Gas and Vapour Power Cycles

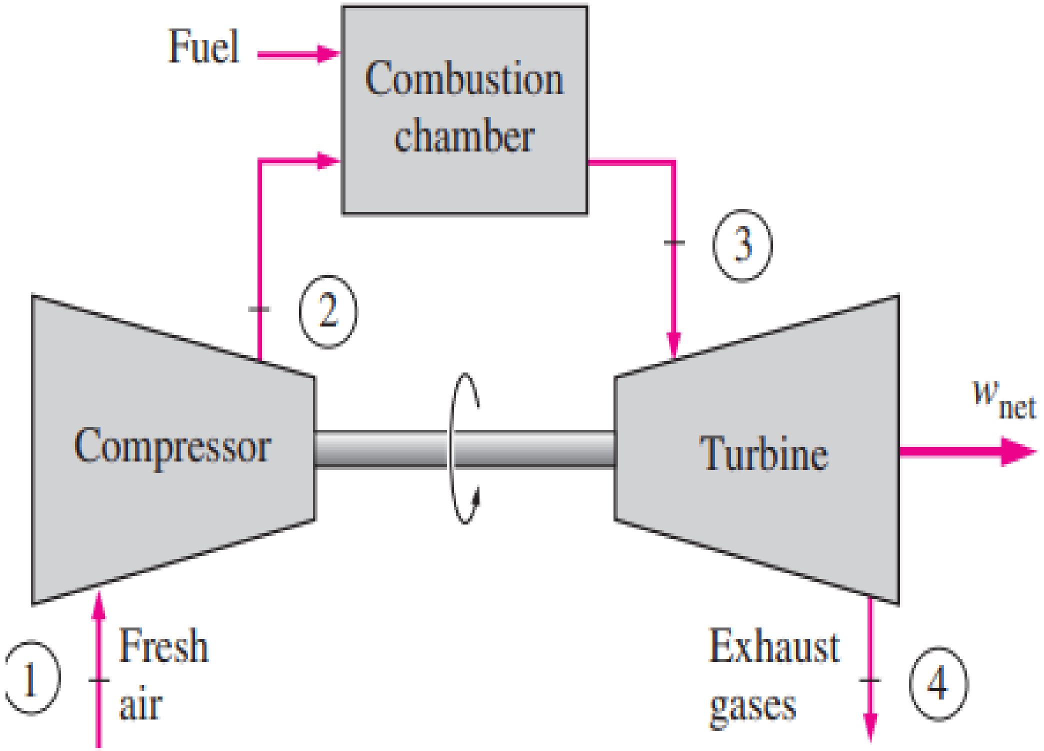
Milind Atrey
INOX Chair Professor
Department of Mechanical Engineering
Indian Institute of Technology Bombay
Mumbai – 400076
INDIA

Brayton Cycle

- George Brayton : Reciprocating oil-burning engine (1870)

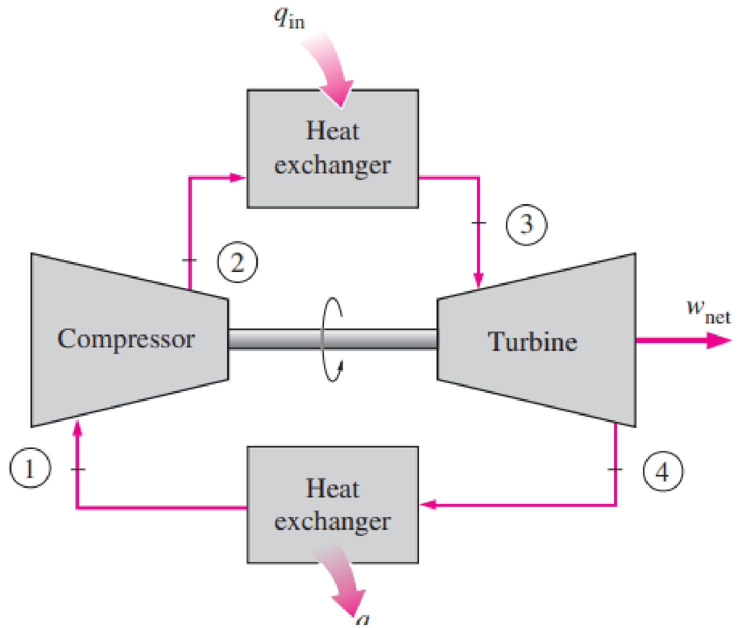
- Today, it is used for gas turbines only where both the compression and expansion processes take place in rotating machinery. Gas turbines usually operate on an open cycle.

- 1-2 Compression of fresh air - temperature and pressure increase.
- 2-3 Combustion Chamber where the fuel is burned at constant pressure.
- 3-4 Expansion in Turbine. – Power generation
- Exhaust to atmosphere



Brayton Cycle

- Closed Cycle. The combustion process is replaced by a constant-pressure heat-addition process from an external source, and the exhaust process is replaced by a constant pressure heat-rejection process to the ambient air.



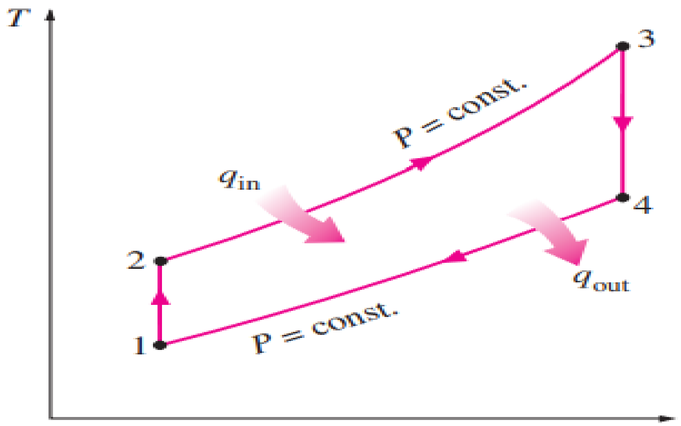
- Four internally reversible processes:

1-2 Isentropic compression (in a compressor)

2-3 Constant-pressure heat addition

3-4 Isentropic expansion (in a turbine)

4-1 Constant-pressure heat rejection



(a) T-s diagram

Brayton Cycle

- When the changes in kinetic and potential energies are neglected, the energy balance for a steady-flow process can be expressed, on a unit–mass basis, as :

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) \qquad q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

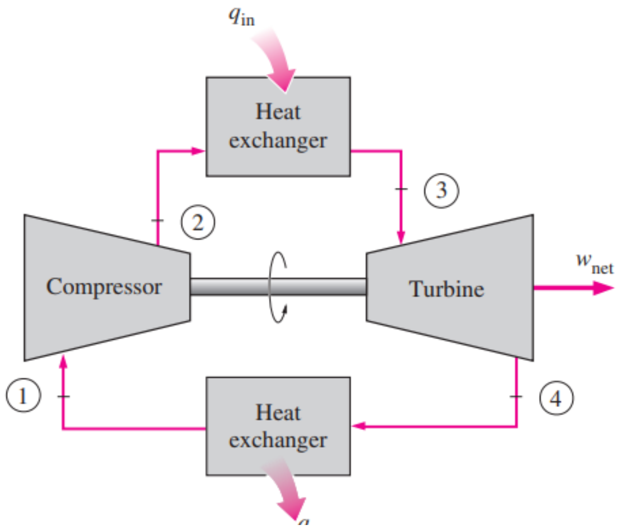
$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

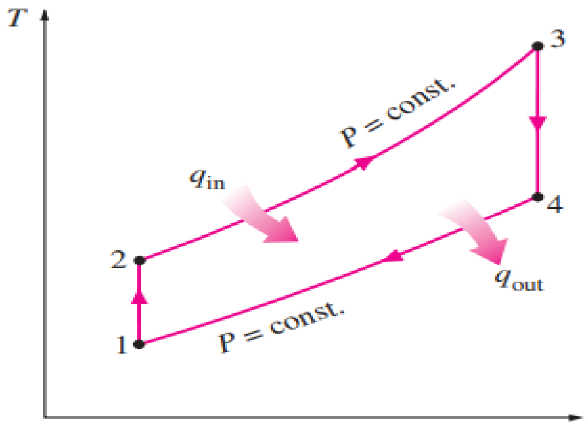
- Processes 1-2 and 3-4 are isentropic, and P2 = P3 and P4=P1

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

$$r_p = \frac{P_2}{P_1}$$





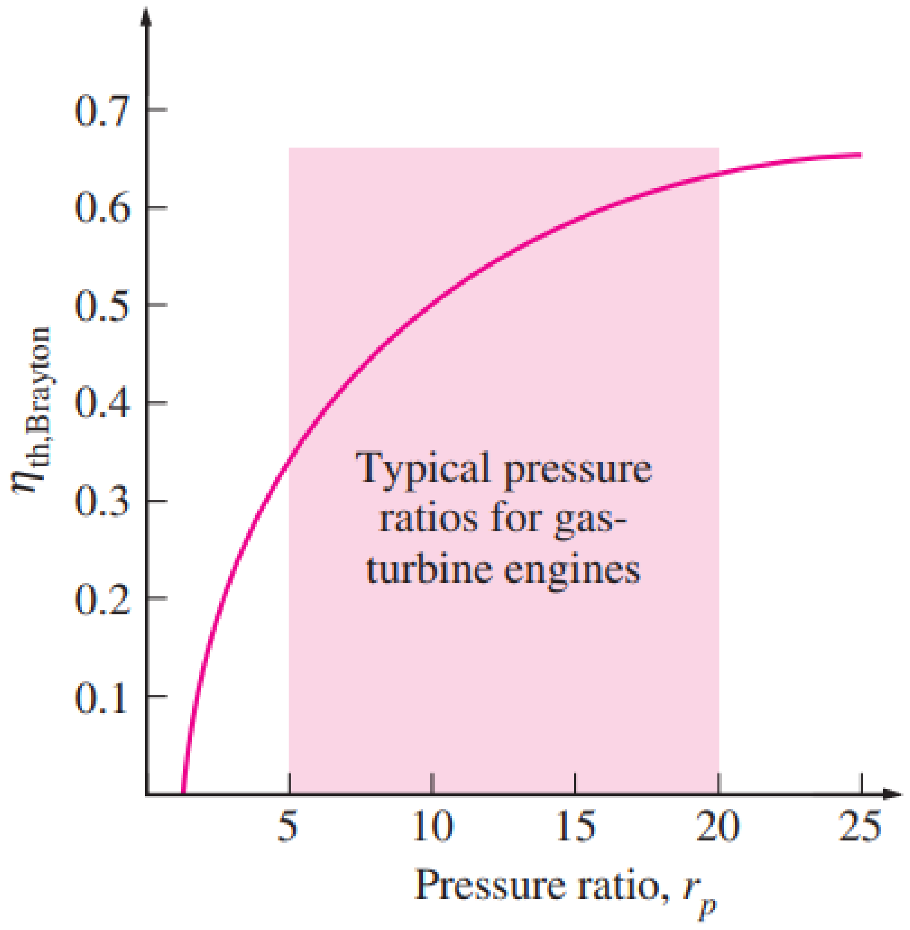
(a) T-s diagram

Brayton Cycle

- Equation shows that under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle depends on the pressure ratio of the gas turbine and the specific heat ratio of the working fluid.

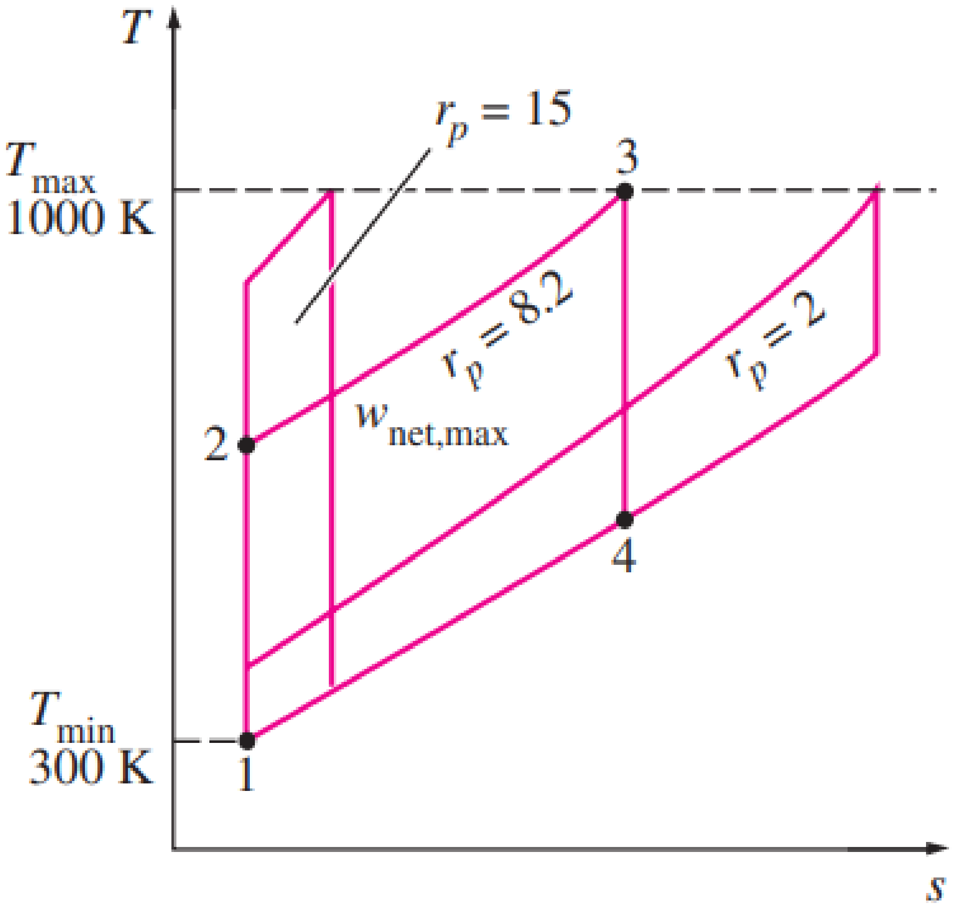
- The thermal efficiency increases with both of these parameters, which is also the case for actual gas turbines.

- Thermal efficiency versus the pressure ratio is given for k=1.4



Brayton Cycle

- The highest temperature in the cycle occurs at the end of the combustion process (state 3), and it is limited by the maximum temperature that the turbine blades can withstand.
- This also limits the pressure ratios that can be used in the cycle.
- For a fixed turbine inlet temperature T3, the net work output per cycle increases with the pressure ratio, reaches a maximum, and then starts to decrease.

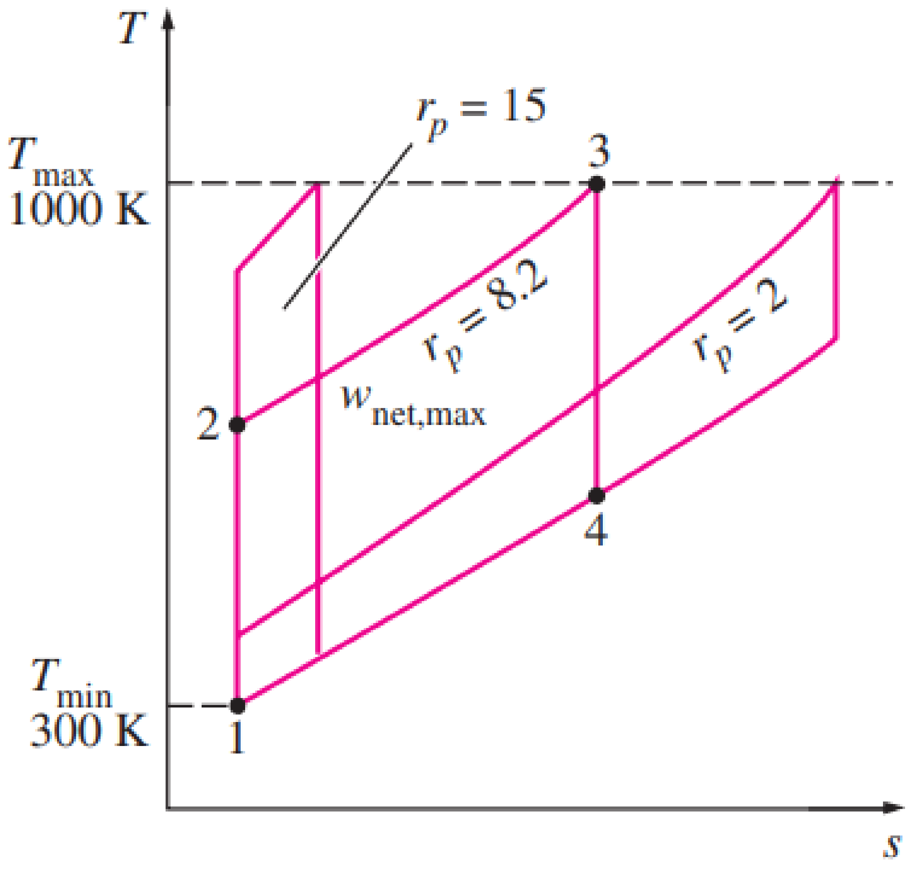


Brayton Cycle

- Therefore, there should be a compromise between the pressure ratio (thus the thermal efficiency) and the net work output.

- With less work output per cycle, a larger mass flow rate (thus a larger system) is needed to maintain the same power output, which may not be economical.

- In most common designs, the pressure ratio of gas turbines ranges from about 11 to 16.



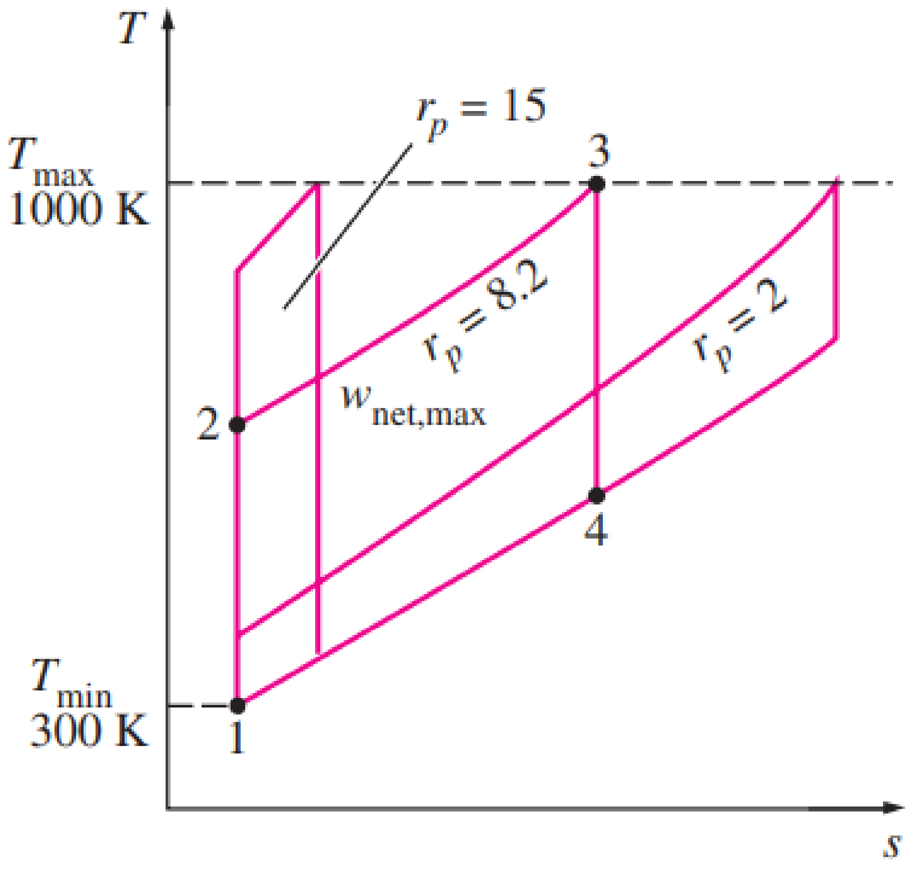
Brayton Cycle

- Air in gas turbines performs two important functions:

  (a) It supplies the necessary oxidant for the combustion of the fuel.

