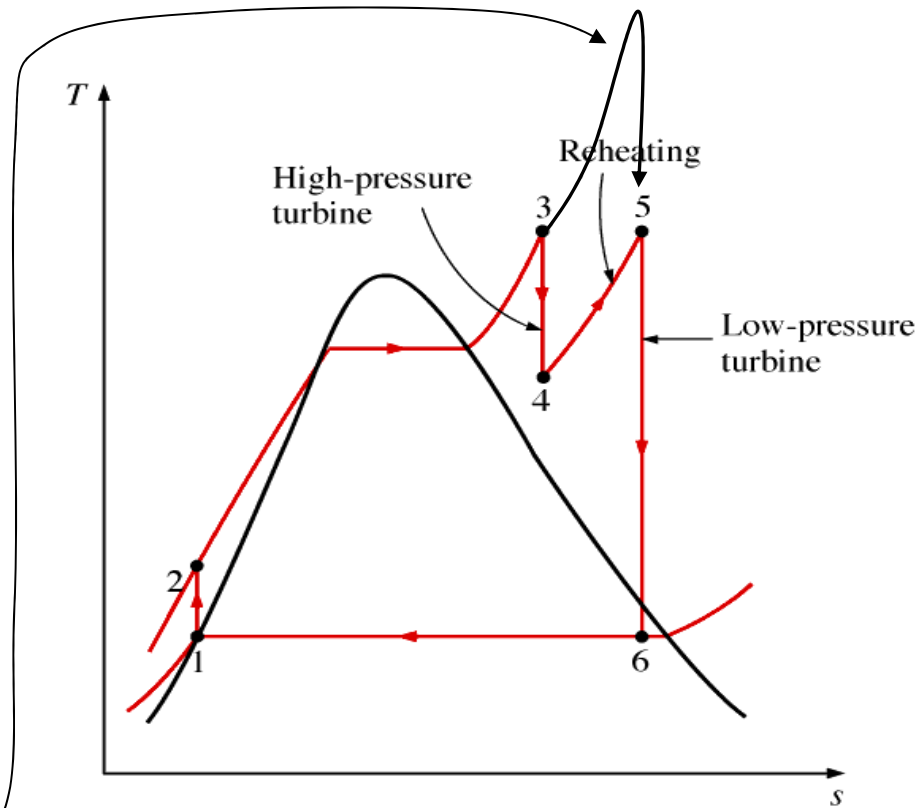
The only difference is

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

$$\text{and } w_{net,out} = w_{turb,1} + w_{turb,2} = (h_3 - h_4) + (h_5 - h_6)$$

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

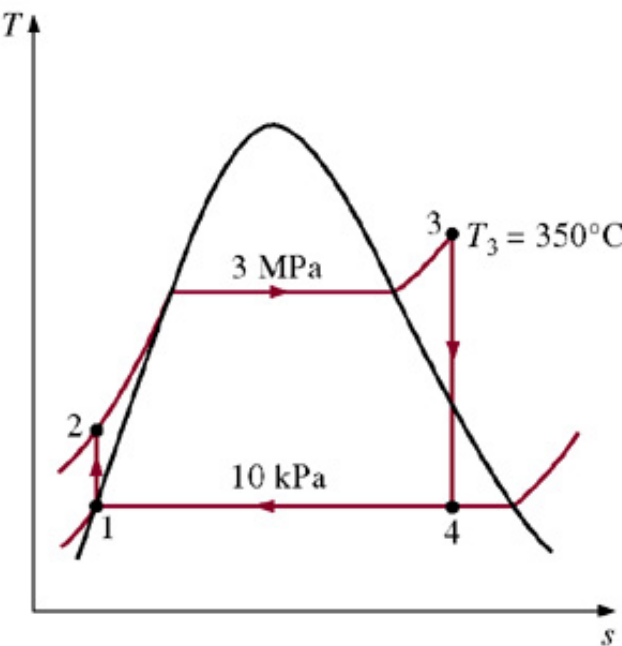
1. The incorporation of the single reheat in a modern power plant improve the cycle efficiency by 4 to 5%.
2. The use of more than two reheat stages is not practical.
3. If we had materials that could withstand sufficiently high temperatures, there would be no need for the reheat cycle.