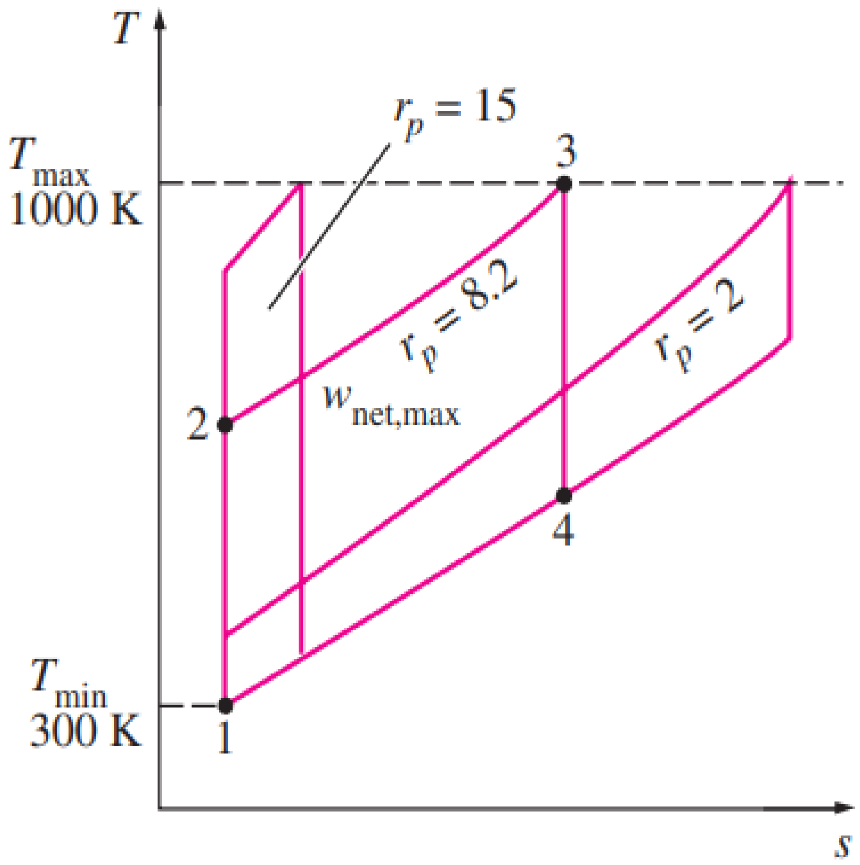
  (b) it serves as a coolant to keep the temperature of various components within safe limits.

- The second function is accomplished by drawing in more air than is needed for the complete combustion of the fuel.

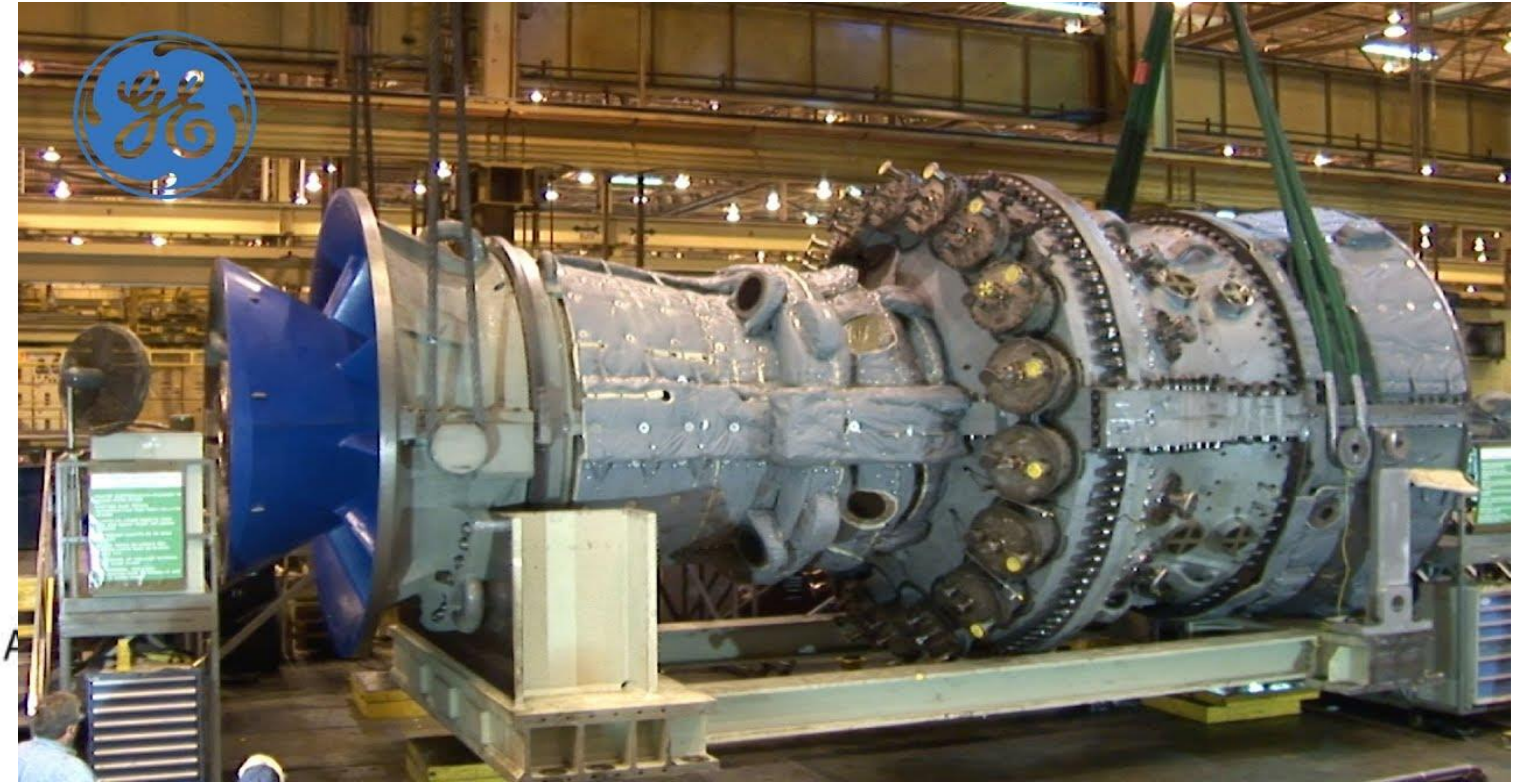


Brayton Cycle

- In gas turbines, an air–fuel mass ratio of 50 or above is normally used.
- Therefore, in a cycle analysis, treating the combustion gases as air does not cause any appreciable error.
- Also, the mass flow rate through the turbine is greater than that through the compressor, the difference being equal to the mass flow rate of the fuel.
- Thus, assuming a constant mass flow rate throughout the cycle yields conservative results for open-loop gas-turbine engines



Brayton Cycle



Brayton Cycle

- The two major application areas of gas-turbine engines are aircraft propulsion and electric power generation.

- For aircraft propulsion : Gas turbine produces enough power to drive the compressor and a small generator. The high-velocity exhaust gases are responsible for producing the necessary thrust to propel the aircraft.

- Gas turbines : Stationary power plants to generate electricity as stand-alone units or in conjunction with steam power plants on the high-temperature side. The exhaust gases of the gas turbine serve as the heat source for the steam.

- The gas-turbine cycle can also be executed as a closed cycle for use in nuclear power plants.

Brayton Cycle

- In gas-turbine power plants, the **ratio of the compressor work to the turbine work**, **back work ratio**, is very high. Usually more than one-half of the turbine work output is used to drive the compressor. If the isentropic efficiencies of the compressor and the turbine are low this ratio is much higher.

- Opposite to this is in **steam power plants**, where the back work ratio is only a few percent. This as the liquid is pumped in steam power plants instead of a gas

- A power plant with a high back work ratio requires a larger turbine to provide the additional power requirements of the compressor. Therefore, the turbines used in gas-turbine power plants are larger than those used in steam power plants of the same net power output.

Development of Gas Turbine

- Gas Turbine Development – from 1930, cycle efficiency of 17 % The early gas turbines built in the 1940s and even 1950s had simple-cycle efficiencies of about 17 % due to low compressor and turbine efficiencies and low turbine inlet temperatures due to metallurgical limitations – Therefore limited usage

- The efforts to improve the cycle efficiency concentrated in three areas:

  (a) Increasing the turbine inlet (or firing) temperatures

  (b) Increasing the efficiencies of turbomachinery components

  (c) Adding modifications to the basic cycle

- GE Gas Turbine in 1990 had a pressure ratio of 13.5 and generated 135.7 MW of net power at a thermal efficiency of 33 percent in simple-cycle operation.
- Recently GE uses a turbine inlet temperature of 1425°C - 282 MW with 39.5 % efficiency

Actual Gas-Turbine Cycles

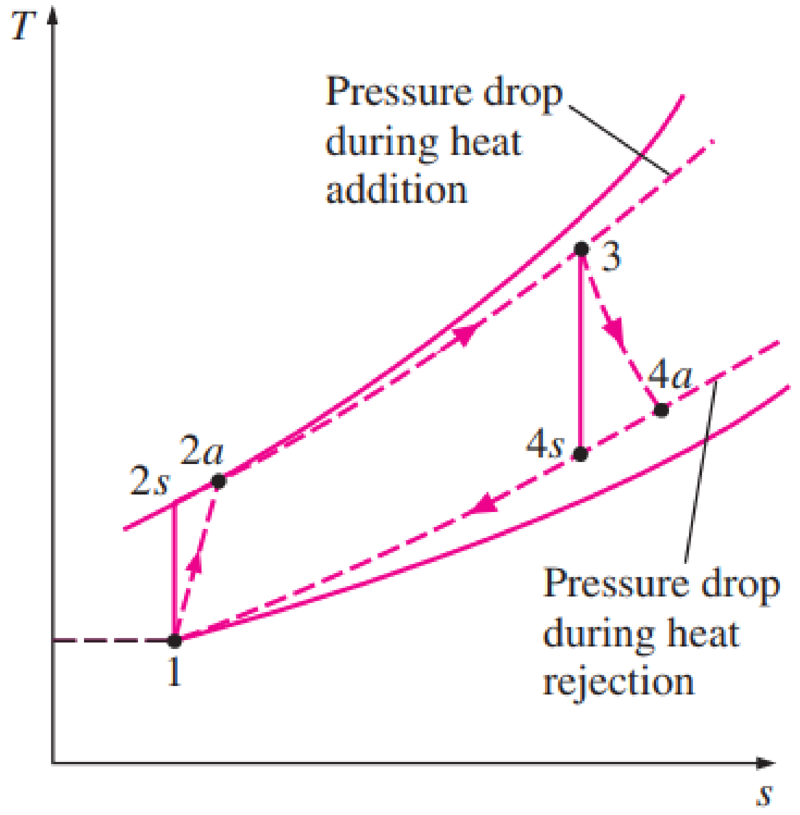
- Actual η differs from the ideal Brayton
- This is due to : (a) pressure drop during the heat-addition and heat rejection processes

(b) Actual work input to the compressor is more

(c) Work output is less due to irreversibility.

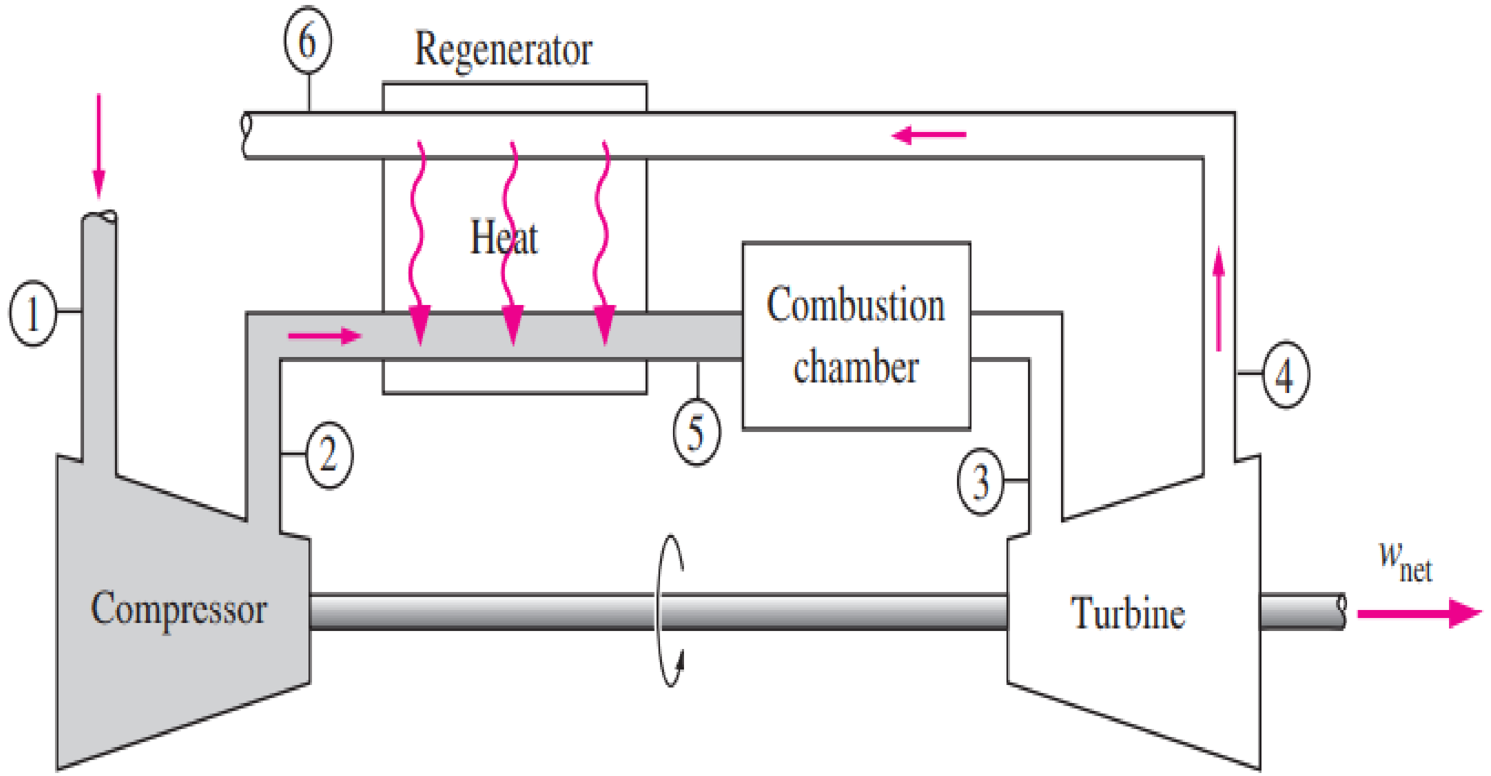
- Isentropic efficiencies of the turbine and compressor as :

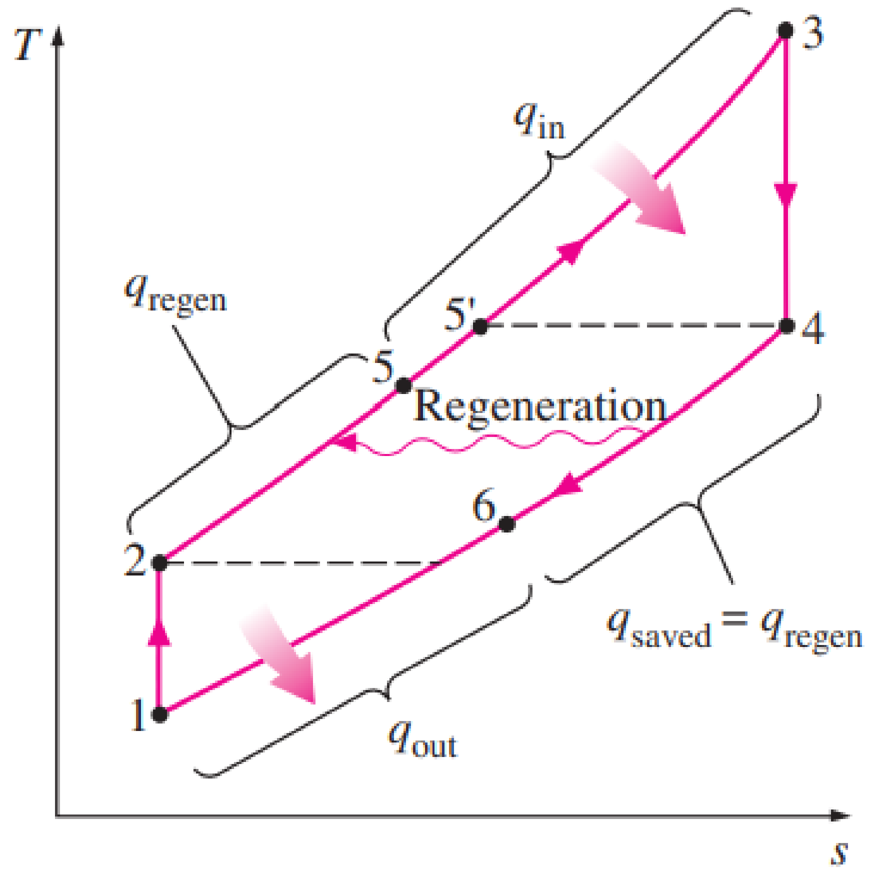
$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$



where states 2a and 4a are the actual exit states of the compressor and the turbine, respectively, and 2s and 4s are the corresponding states for the isentropic case

Brayton Cycle with Regeneration



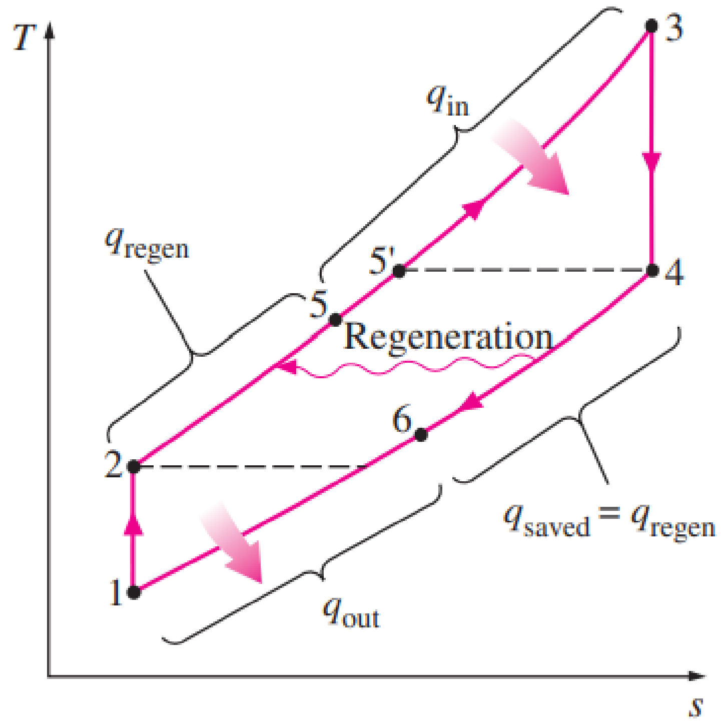


Brayton Cycle with Regeneration

- In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor.

- Therefore, the high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger, which is also known as a regenerator or a recuperator.

- Part of energy of the exhaust gases is used to preheat the air entering the combustion chamber. - Increases η
- Use of a regenerator is recommended only when the turbine exhaust temperature is higher than the compressor exit temperature This situation is encountered in gas-turbine engines operating at very high pressure ratios.

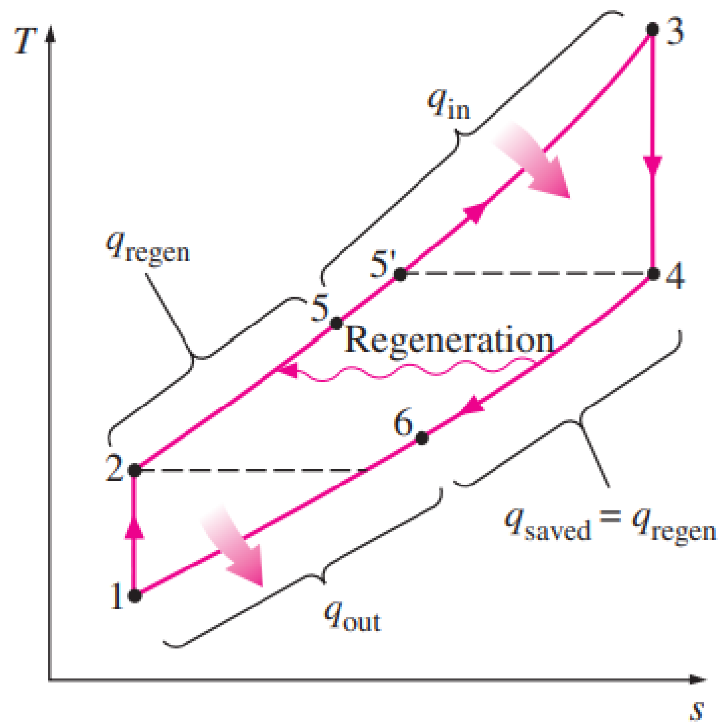


Brayton Cycle with Regeneration

- T4 - The highest temperature occurring within the regenerator. It is the temperature of the exhaust gases leaving the turbine and entering the regenerator.

- Air normally leaves the regenerator at a lower temperature, T5. In the limiting (ideal) case, the air exits the regenerator at the inlet temperature of the exhaust gases T4.

- Under Ideal conditions : $q_{\text{regen,act}} = h_5 - h_2$



$$q_{\text{regen,max}} = h_{5'} - h_2 = h_4 - h_2 \qquad \epsilon = \frac{q_{\text{regen,act}}}{q_{\text{regen,max}}} = \frac{h_5 - h_2}{h_4 - h_2}$$

- When the cold-air-standard assumptions are utilized, it reduces to

$$\epsilon \cong \frac{T_5 - T_2}{T_4 - T_2}$$

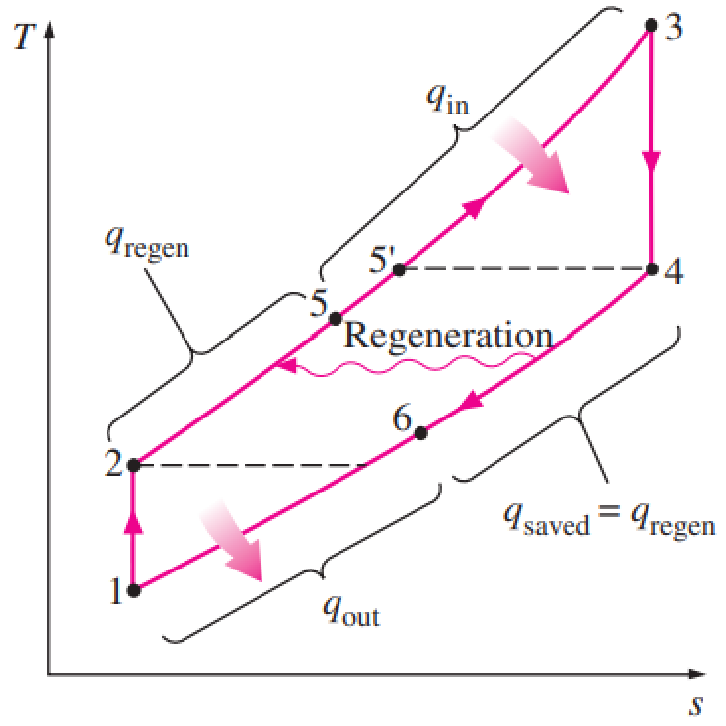
Brayton Cycle with Regeneration

- Achieving a higher effectiveness requires the use of a larger regenerator – costly and causes a larger pressure drop.

- Use of a regenerator with a very high effectiveness cannot be justified economically unless the savings from the fuel costs exceed the additional expenses involved.

- The effectiveness of most regenerators used in practice is below 0.85.

- Thermal efficiency, $\eta_{th,\ regen}$ of an ideal Brayton cycle with regeneration can be calculated.



Brayton Cycle with Regeneration

$$\eta = \frac{w_{turbine} - w_{compressor}}{q_{in}}$$

$q_{in} = C_p\left(T_3 - T_5\right)$ and $w_{turb} = C_p\left(T_3 - T_4\right)$

For an ideal regenerator in which we have: T_5=T_4
We get:

$$q_{in} = w_{turb}$$

Therefore, $\eta = 1 - \frac{w_c}{w_t} = 1 - \frac{C_p\left(T_2 - T_1\right)}{C_p\left(T_3 - T_4\right)} = 1 - \frac{T_1}{T_3}\frac{\left(\frac{T_2}{T_1} - 1\right)}{\left(1 - \frac{T_4}{T_3}\right)}$

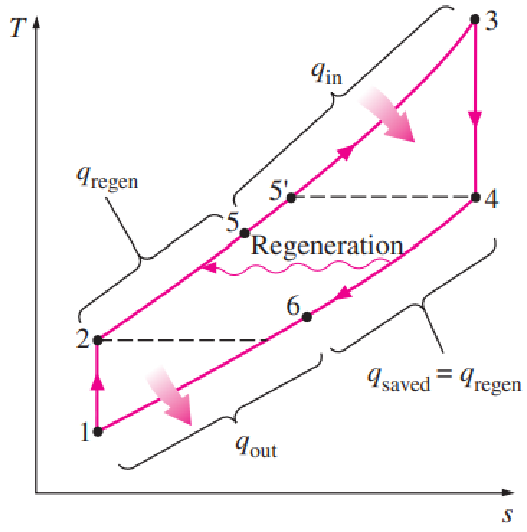
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = r_p^{\frac{k-1}{k}}$$

and

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{k-1}{k}} = r_p^{\frac{k-1}{k}}$$ therefore $$\frac{T_4}{T_3} = r_p^{\frac{1-k}{k}}$$

If we replace in (I)

$$\eta = 1 - \frac{T_1}{T_3}\frac{r_p^{\frac{k-1}{k}} - 1}{1 - r_p^{\frac{1-k}{k}}}$$



$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$

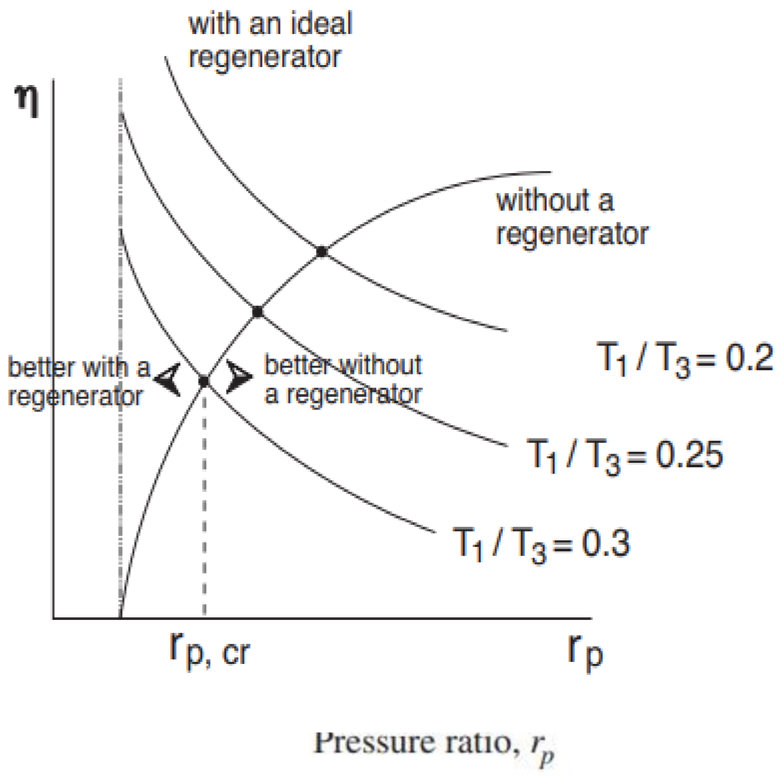
Brayton Cycle with Regeneration

$$\eta_{\text{th,regen}} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$

- η_{th} of an ideal Brayton cycle with regeneration depends on the ratio of the minimum to maximum temperatures as well as the pressure ratio.

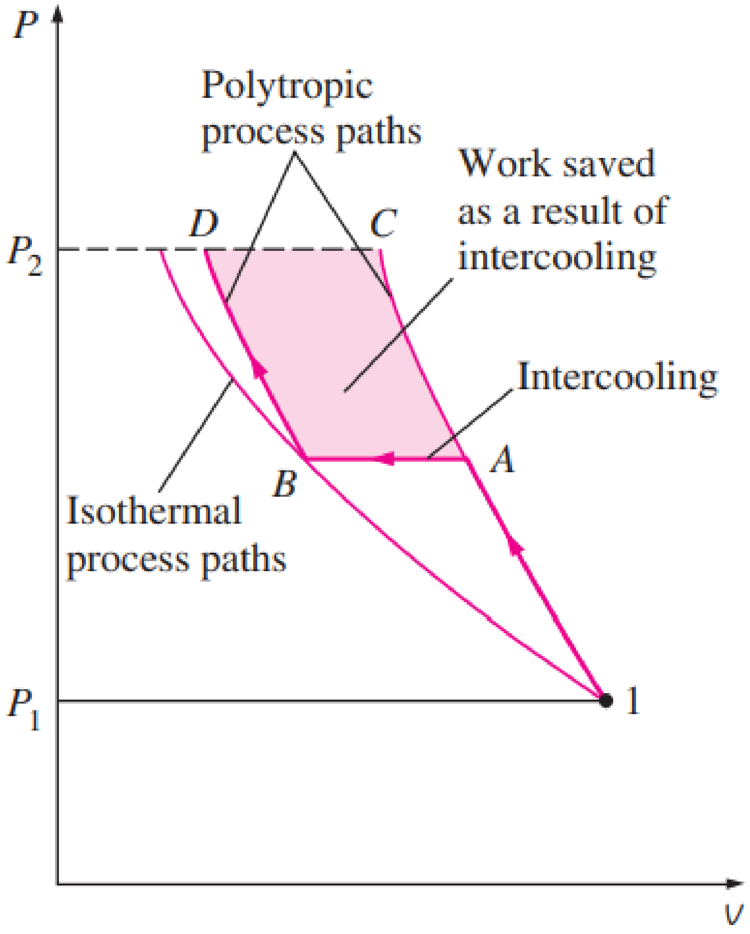
- Plot of η_{th} vs pressure ratios and minimum-to-maximum temperature ratios.

- The figure shows that regeneration is most effective at lower pressure ratios and low minimum-to-maximum temperature ratios.



Brayton Cycle with Intercooling, Reheating and Regeneration

- Net work of a gas-turbine cycle = Turbine work output - compressor work input
- This work can be increased by either decreasing the compressor work or increasing the turbine work, or both.
- Compressor work can be decreased by multistage Compression with intercooling
- As the number of stages is increased, the compression process becomes nearly isothermal at the compressor inlet temperature, and the compression work decreases.



Brayton Cycle with Intercooling, Reheating and Regeneration

- The work output of a turbine operating between two pressure levels can be increased by expanding the gas in stages and reheating it in between—that is, utilizing **multistage expansion with reheating.** As the number of stages is increased, the expansion process becomes nearly isothermal.

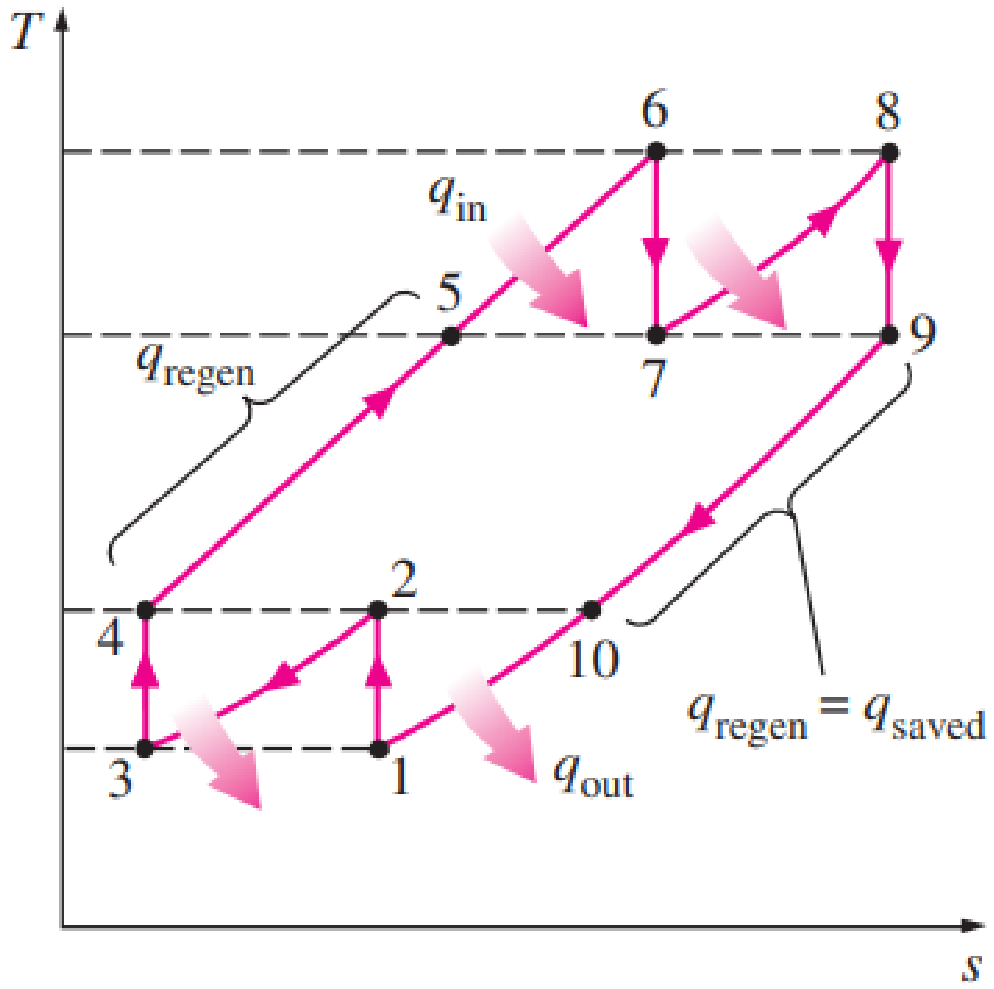
- The steady-flow compression or expansion work is proportional to the specific volume of the fluid. Therefore, the specific volume of the working fluid should be as low as possible during a compression process and as high as possible during an expansion process. This is precisely what intercooling and reheating accomplish.

- Combustion in gas turbines typically occurs at four times the amount of air needed for complete combustion to avoid excessive temperatures. Therefore, the exhaust gases are rich in oxygen, and reheating can be accomplished by simply spraying additional fuel into the exhaust gases between two expansion states.

Brayton Cycle with Intercooling, Reheating and Regeneration

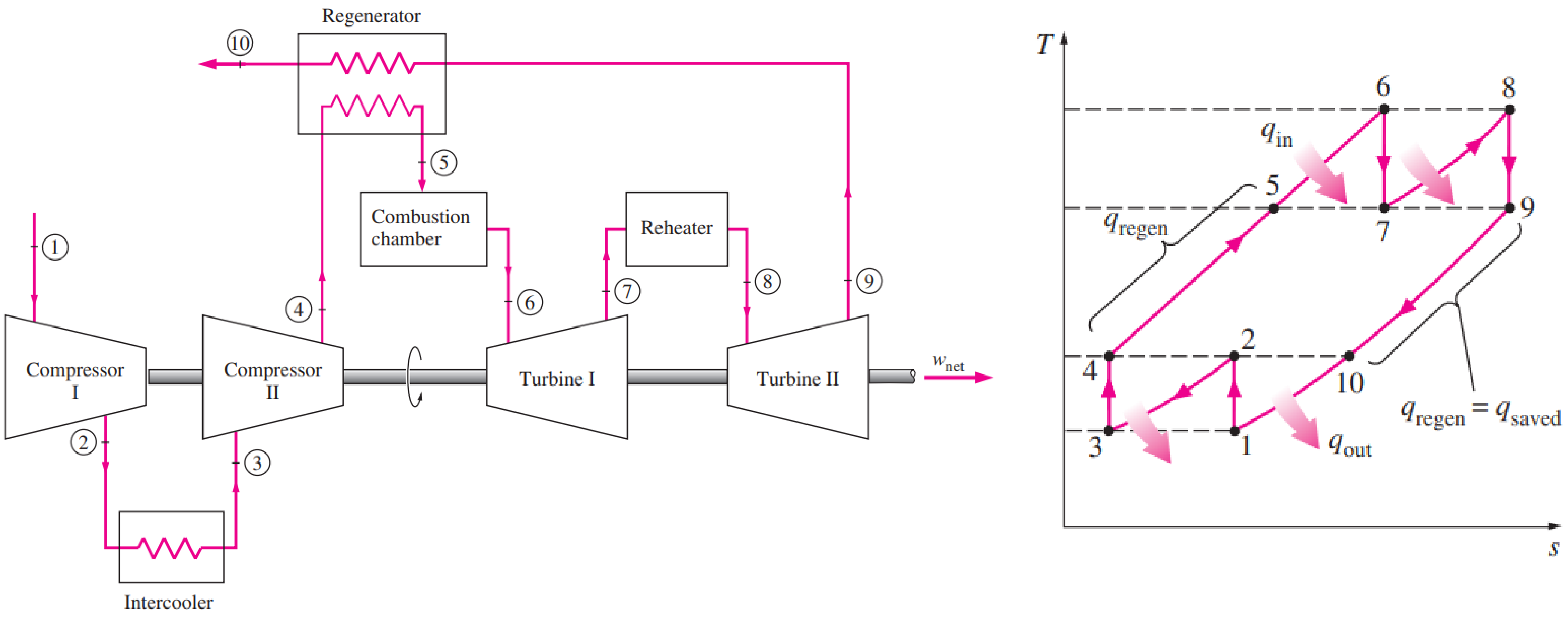
- The working fluid leaves the compressor at a lower temperature, and the turbine at a higher temperature, when intercooling and reheating are utilized.