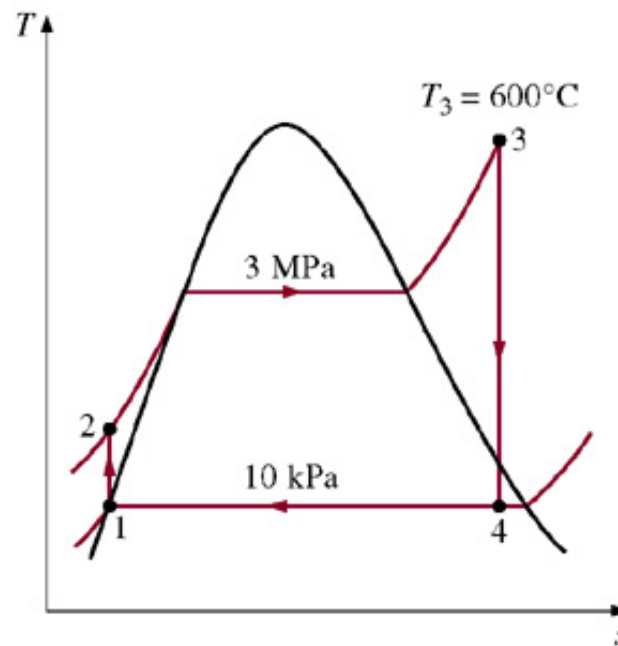
Example: Effect of Boiler Pressure and Temperature on Efficiency

Consider a steam power plant operating on the ideal Rankine cycle. The steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 10 kPa. Determine

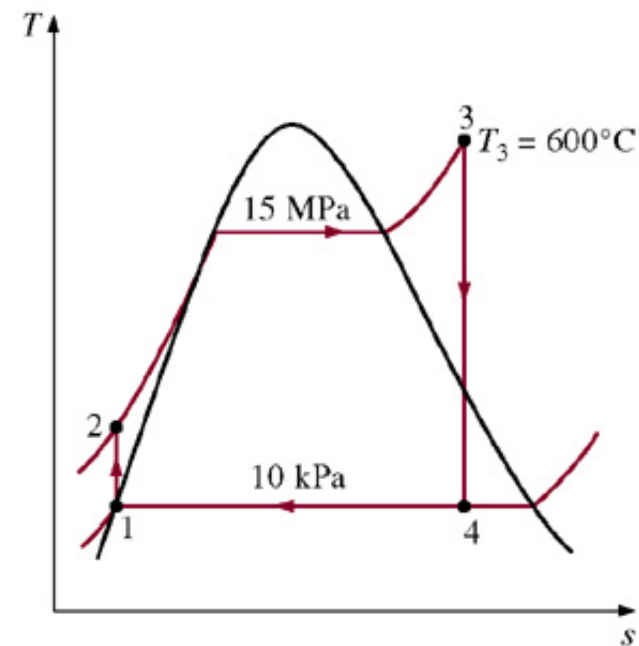
- the thermal efficiency of this power plant,
- the thermal efficiency if steam is superheated to 600°C instead of 350°C, and
- the thermal efficiency if the boiler pressure is raised to 15 MPa while the turbine inlet temperature is maintained at 600°C.



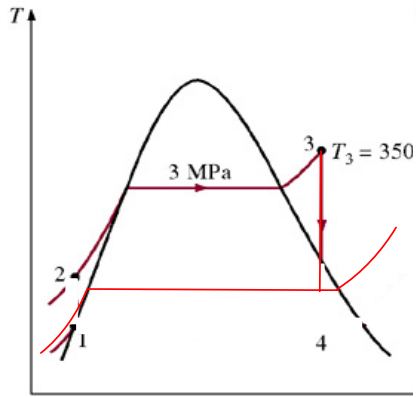
(a)



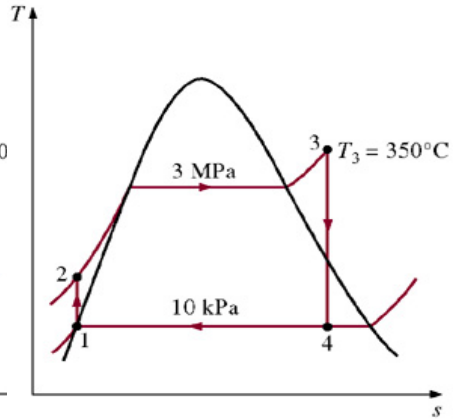
(b)