- This makes regeneration more attractive since a greater potential for regeneration exists. Also, the gases leaving the compressor can be heated to a higher temperature before they enter the combustion chamber because of the higher temperature of the turbine exhaust



Brayton Cycle with Intercooling, Reheating and Regeneration

- T-s diagram of an ideal two-stage gas-turbine cycle with intercooling, reheating, and regeneration



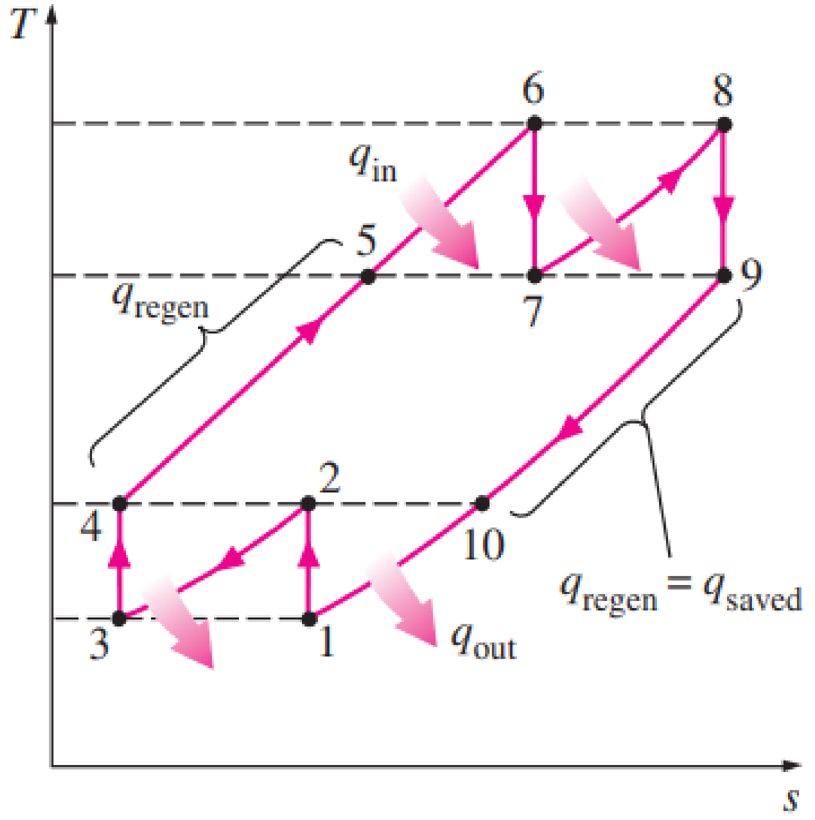
Brayton Cycle with Intercooling, Reheating and Regeneration

- The gas enters the first stage of the compressor at state 1, is compressed isentropically to an intermediate pressure P2, is cooled at constant pressure to state 3 (T3=T1), and is compressed in the second stage isentropically to the final pressure P4.

- At 4, the gas enters the regenerator, where it is heated to T5 at constant pressure. In an ideal regenerator, T5=T9.

- The primary heat addition (or combustion) process takes place between states 5 and 6.

- The gas enters the first stage of the turbine at state 6 and expands isentropically to state 7, where it enters the reheater.



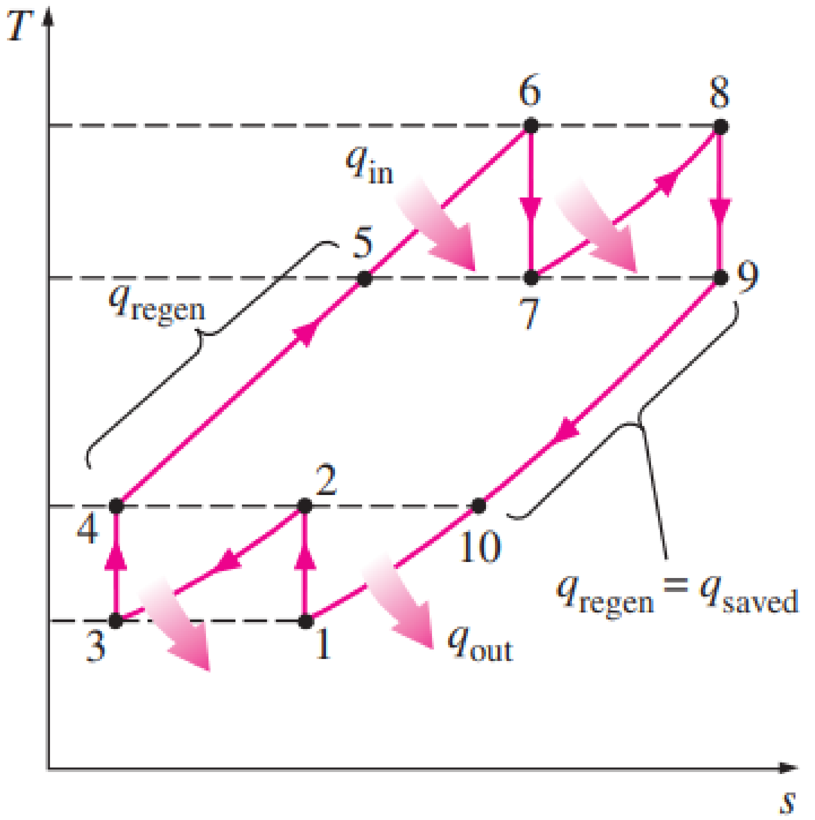
Brayton Cycle with Intercooling, Reheating and Regeneration

- At 7, gas enters the reheater. It is reheated at constant pressure to state 8 (T8 = T6), where it enters the second stage of the turbine.

- The gas exits the turbine at state 9 and enters the regenerator, where it is cooled to state 10 at constant pressure.

- The cycle is completed by cooling the gas to the initial state (or purging the exhaust gases).

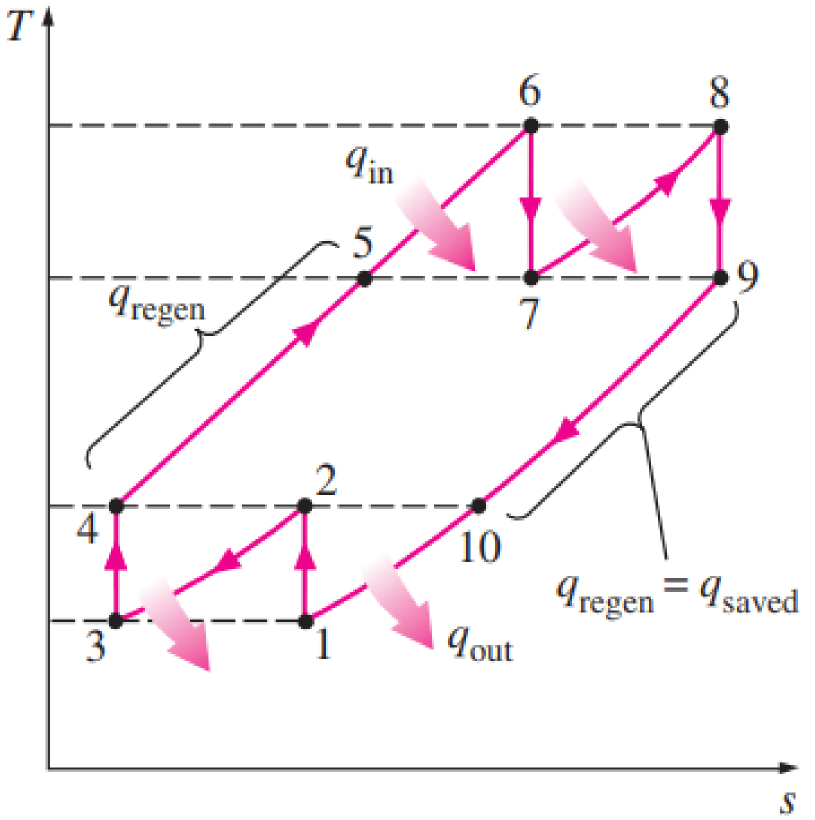
- The work input to a two-stage compressor is minimized when equal pressure ratios are maintained across each stage. It can be shown that this procedure also maximizes the turbine work output



Brayton Cycle with Intercooling, Reheating and Regeneration

- for best performance, it can be shown,

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} \quad \text{and} \quad \frac{P_6}{P_7} = \frac{P_8}{P_9}$$



- In actual gas-turbine cycles, the irreversibilities within the compressor, the turbine, and the regenerator as well as the pressure drops in the heat exchangers should be taken into consideration

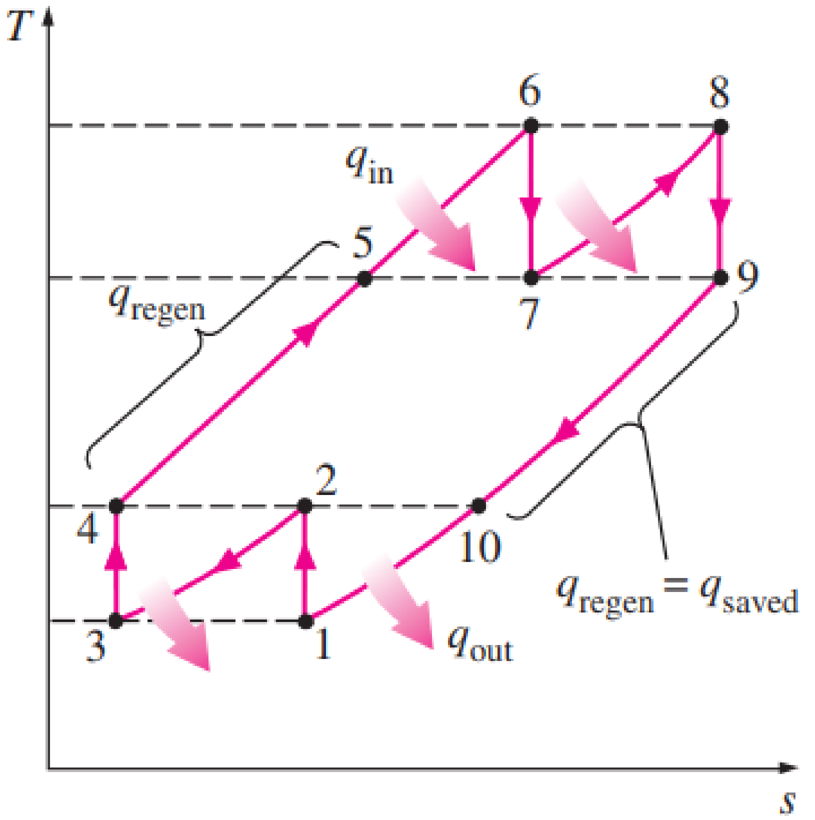
- The back work ratio of a gas-turbine cycle improves as a result of intercooling and reheating. But this may not improve η_{th}

Brayton Cycle with Intercooling, Reheating and Regeneration

- It may be noted that intercooling and reheating always decreases the η_{th} unless they are accompanied by regeneration.

- This is because intercooling decreases the average temperature at which heat is added, and reheating increases the average temperature at which heat is rejected.

- This is also clear from the figure. Therefore, in gas turbine power plants, intercooling and reheating are always used in conjunction with regeneration.

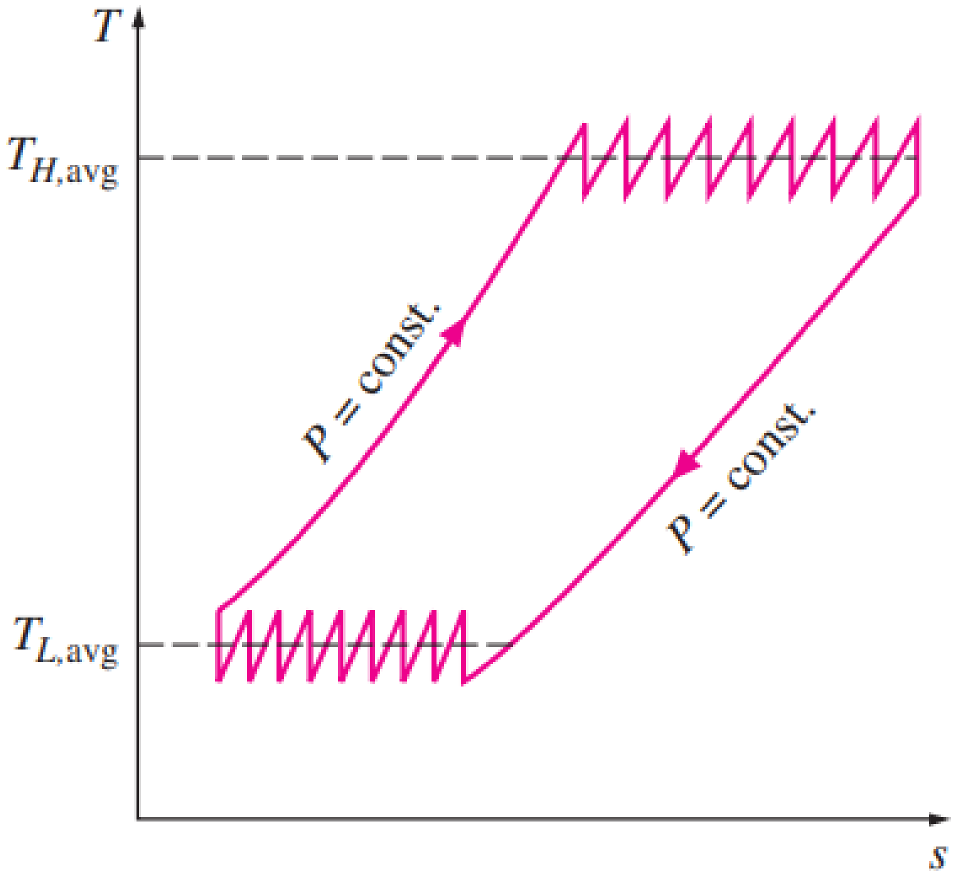


Brayton Cycle with Intercooling, Reheating and Regeneration

- If the number of compression and expansion stages is increased, the ideal gas-turbine cycle with intercooling, reheating, and regeneration approaches the Ericsson cycle.

- The thermal efficiency approaches the theoretical limit (the Carnot efficiency).

- However, the contribution of each additional stage to the thermal efficiency is less and less, and the use of more than two or three stages cannot be justified economically.



Vapor Cycles

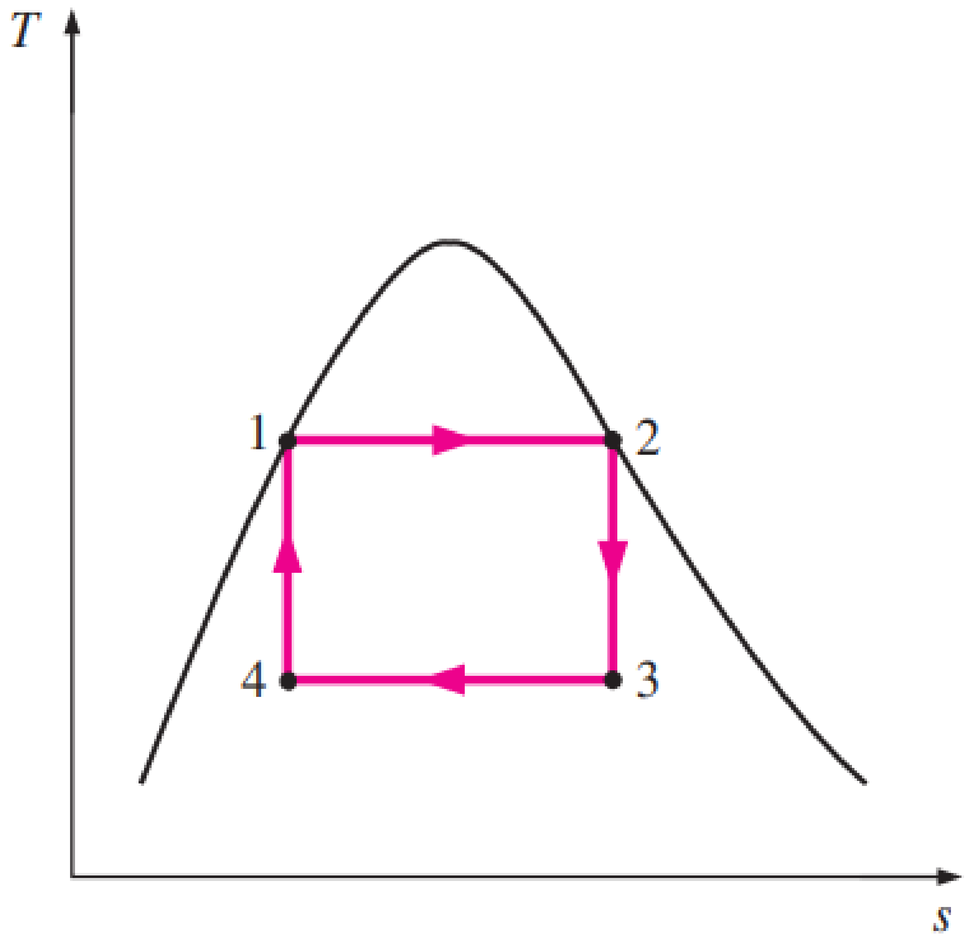
- Gas Power cycles – Gas phase
- Vapor power cycles - Working fluid is alternatively vaporized and condensed.
- Cogeneration : Power generation coupled with process heating
- Modifications in Basic Vapor Power cycles are made to increase efficiency.
- Reheat and Regenerative cycles, combined gas–vapor power cycles.
- Steam Power cycles, Power plants.