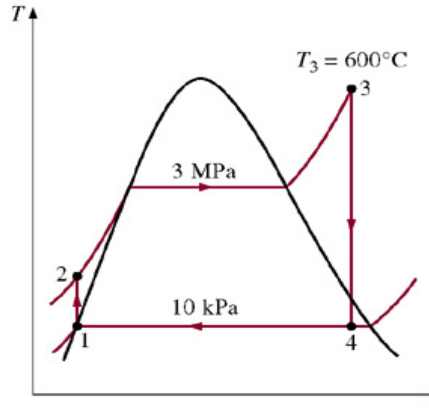
(c)



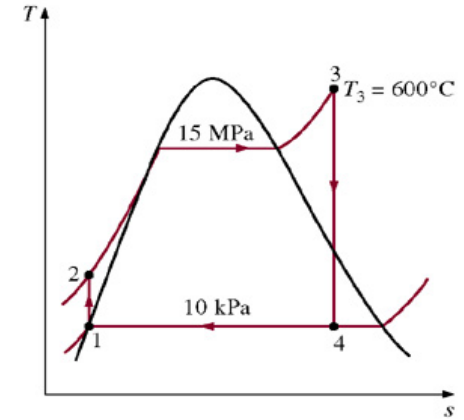
(a)



(a)



(b)



(c)

v1	0.001037
wp	3.03
h1	384.39
h2	387.42
h3	3115.3
h4	2402.6
qin	2727.9
qout	2018.2
wnet	709.7
eff	26

v1	0.00101
wp	3.02
h1	191.83
h2	194.85
h3	3115.3
h4	2135.7
qin	2920.5
qout	1943.9
wnet	976.6
eff	33.5

v1	0.00101
wp	3.02
h1	191.83
h2	194.85
h3	3682.3
h4	2379.9
qin	3487.5
qout	2188.1
wnet	1299.4
eff	37.3

v1	0.00101
wp	?
h1	191.83
h2	206.97
h3	3582.3
h4	2114.9
qin	3375.3
qout	1923.1
wnet	1452.2
eff	43.5

Ideal Regenerative Rankine Cycle with Open Feedwater Heater

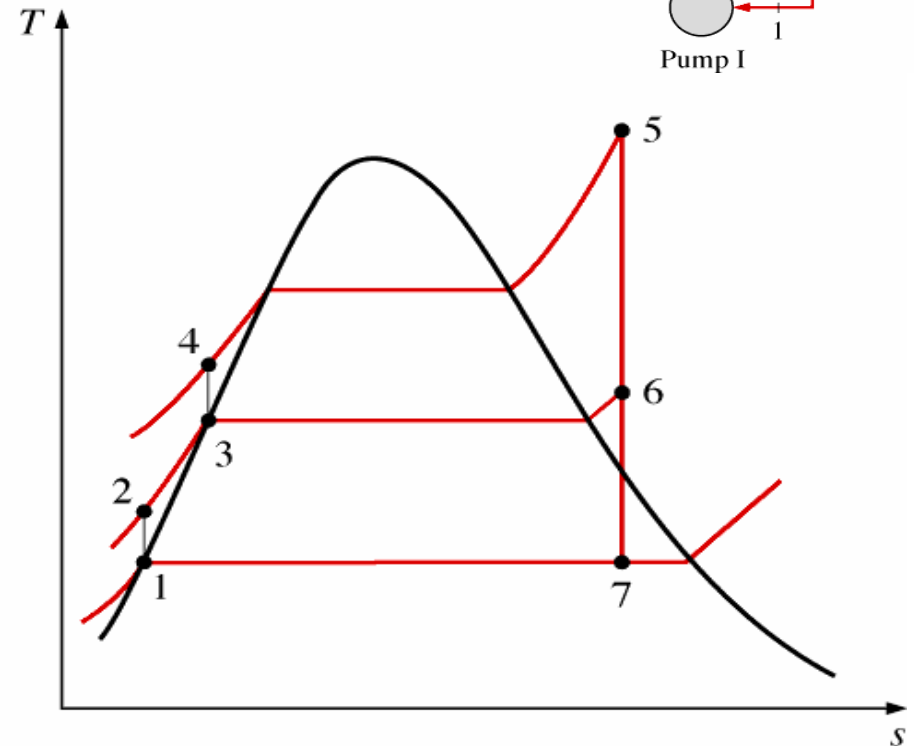
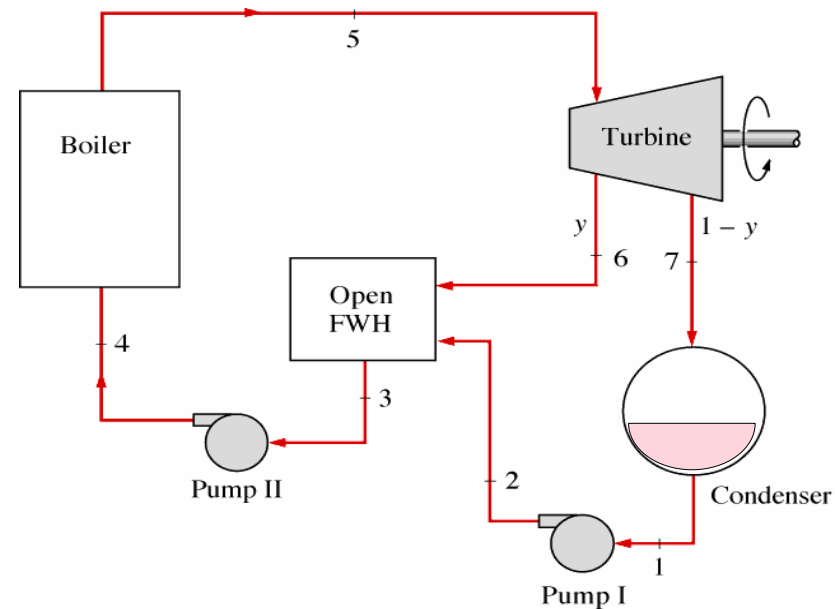
1- A fraction of the steam, y , is extracted from the turbine.