Carnot Vapor Cycle

- Carnot cycle is not a suitable model for power cycles.
- Steam is the working fluid
- Consider a steady-flow Carnot cycle executed within the saturation dome of a pure substance.
- 1-2 Heating reversibly and isothermally in a boiler
- 2-3 Expanded isentropically in a turbine

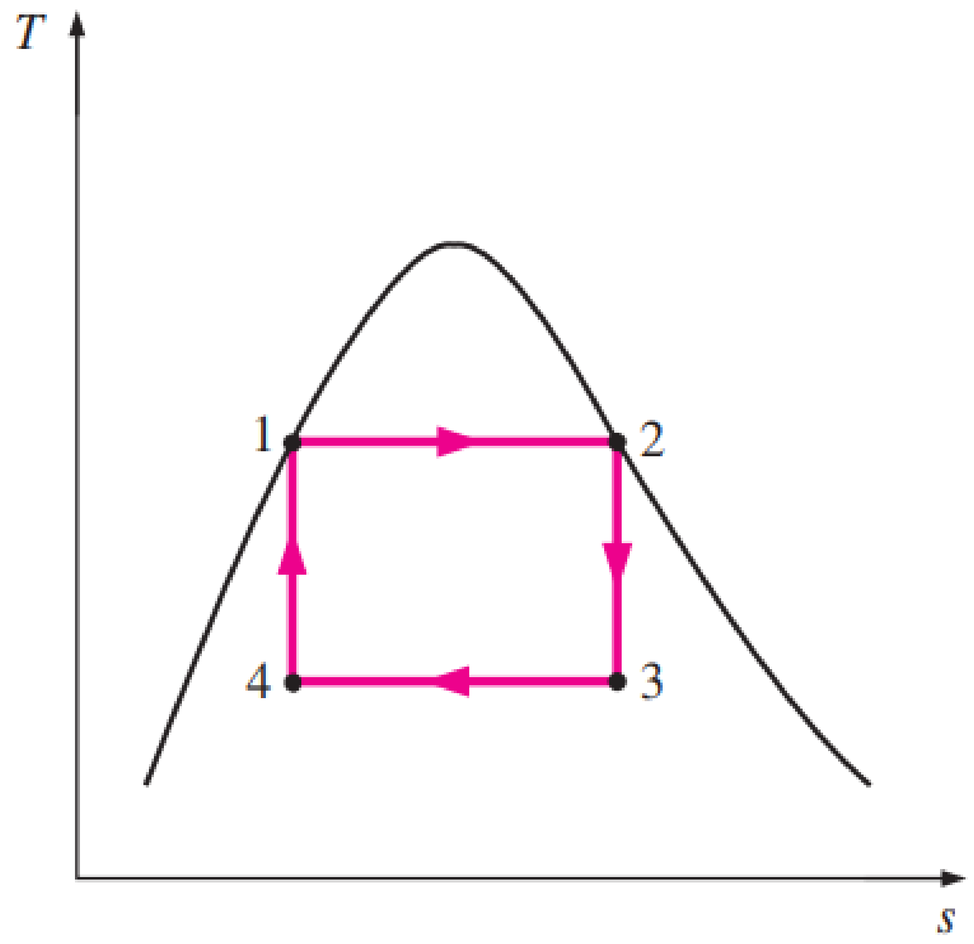
3-4 Reversible Isothermal condensation

4-1 Isnetropic Compression



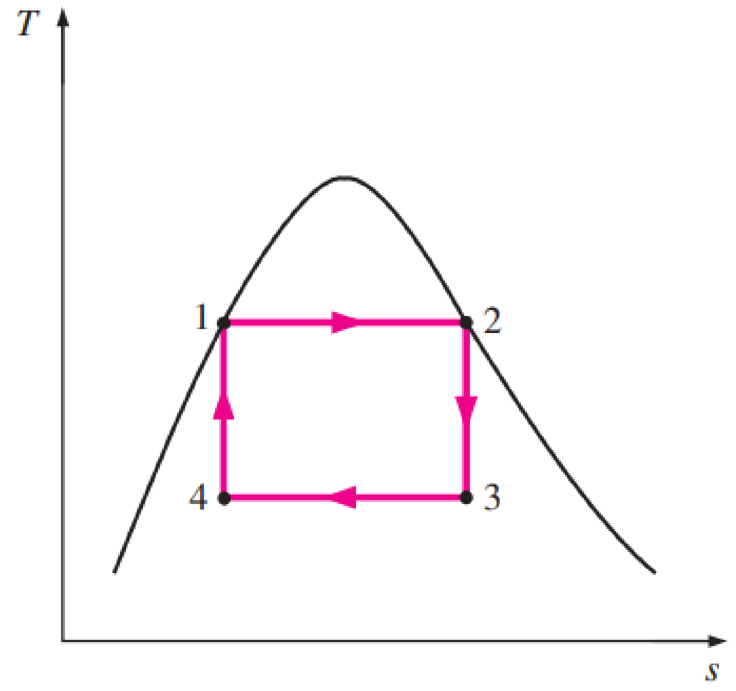
Carnot Vapor Cycle - Impractical

- Processes 1-2 and 3-4 phase change processes where P and T are constant - Possible
- Limitations : Heat transfer in 2-phase limits the maximum temperature in the cycle, which is critical temperature of water, 374 ^{o}C.
- Any attempt to raise the maximum temperature in the cycle involves heat transfer to the working fluid in a single phase, which is not easy to accomplish isothermally.



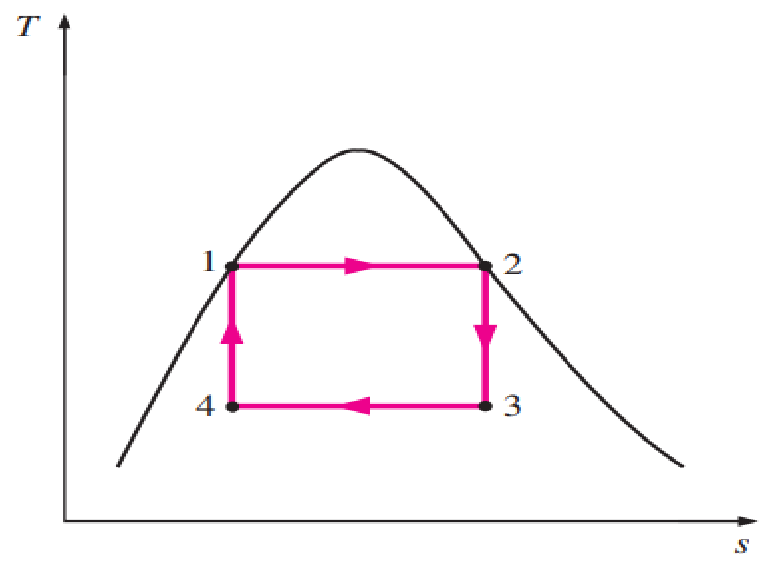
Carnot Vapor Cycle - Impractical

- The isentropic expansion process (process 2-3) can be approximated closely by a well-designed turbine.
- However, the quality of the steam decreases during this process, as shown on the T-s diagram
- Thus the turbine has to handle steam with low quality, that is, steam with a high moisture content.
- The impingement of liquid droplets on the turbine blades causes erosion and is a major source of wear.
- Thus steam with qualities less than about 90 percent cannot be tolerated in the operation of power plants.- Calls for change of working fluid



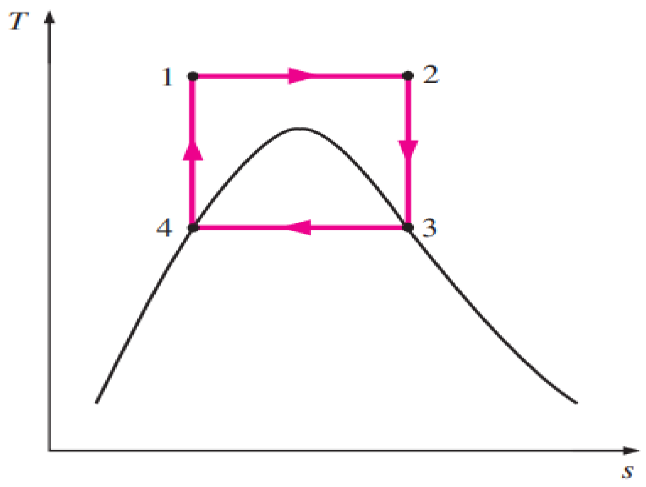
Carnot Vapor Cycle - Impractical

- process 4-1- involves the compression of a liquid–vapor mixture to a saturated liquid. – difficult



- It is not easy to control the condensation process so precisely as to end up with the desired quality at state 4. And it is not practical to design a compressor that handles two phases.

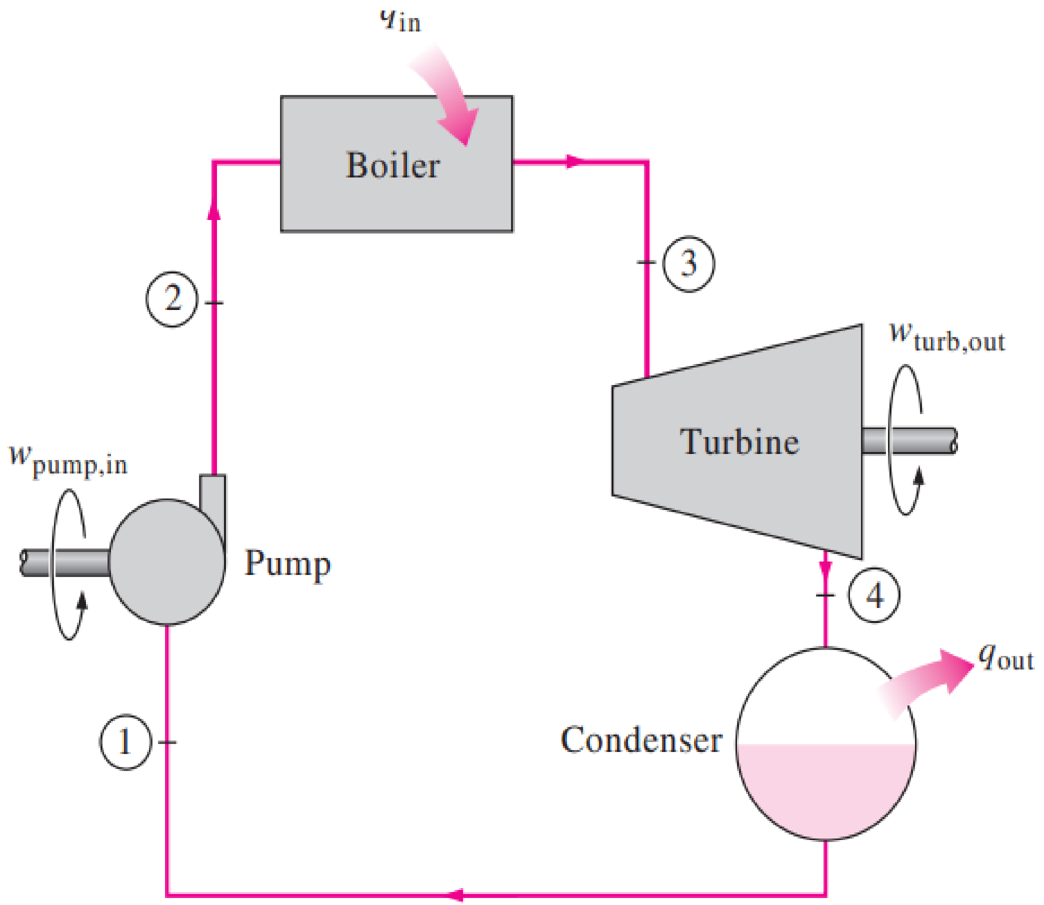
- Changes in Carnot cycle : Isentropic compression to extremely high pressures and isothermal heat transfer at variable pressures - difficult



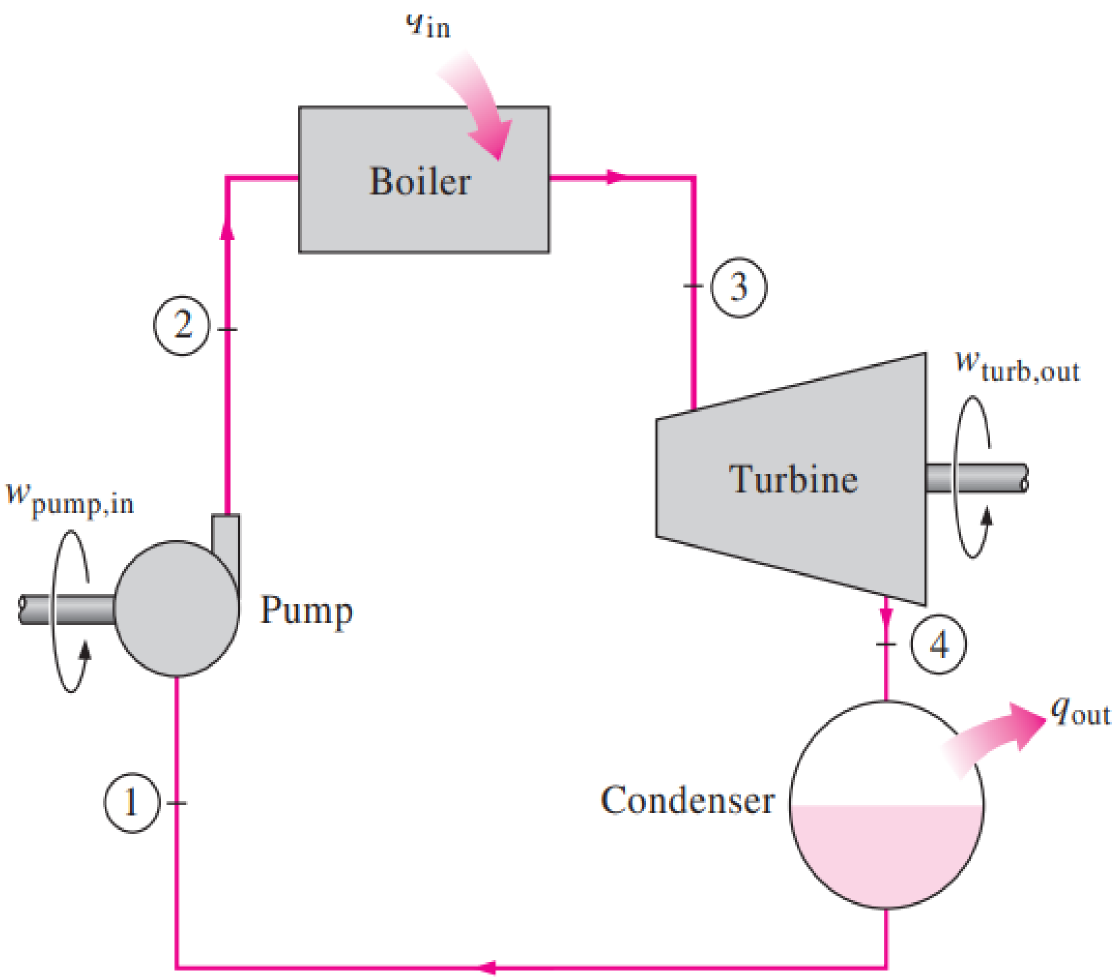
- Carnot cycle - not possible as vapor Power cycle.

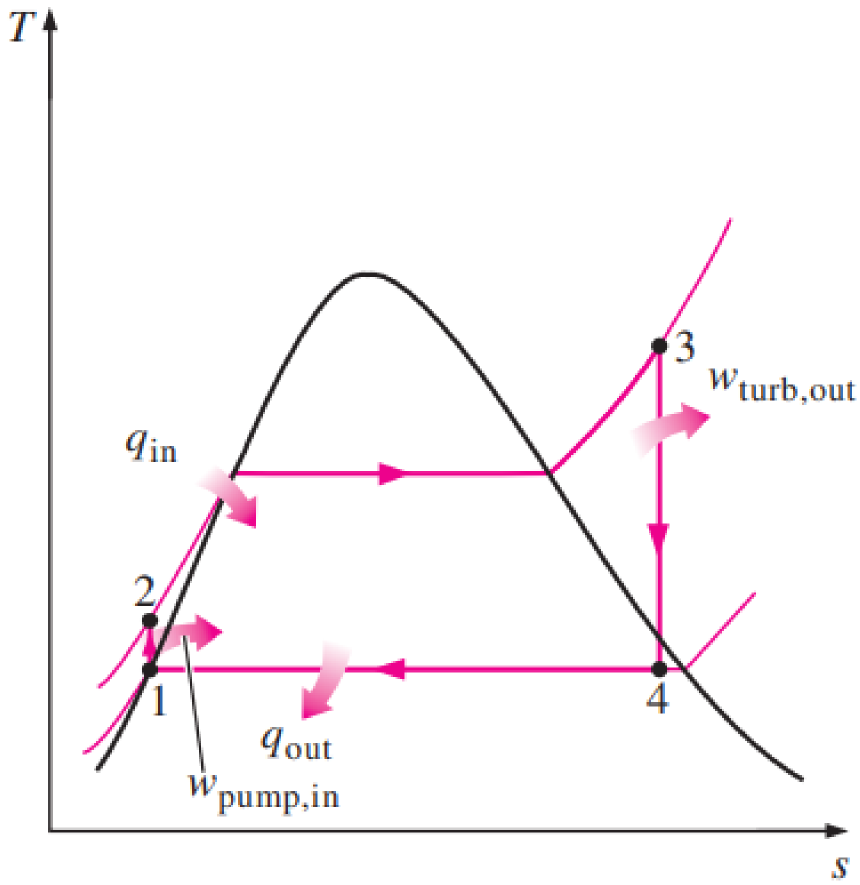
Rankine Cycle

- Many impracticalities - Carnot cycle
- Rankine Cycle - Steam, superheated in the boiler and condensing it completely in the condenser.
- 4-Processes
- 1-2 Isentropic compression - pump
- 2-3 Constant pressure heat addition - boiler
- 3-4 Isentropic expansion - turbine
- 4-1 Constant pressure heat rejection -condenser



Rankine Cycle





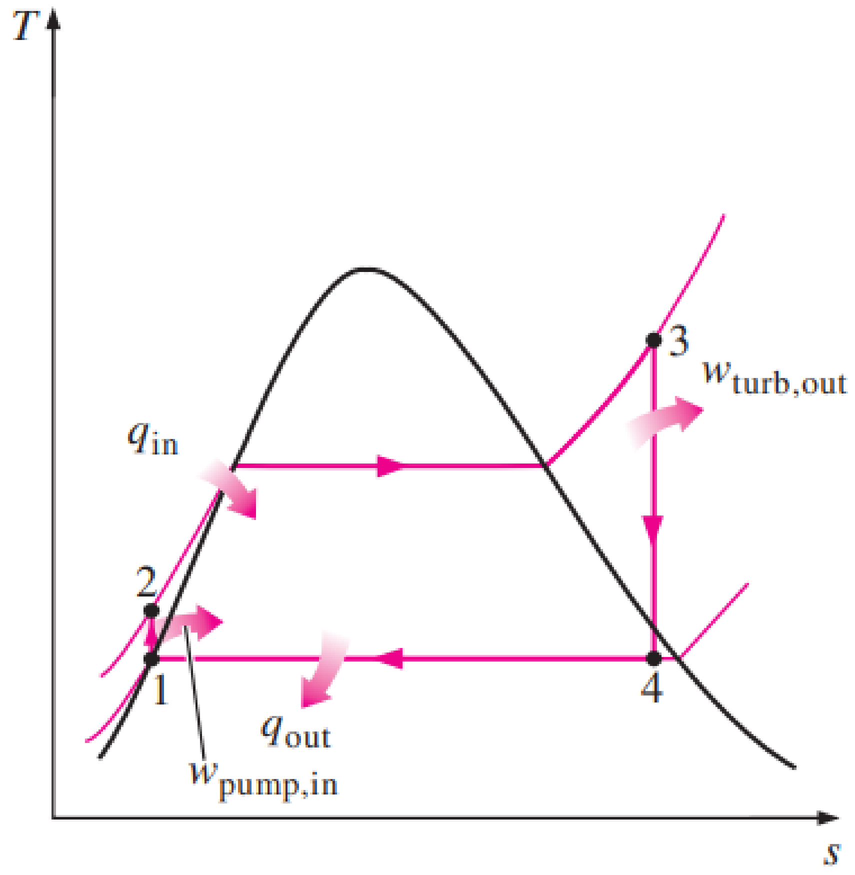
Rankine Cycle

- 1-2 Isentropic Compression to the boiler pressure. Increase in temperature.

- 2-3 Water enters the boiler as a compressed liquid at state 2 and leaves as a superheated vapor at state 3.

- The boiler is basically a large heat exchanger where the heat originating from combustion gases, nuclear reactors, or other sources is transferred to the water essentially at constant pressure.

- Called as Steam Generator.



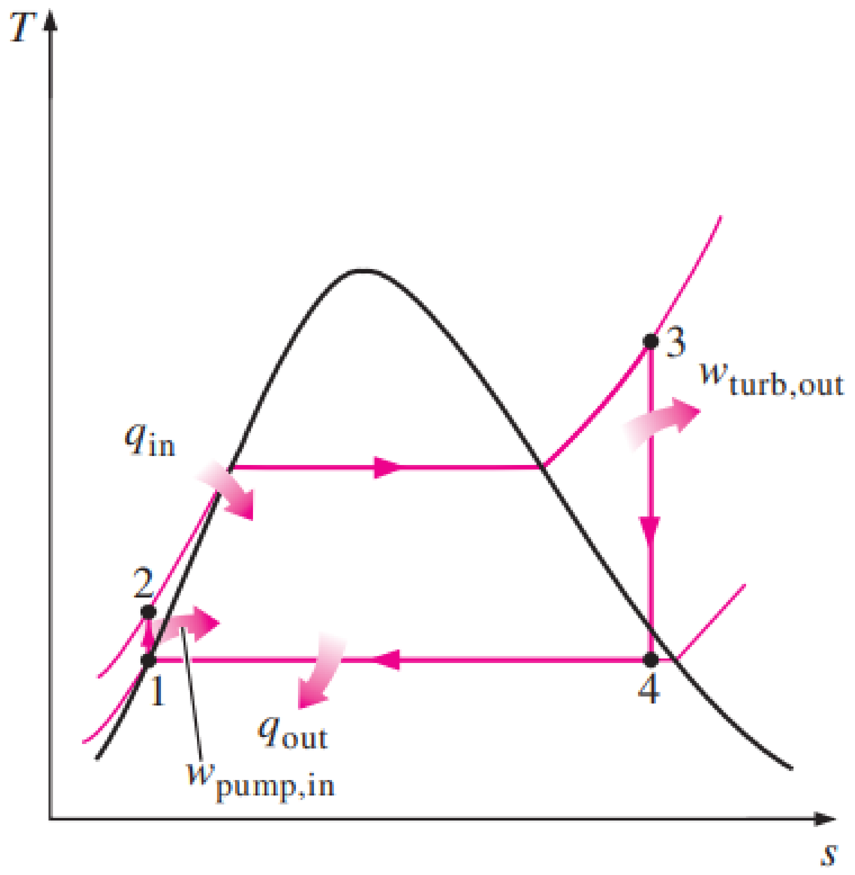
Rankine Cycle

- 3-4 : Superheated vapor at state 3 expands isentropically in Turbine. Produces work

- 3-4 : The pressure and the temperature of steam drop during this process to the values at state 4, where steam enters the condenser – state of saturated liquid.

- 4-1 Steam is condensed at constant pressure in the condenser, which is basically a large heat exchanger, by rejecting heat to a cooling medium such as a lake, a river, or the atmosphere.

- Steam leaves the condenser as saturated liquid and enters the pump, completing the cycle.



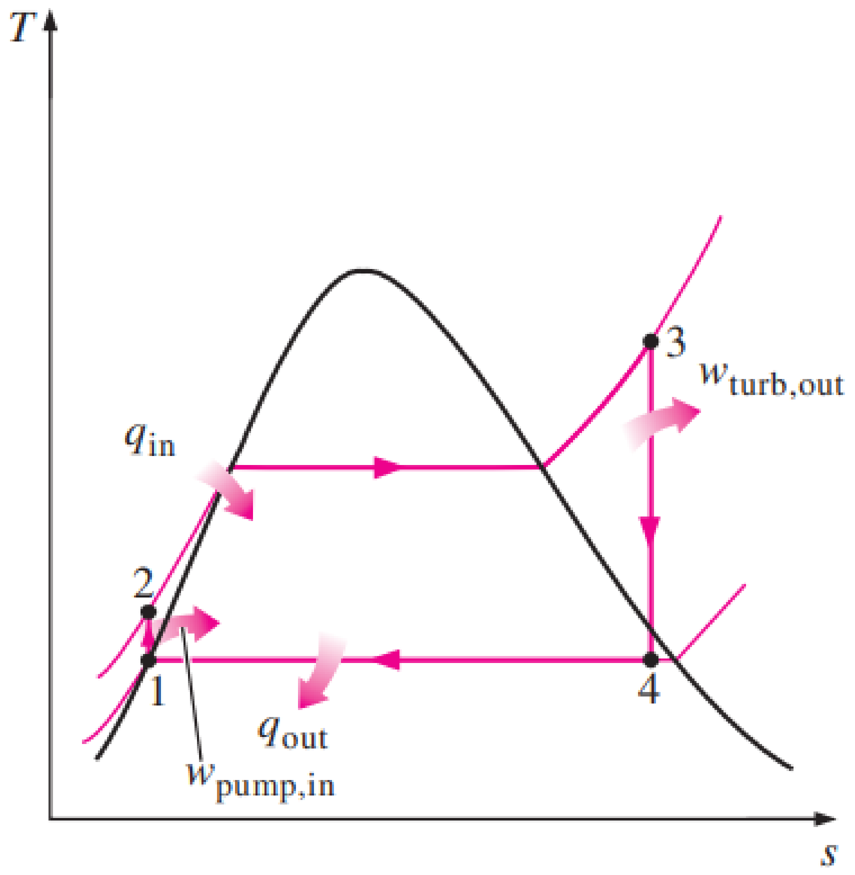
Rankine Cycle

- Power plants are cooled by air (instead of water) where water is scarce. - Dry cooling

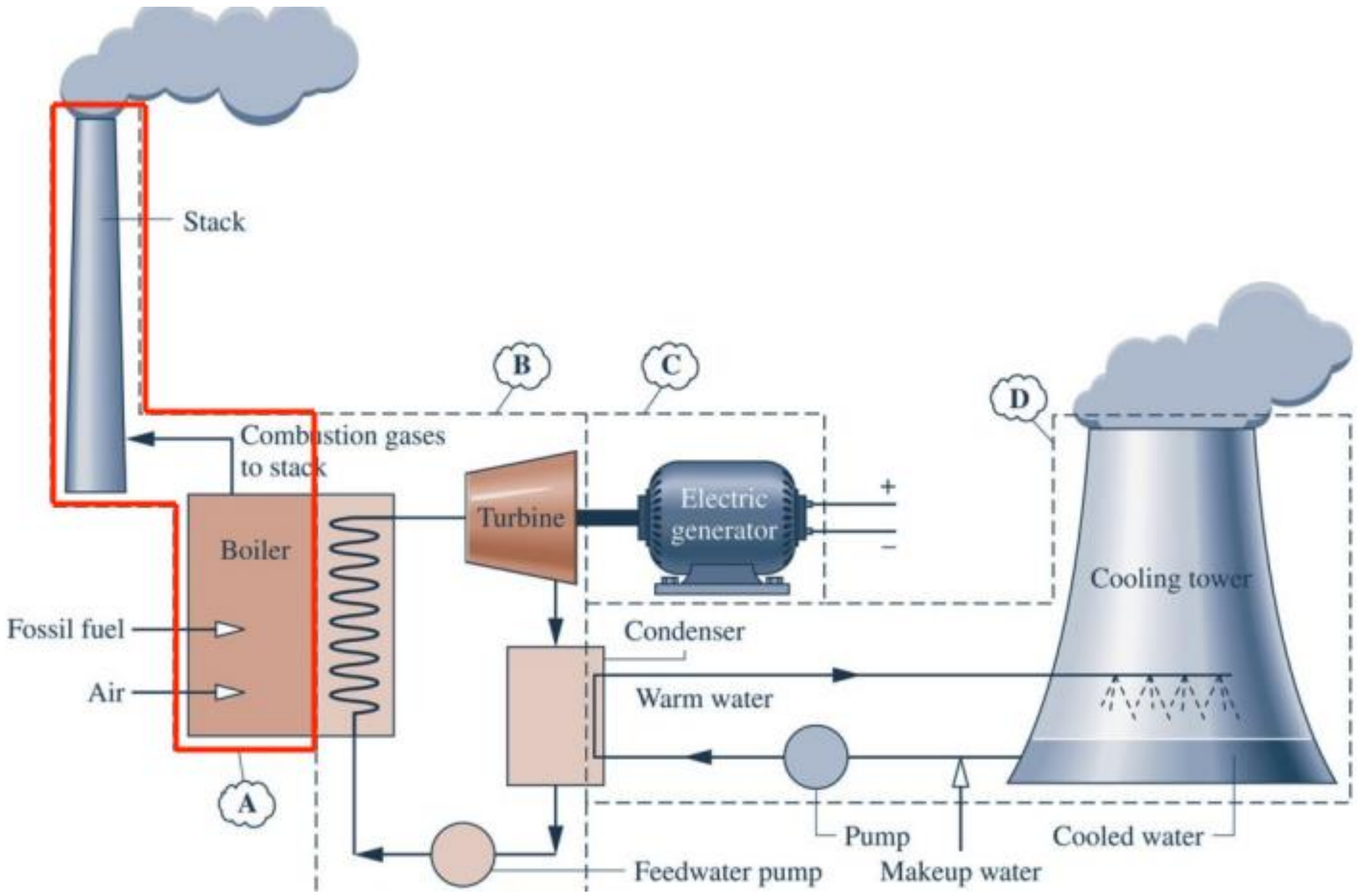
- The area under T-s diagram represents the heat transfer for internally reversible processes.

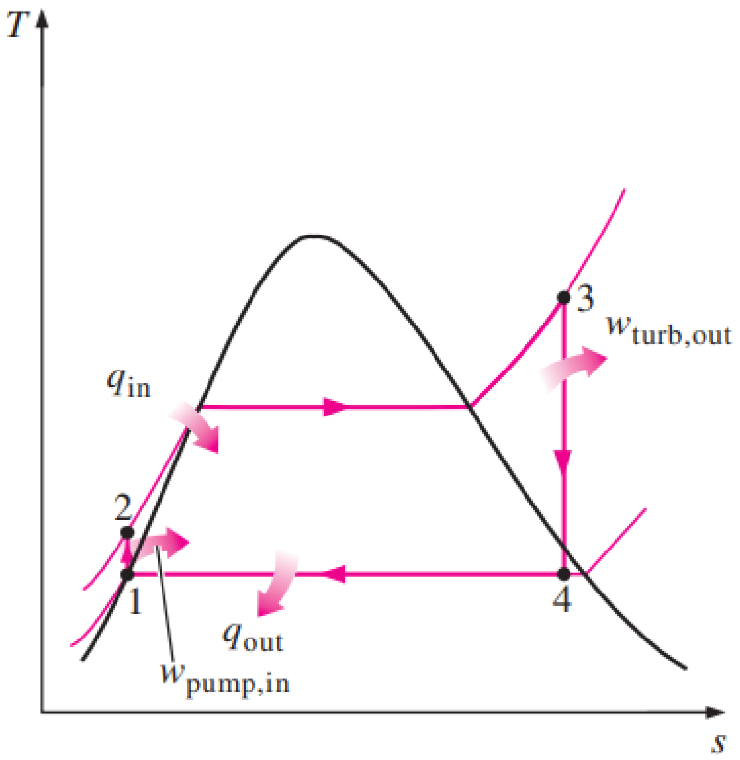
- Area under process curve 2-3 represents the heat transferred to the water in the boiler and the area under the process curve 4-1 represents the heat rejected in the condenser.

- The difference between these two (the area enclosed by the cycle curve) is the net work produced during the cycle.



Rankine Cycle

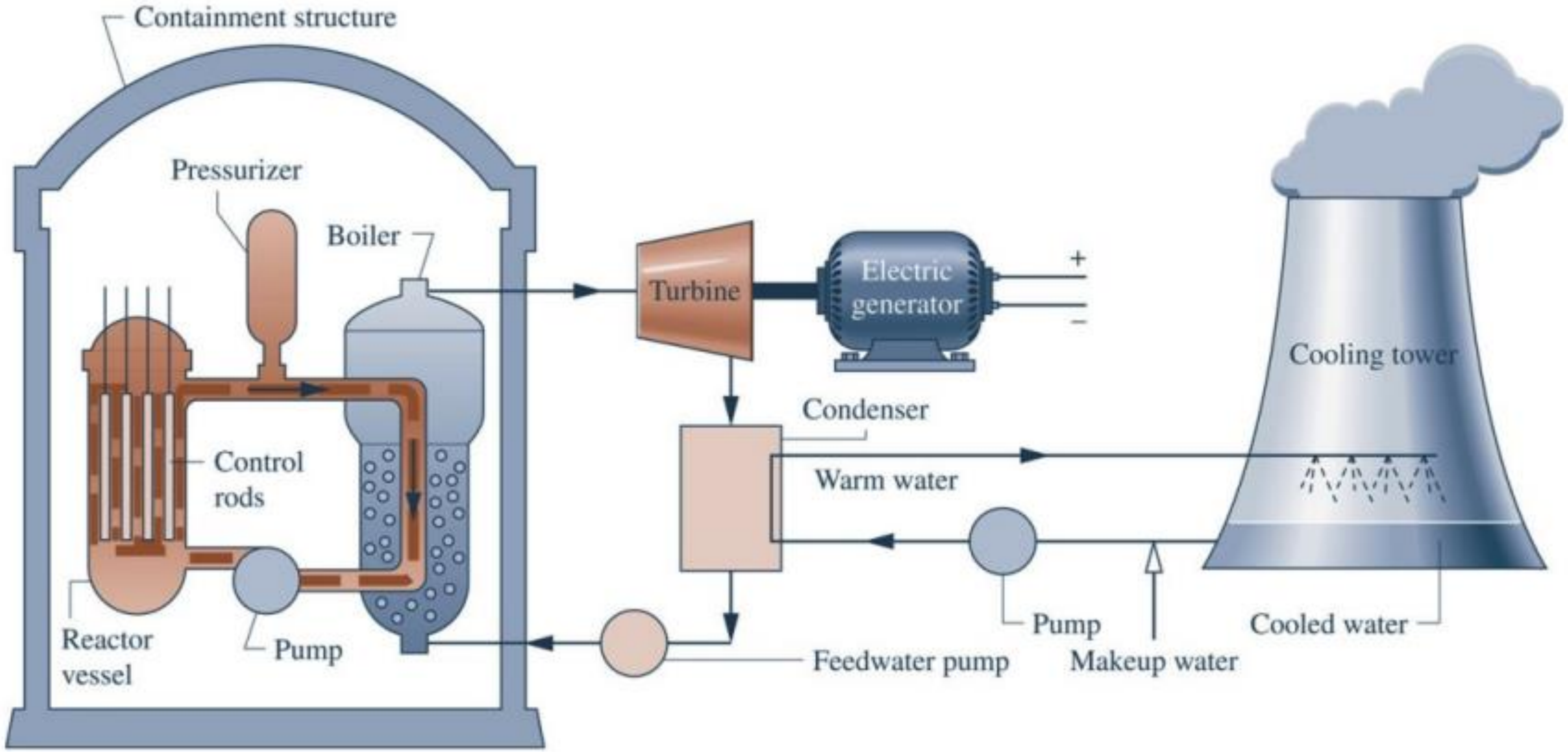


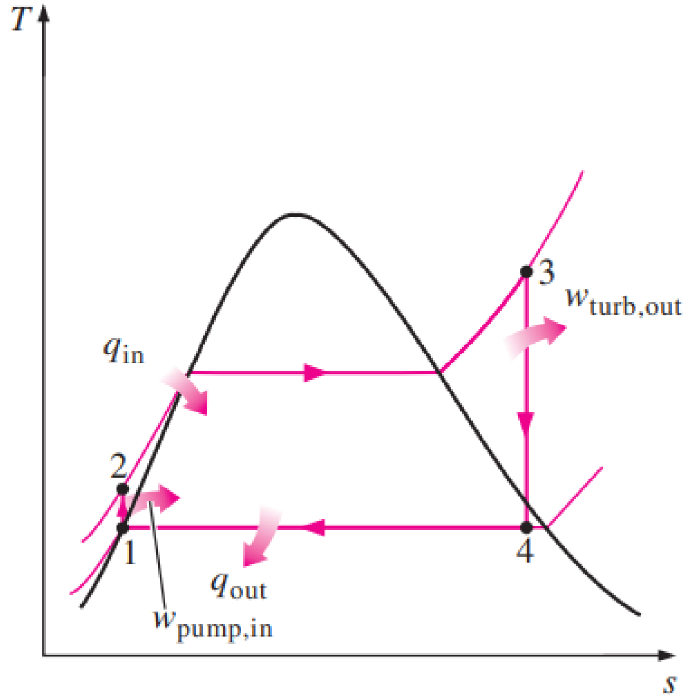


A boiler stack is a critical component of a steam boiler, responsible for emitting the hot gaseous byproducts of combustion safely out of the system.

Rankine Cycle – Nuclear Plant

In nuclear plants, the energy required for vaporization originates in a controlled nuclear reaction.





Energy Analysis of Rankine Cycle

- All the four processes of the Rankine cycle can be analyzed as steady-flow processes. The kinetic and potential energy changes are neglected.

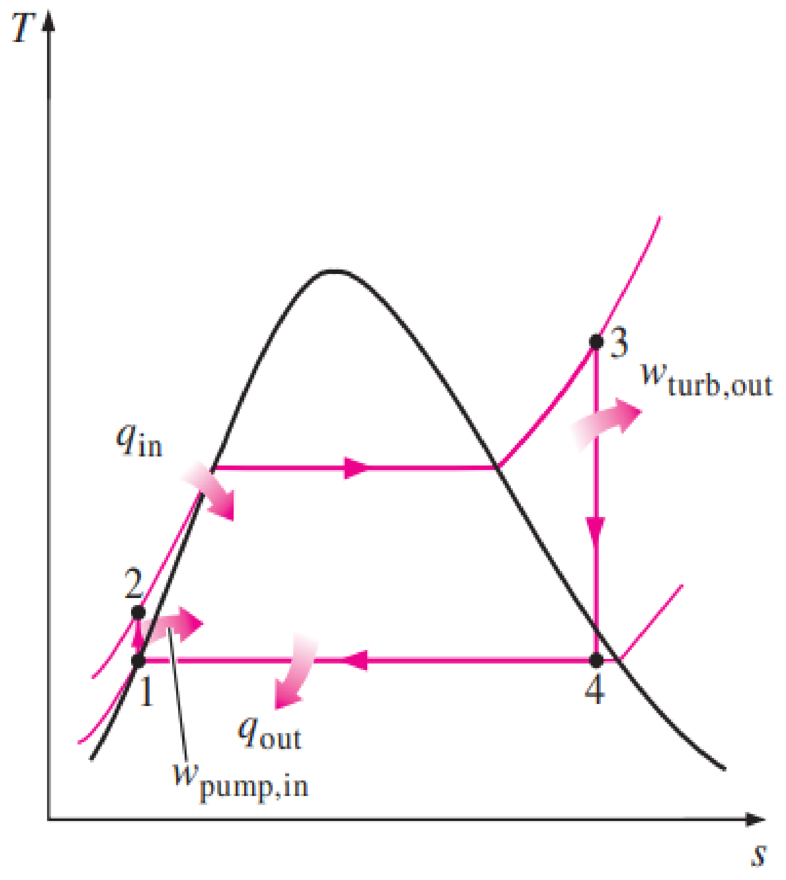
- The steady-flow energy equation per unit mass of steam reduces to :

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

- Boiler and condenser – no W. Pump and the Turbine are assumed to be isentropic.