$$y = \dot{m}_6 / \dot{m}_5$$

2- The remaining steam $(1-y) \cdot \dot{m}_5$ is expanded to the condenser pressure where it is condensed to saturated liquid (state 1).

3- Then it is compressed isentropically to state 2 where it is mixed in the FWH with stream 6 at the same pressure ($P_6 = P_2 = P_3$).

4- The mixture leaves the FWH as a saturated liquid (state 3).



Thermal Efficiency of Regenerative Rankine Cycle with Open Feedwater Heater

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

$$q_{in} = h_5 - h_4$$

$$q_{out} = (1 - y)(h_7 - h_1)$$

To find y , apply 1st law to FWH

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

$$\Rightarrow (\dot{m}_5 - \dot{m}_6) h_2 + \dot{m}_6 h_6 = \dot{m}_5 h_3$$

divide by \dot{m}_5

$$\Rightarrow (1 - y) h_2 + y h_6 = h_3$$

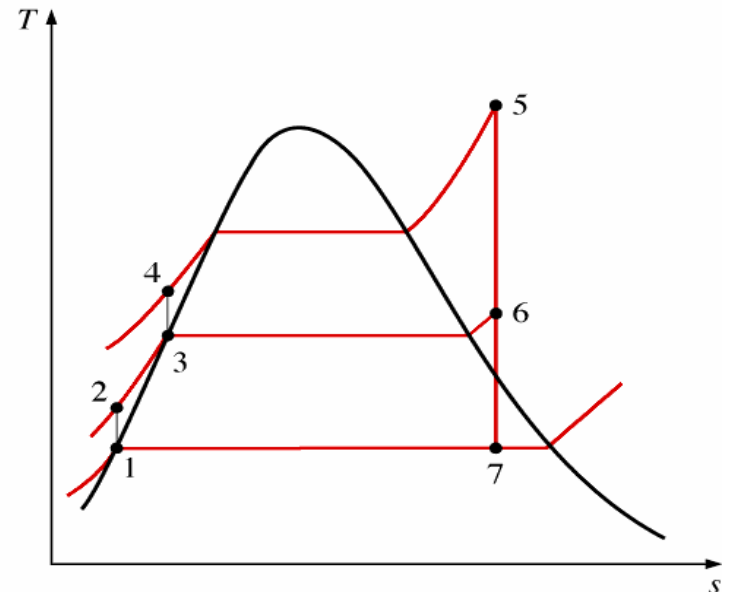
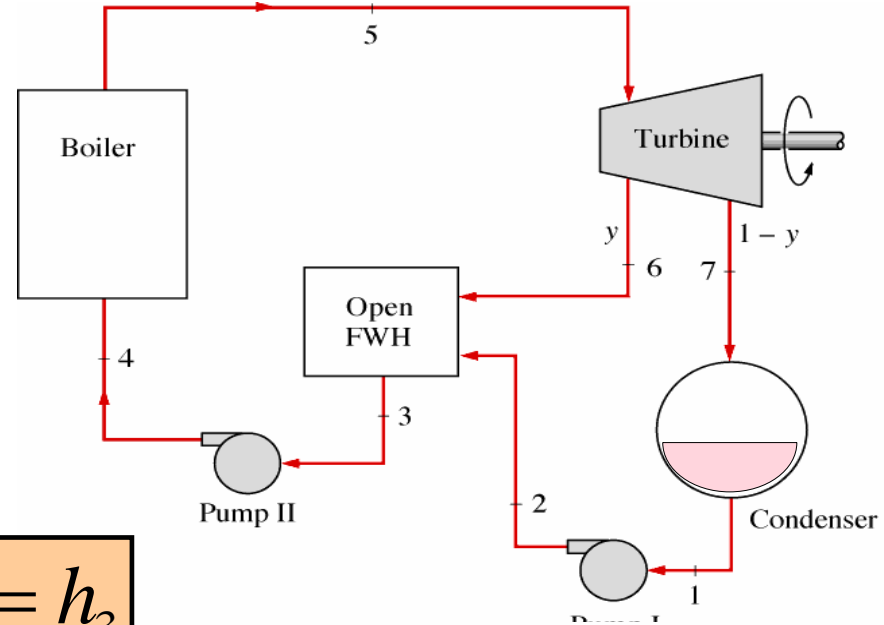
where $y = \dot{m}_6 / \dot{m}_5$

Also note that

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

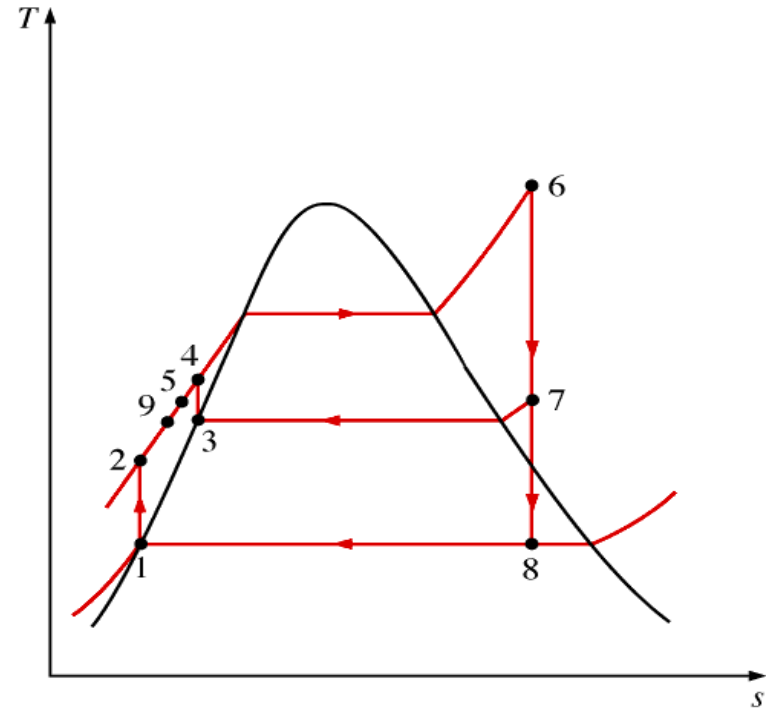
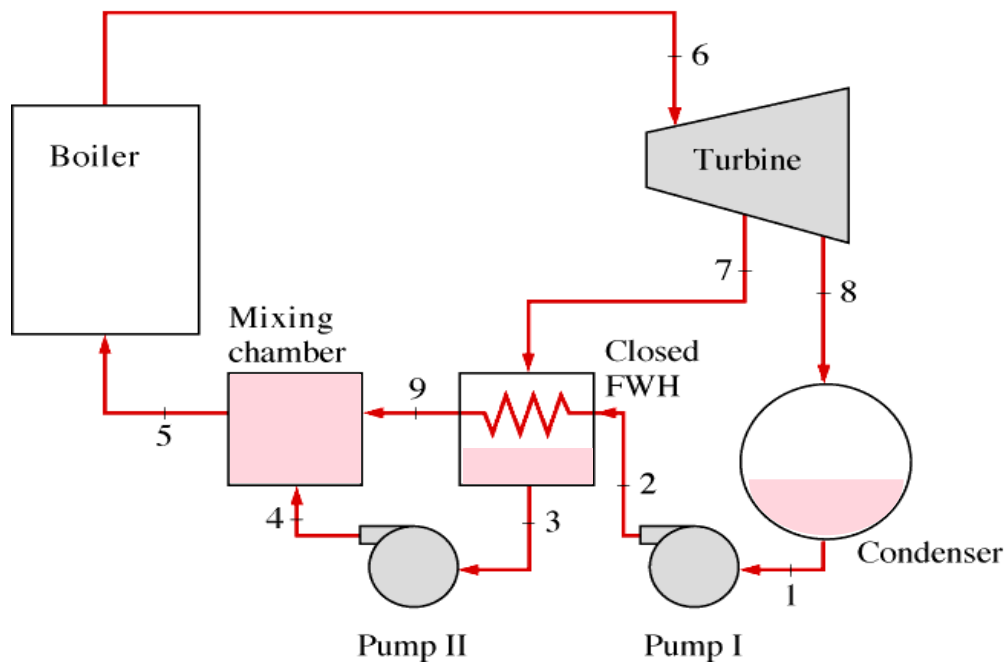
$$w_{turb,out} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