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

where : $h_1 = h_f$ @ P_1 and $v = v_1 = v_f$ @ P_1

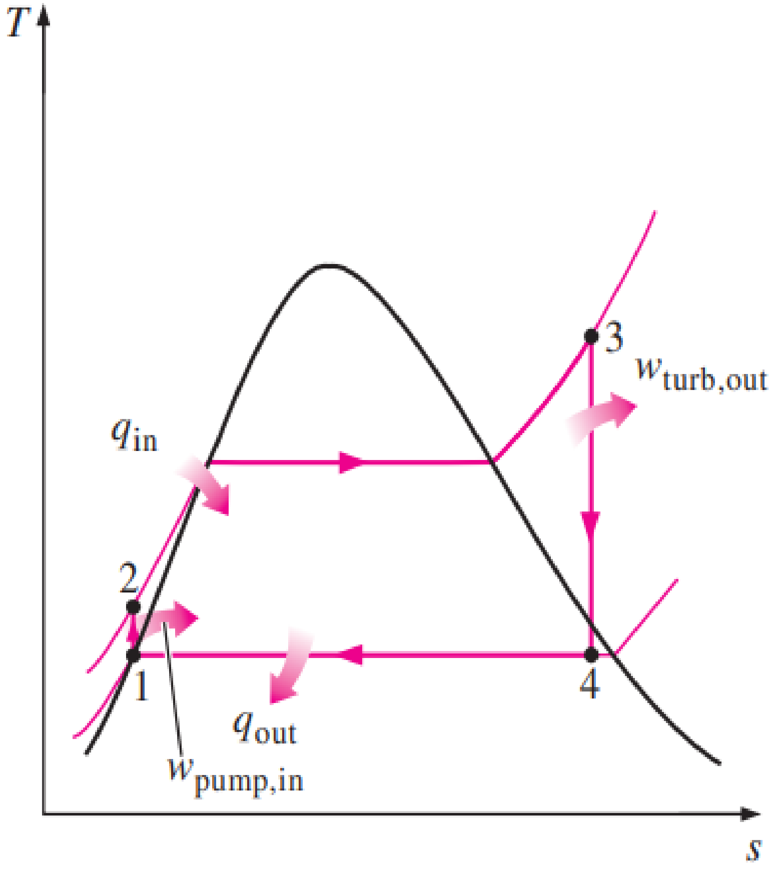


Energy Analysis of Rankine Cycle

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

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

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



- Thermal efficiency of the Rankine cycle is

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

where : $W_{net} = q_{in} - q_{out} = W_{turb,out} - W_{pump,in}$

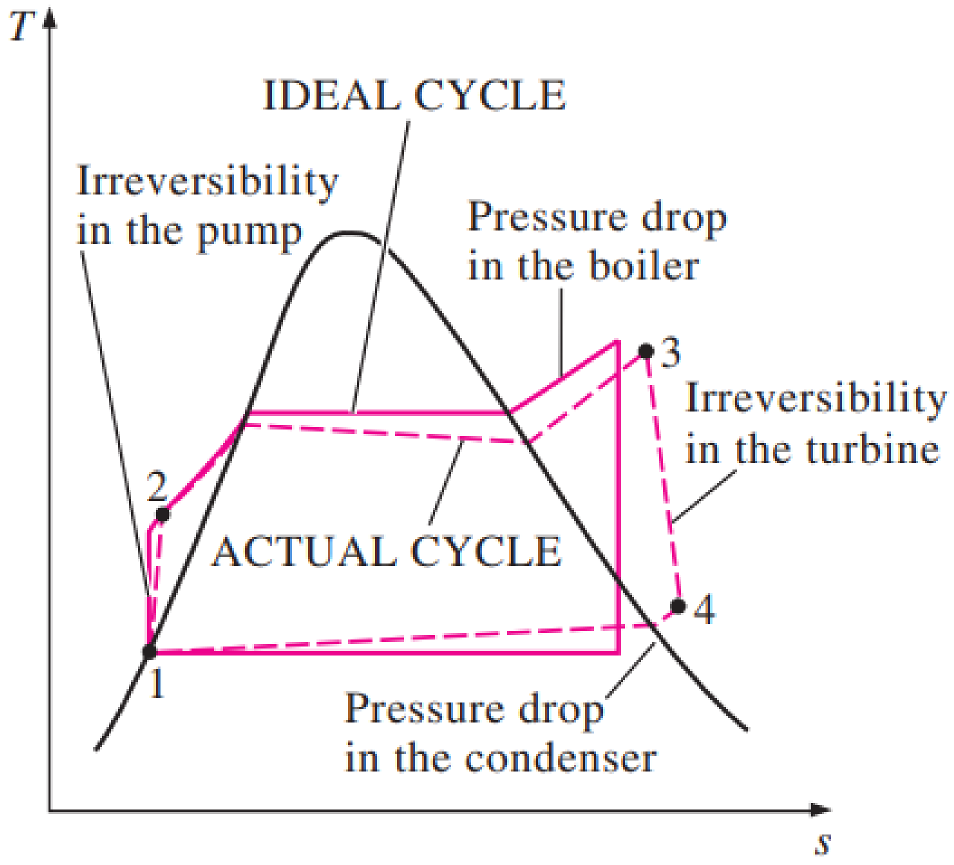
- η_{th} can also be interpreted as the ratio of the area enclosed by the cycle on a T-s diagram to the area under the heat-addition process

Deviations from Theoretical Rankine Cycle

- Fluid friction and heat loss to the surroundings are the two common sources of irreversibilities. Due to this, steam leaves the boiler at a somewhat lower pressure.

- The pressure at the turbine inlet is somewhat lower than that at the boiler exit due to the pressure drop in the connecting pipes.

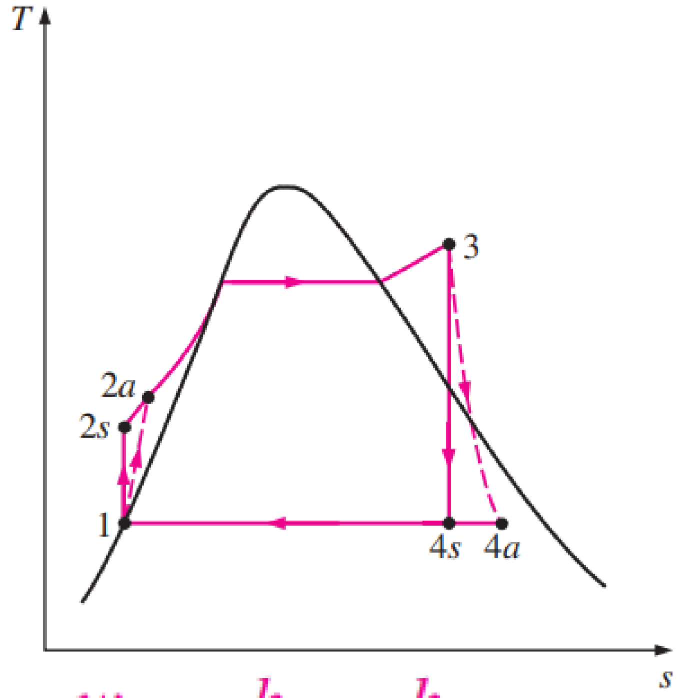
- The pressure drop in the condenser is usually very small. To compensate for these pressure drops, the water must be pumped to a sufficiently higher pressure than the ideal cycle calls for. This requires a larger pump and larger work input to the pump.



Deviations from Theoretical Rankine Cycle

- The other major source of irreversibility is the heat loss from the steam to the surroundings as the steam flows through various components.

- To maintain the same level of net work output, more heat needs to be transferred to the steam in the boiler to compensate for these undesired heat losses. As a result, cycle efficiency decreases.



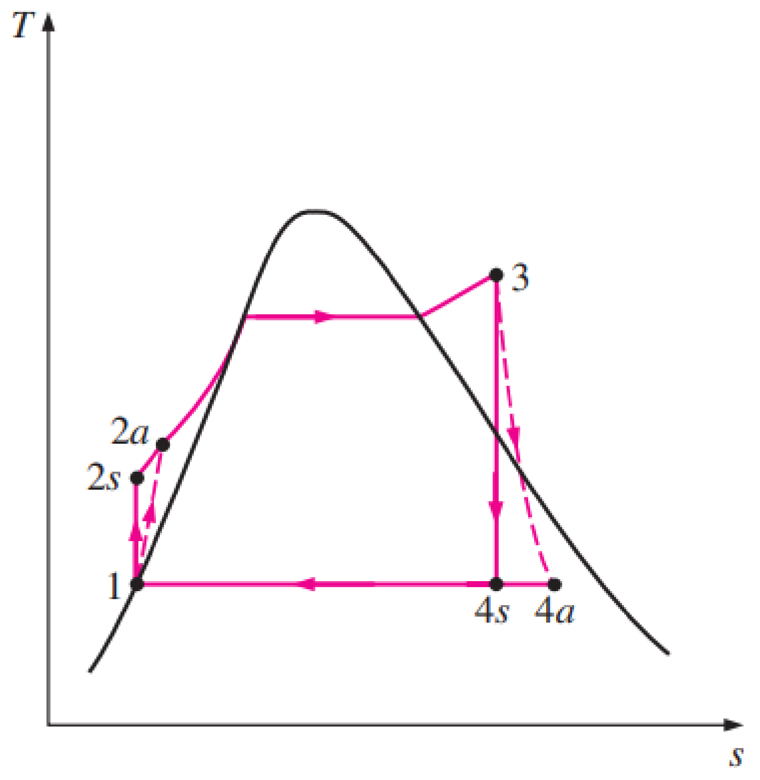
- A pump requires a greater work input, and a turbine produces a smaller work output as a result of irreversibilities.
- Isentropic Efficiency :

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

- where states 2a and 4a are the actual exit states of the pump and the turbine, respectively, and 2s and 4s are the corresponding states for the isentropic case

Deviations from Theoretical Rankine Cycle

- In actual condensers, the liquid is usually subcooled to prevent the **onset of cavitation**, the rapid vaporization and condensation of the fluid at the low-pressure side of the pump impeller, which may damage it.

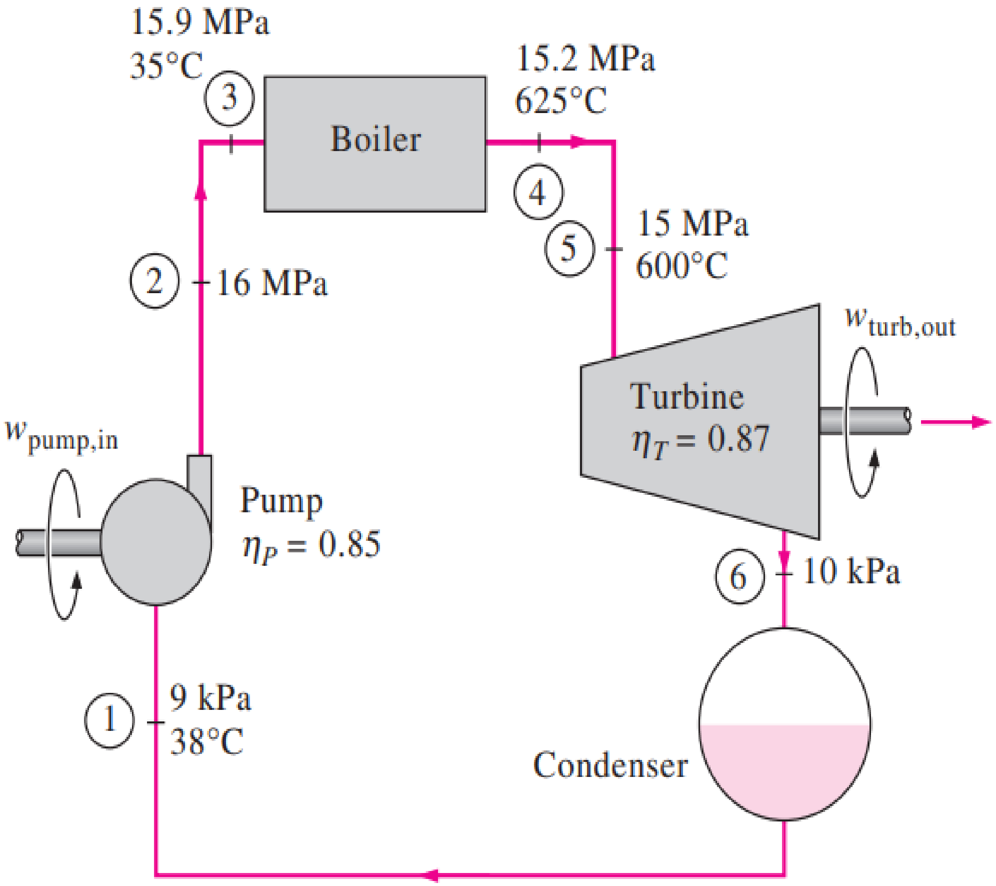


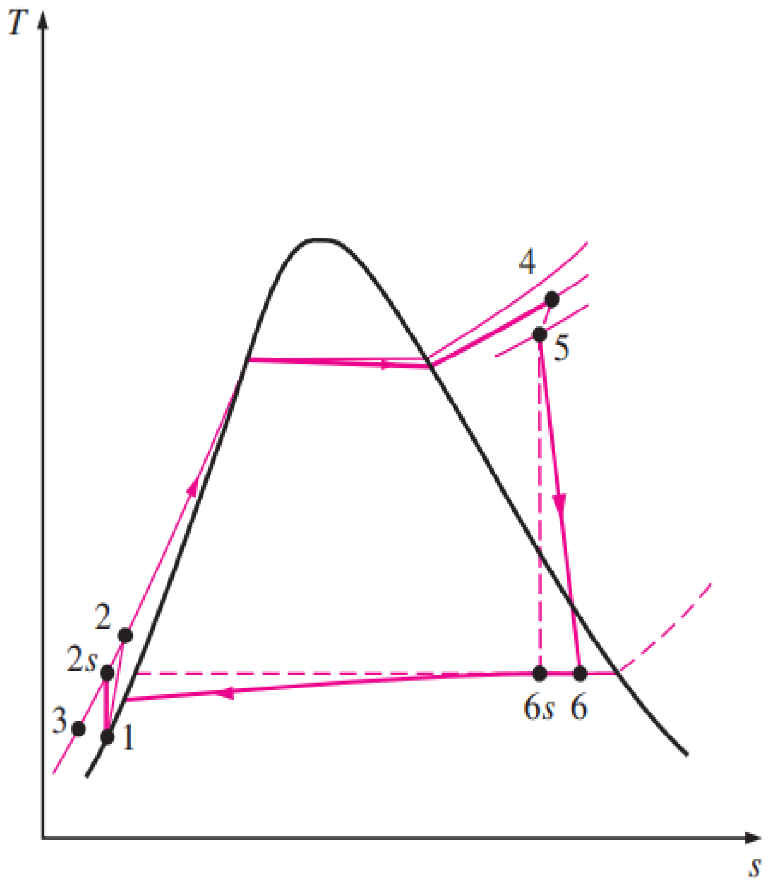
- Additional losses occur at the bearings between the moving parts as a result of friction.

- Steam that leaks out during the cycle and air that leaks into the condenser represent two other sources of loss.

- Also the power consumed by the auxiliary equipment such as fans that supply air to the furnace should also be considered in evaluating the overall performance of power plants.

Deviations from Theoretical Rankine Cycle





Making Rankine Cyle Efficient

- Small increases in thermal efficiency can mean large savings from the fuel requirements.

- All the modifications to increase the thermal efficiency of a power cycle is the same:

  i) Increase the average temperature at which heat is transferred to the working fluid in the boiler, or decrease the average temperature at which heat is rejected from the working fluid in the condenser.
  ii) That means, the average fluid temperature should be as high as possible during heat addition and as low as possible during heat rejection

- Three ways to make simple Rankine cycle more efficient.

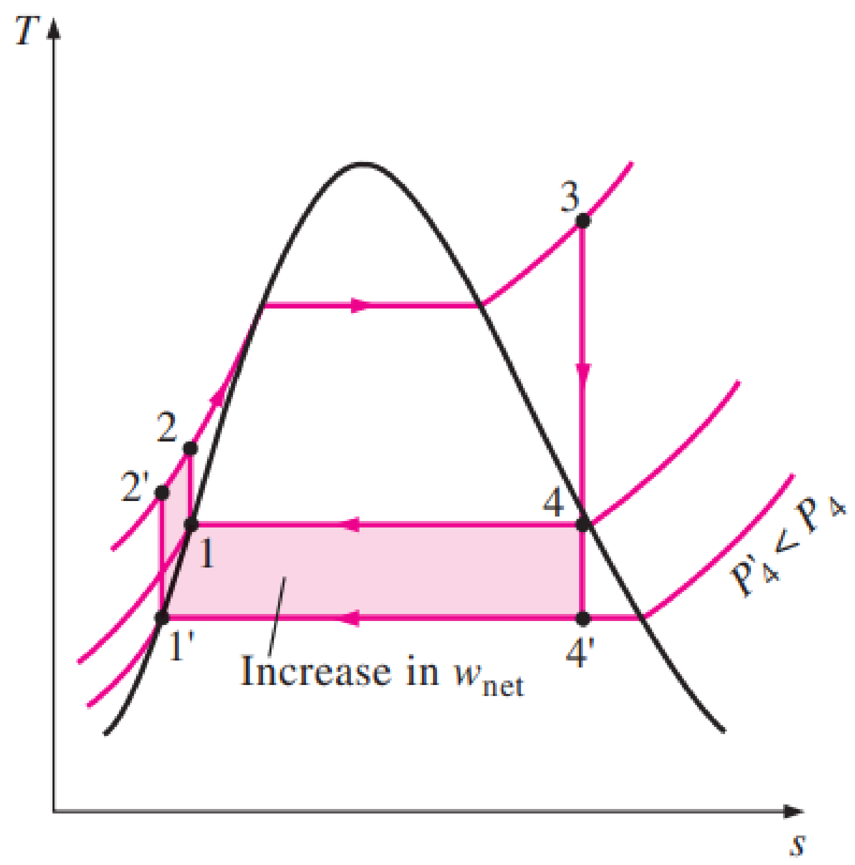
Making Rankine Cycle Efficient
I) Lower Condenser Pressure, $T_{low, avg}$

- Lowering the operating pressure of the condenser lowers the temperature of the steam, and thus the temperature at which heat is rejected. The turbine inlet state is maintained the same.

- The colored area on this diagram represents the increase in net work output as a result of lowering the condenser pressure from P4 to P4’ .

- The heat input requirements also increases, area under 2-2’ but this increase is very small.

- Thus the overall effect of lowering the condenser pressure is an increase in the η_{th} of the cycle.