$$w_{pump,in} = (1 - y)w_{pumpI,in} + w_{pumpII,in}$$

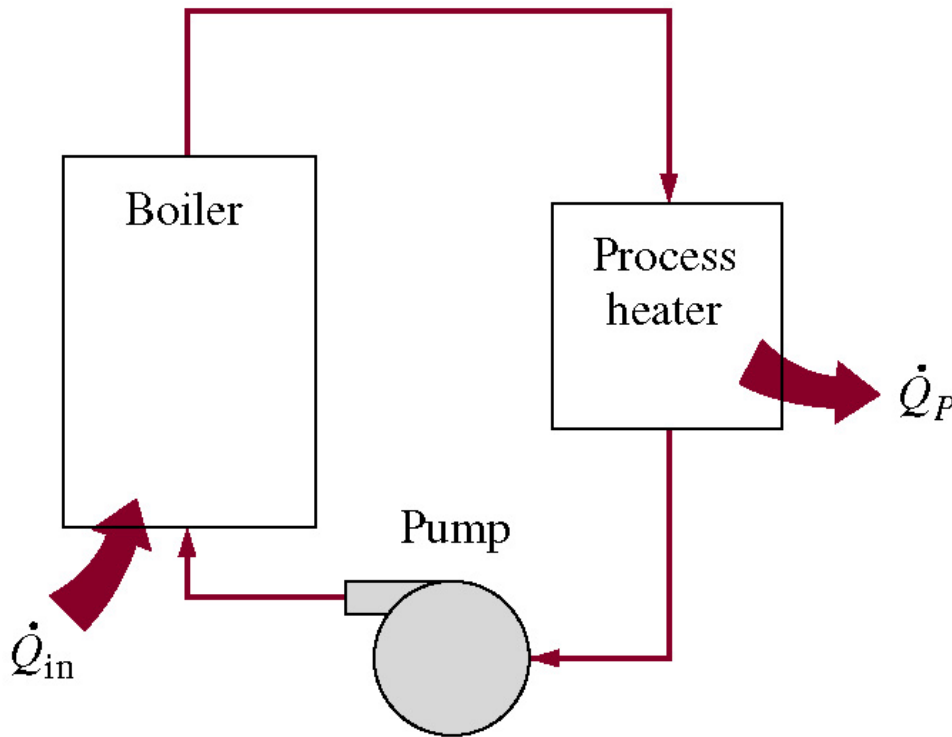


Ideal Regenerative Rankine Cycle with Closed Feedwater Heater

In closed feed water heaters, heat is transferred from the steam to the feed water without mixing. Thus heat transfer is less efficient compared to open feed water heaters.



Cogeneration concept



Process heat goes to different applications such as paper, textile, food processing industries. These industries need steam at about ~5 to 7 atm and ~150 to 200 °C as well as electric power.

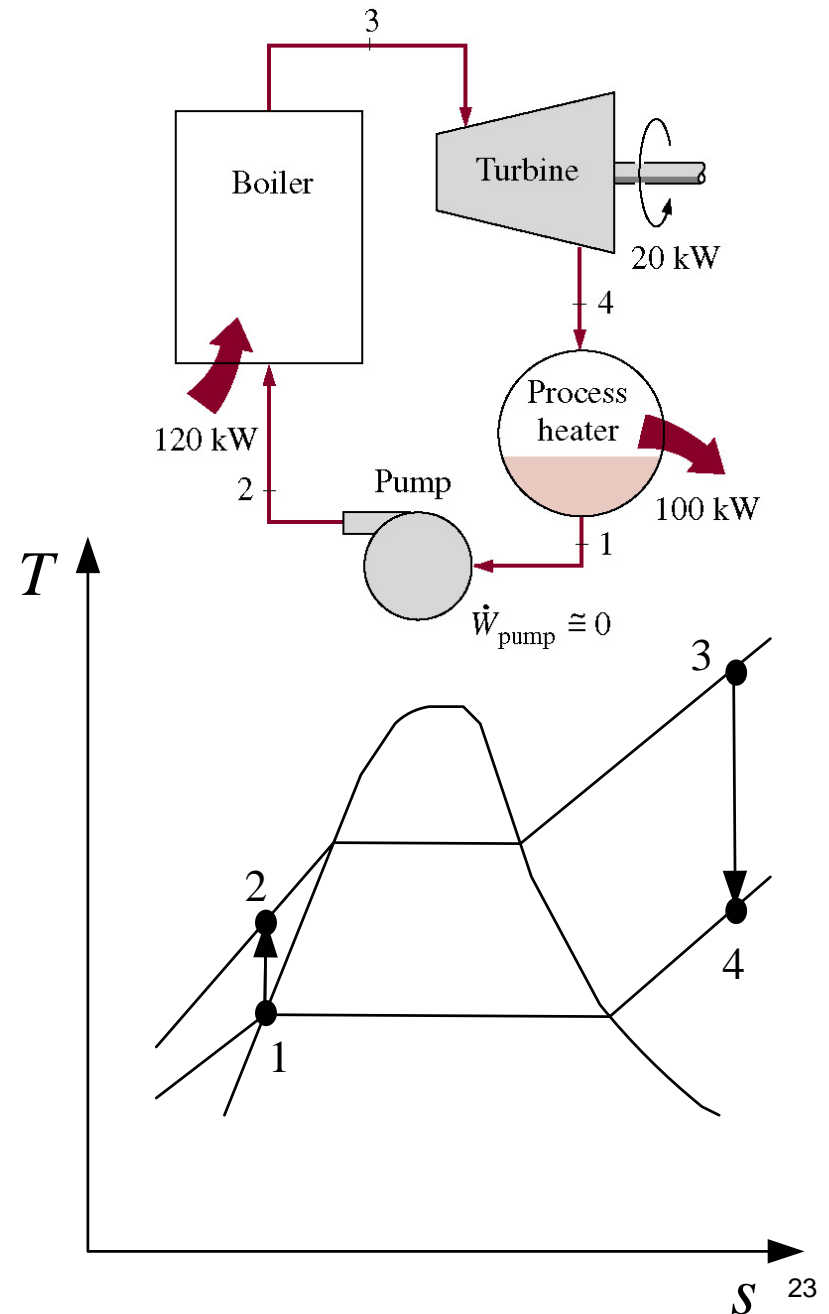
A simple process-heating plant.

Therefore, it is economical to use the high quality energy in the boiler (1370 C) to produce superheated steam.

This steam is used to produce electric power from a turbine.

The steam is extracted from the turbine at the pressure required by the process industry. The striking feature here is the absence of the condenser!

No heat is rejected ($Q_{out}=0$). All the heat possessed by the steam is used by the process industry (Q_p). The steam leaves the process industry as saturated liquid (state 1). Then it is pumped again to the boiler pressure.



Utilization Factor

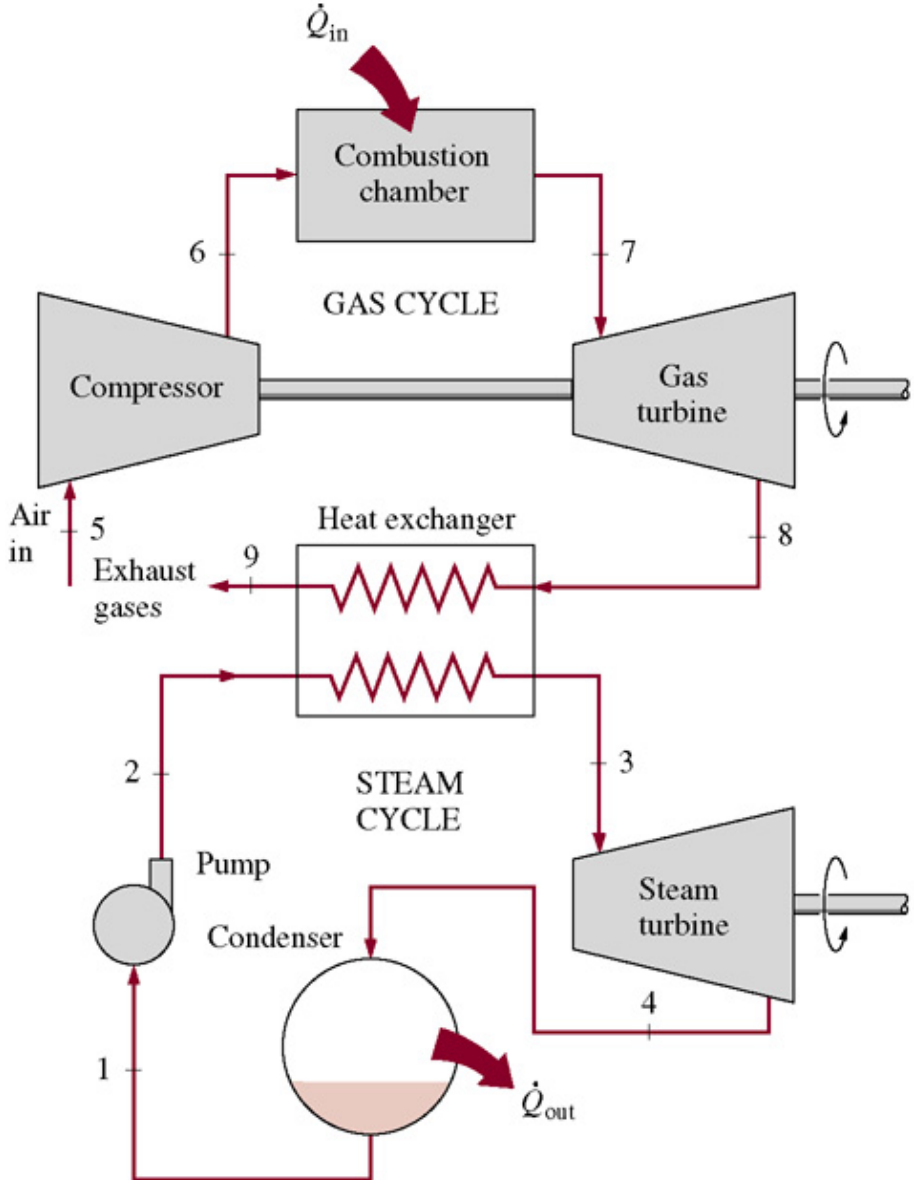
The fraction of energy that is used for either process heat or power generation is called the **utilization factor** of the cogeneration plant.

$$\epsilon_u = \frac{\dot{W}_{net} + \dot{Q}_p}{\dot{Q}_{in}} \qquad \epsilon_u = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} \approx 0$$

the **utilization factor** of the cogeneration plant is obviously a 100 percent. But strictly speaking, \dot{Q}_{out} also includes all heat losses from the piping and combustion inefficiencies. An actual cogeneration plant has a utilization factor of about 80 percent.

**Example 9-8 is cancelled. Instead, solve
HW problem 9-38**

Combined Gas-Steam Power Plant



T8 is about 500 C while T3 is about 450 C. Thus why do not we combine the two cycles.