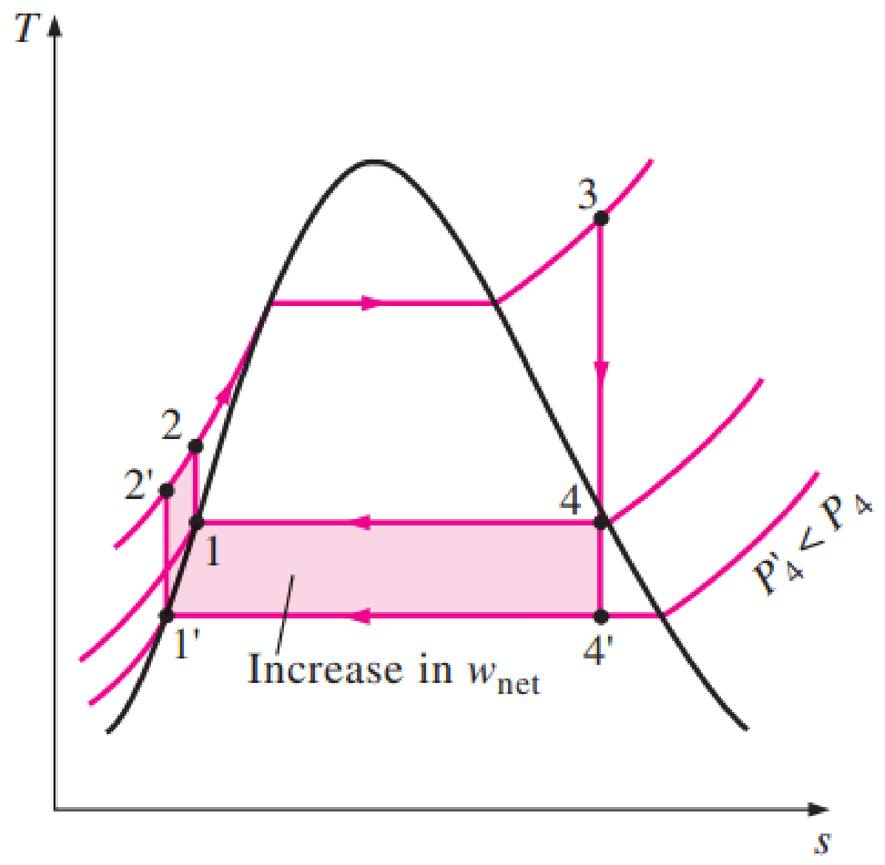


Making Rankine Cycle Efficient
I) Lower Condenser Pressure, $T_{low,\,avg}$

- Operating at lower pressures well below atmospheric pressure is not a major problem since it’s a closed loop.

- However, there is a lower limit on the condenser pressure that can be used. It cannot be lower than the saturation pressure corresponding to the temperature of the cooling medium.

- Lowering the condenser pressure - Air leakage into the condenser. It increases the moisture content of the steam at the final stages of the turbine. – Undesirable for turbine as it decreases the turbine efficiency and erodes the turbine blades.

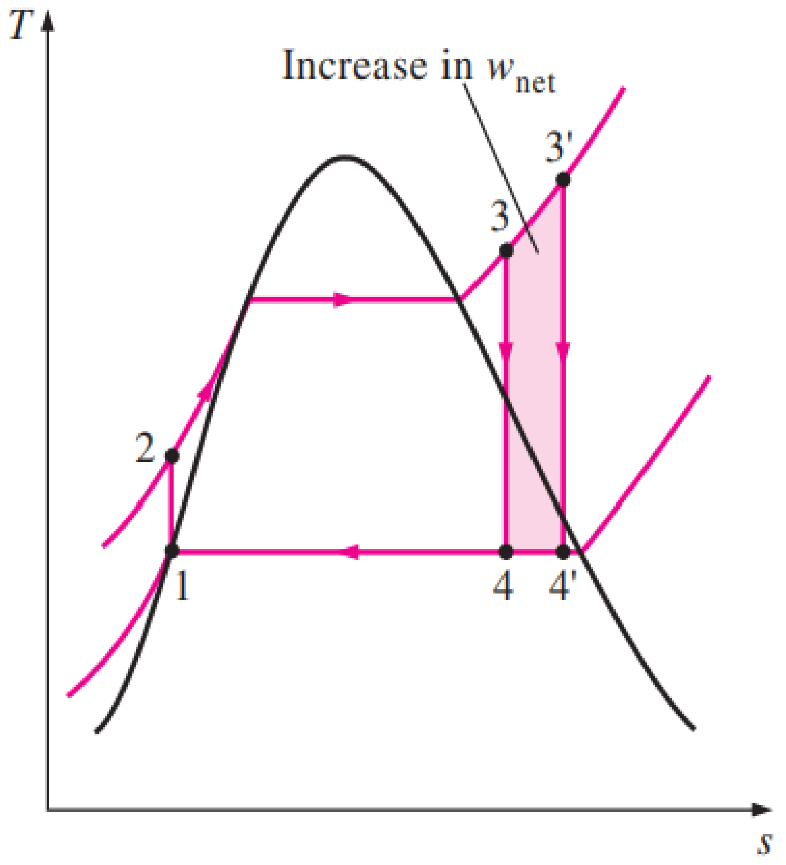


Making Rankine Cyle Efficient
II) Superheating (Increases $T_{high,avg}$)

- Increase $T_{high,avg}$: Increase temperature at which heat is transferred to steam without increasing the boiler pressure by superheating the steam to high temperatures – Increase in net work. Area under 3-3'. This results in both increase net work and heat input increase result in increase in η_{th}

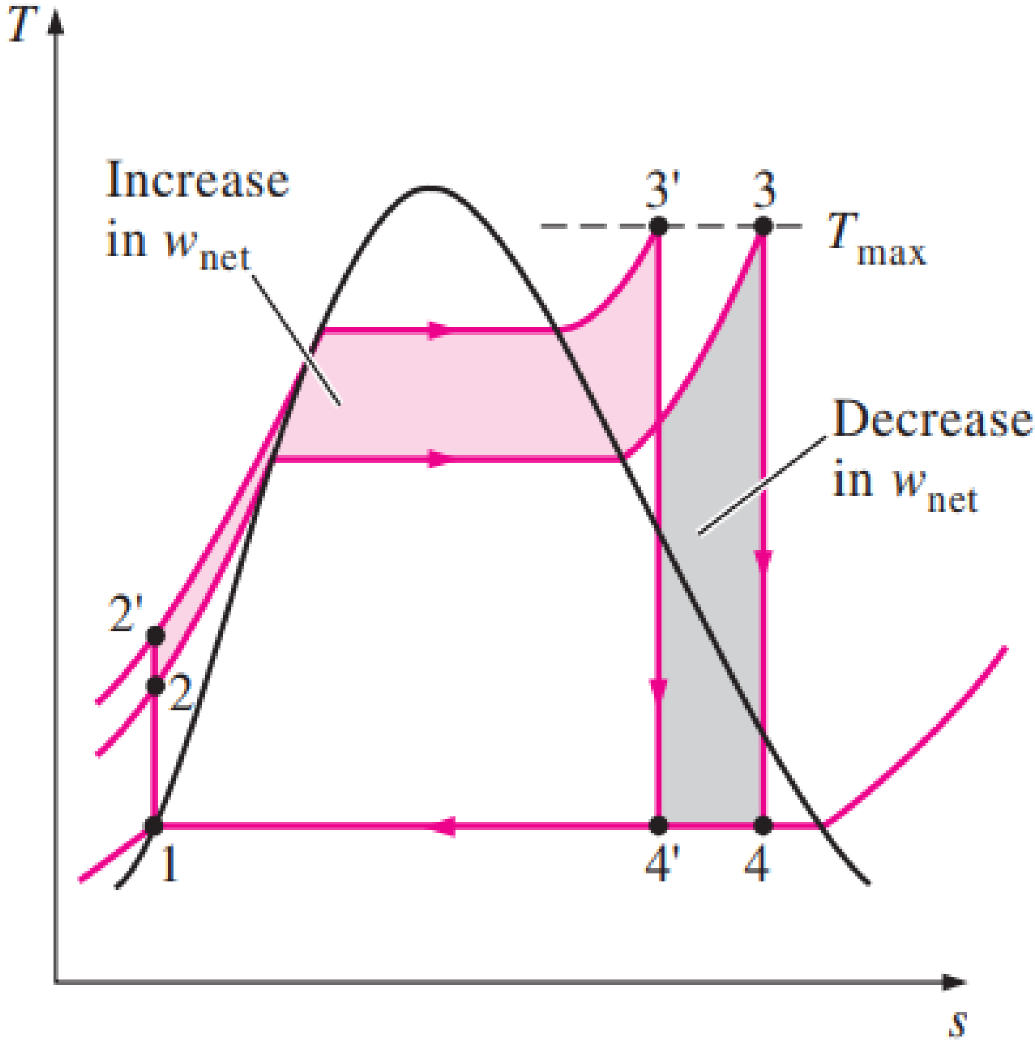
- Also Superheating the steam to higher temperatures decreases the moisture content of the steam at the turbine exit.

- The temperature is limited by metallurgical considerations 620°C . Any increase in this value depends on improving the present materials or finding new ones that can withstand higher temperatures. Ceramics are very promising in this regard.



Making Rankine Cyle Efficient
III) Increasing the Boiler Pressure

- Increase the operating pressure of the boiler – raises the average temperature at which heat is transferred to the steam and thus raises the thermal efficiency of the cycle.
- For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases.
- This undesirable side effect can be corrected, however, by reheating the steam.



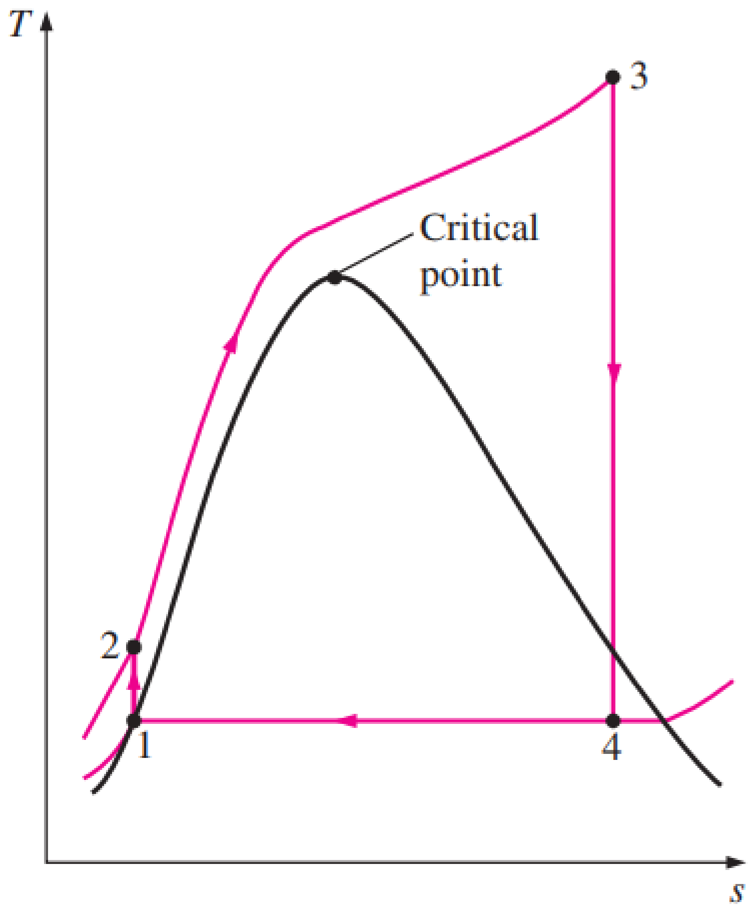
Making Rankine Cyle Efficient
Supercritical Rankine Cycle

- Operating pressures of boilers have gradually increased from about 2.7 MPa in 1922 to over 30 MPa today generating enough steam to produce a net power output of 1000 MW or more in a large power plant.

- Modern plant operates at supercritical pressure of 22 MPa with η_{th} of 40 % for fossil fuel plants and 34 % for nuclear fuel plants.

- 150 supercritical-pressure steam power plants in USA.

- The lower efficiencies of nuclear power plants are due to the lower maximum temperatures used in those plants for safety reasons.



Reheat Rankine Cyle

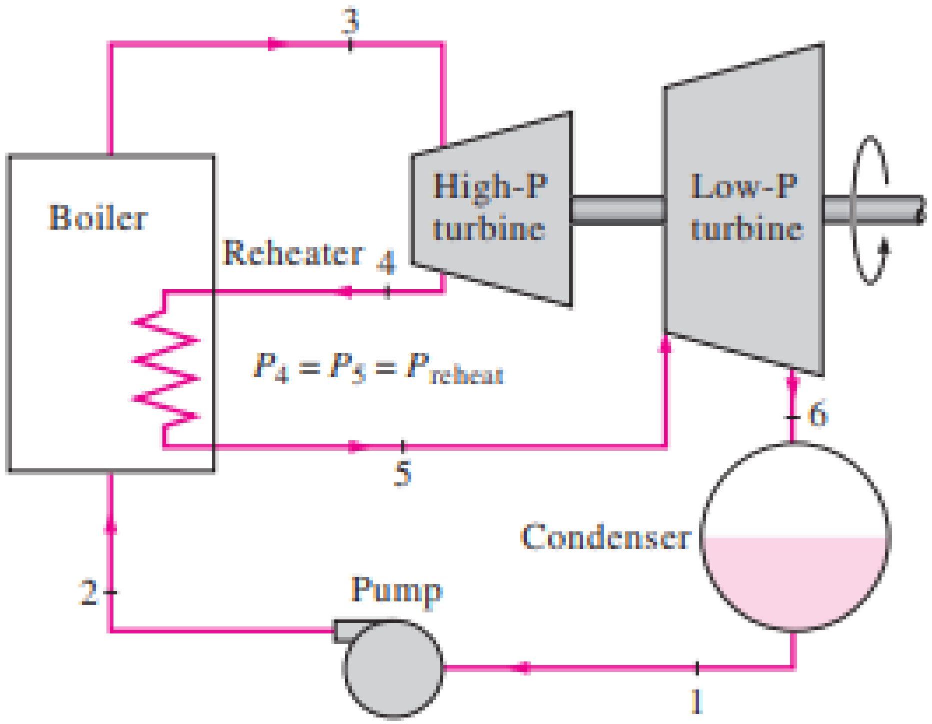
- Increase in the boiler pressure increases the thermal efficiency of the Rankine cycle – it increases the moisture content of the

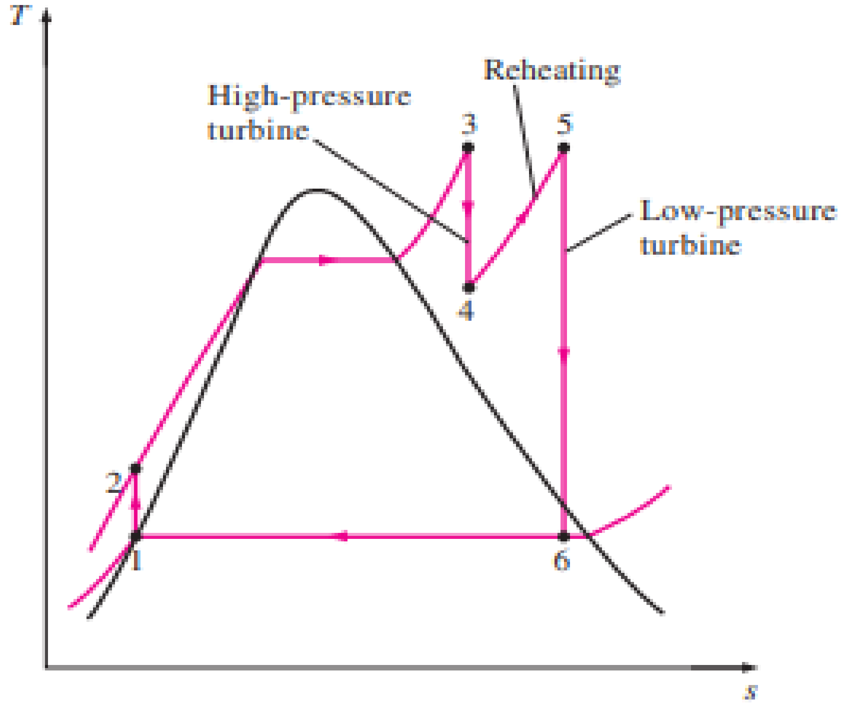
- Can we take advantage of the increased efficiencies at higher boiler pressures without excessive moisture at the final stages of the turbine – 2 Possibilities

1. Superheat the steam to very high temperatures before it enters the turbine.- This would increase the efficiency – not viable as it requires raising the steam temperature to metallurgically unsafe levels.

2. Expand the steam in the turbine in two stages, and reheat.

Reheat Rankine Cyle





Reheat Rankine Cyle

- Here the expansion process takes place in two stages. HP to to an intermediate pressure – reheat at constant pressure, usually to the inlet temperature of the first turbine stage.

- Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure.

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

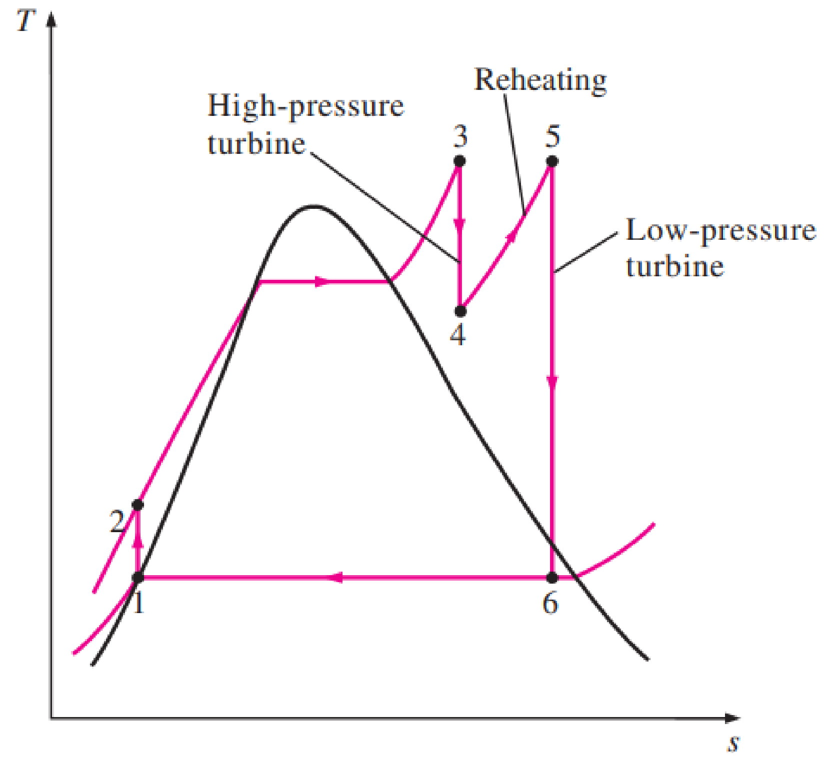
$$w_{\text{turb,out}} = w_{\text{turb,I}} + w_{\text{turb,II}} = (h_3 - h_4) + (h_5 - h_6)$$

Reheat Rankine Cyle

- The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent 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.

- As the number of stages is increased, the expansion and reheat processes approach an isothermal process at the maximum temperature.

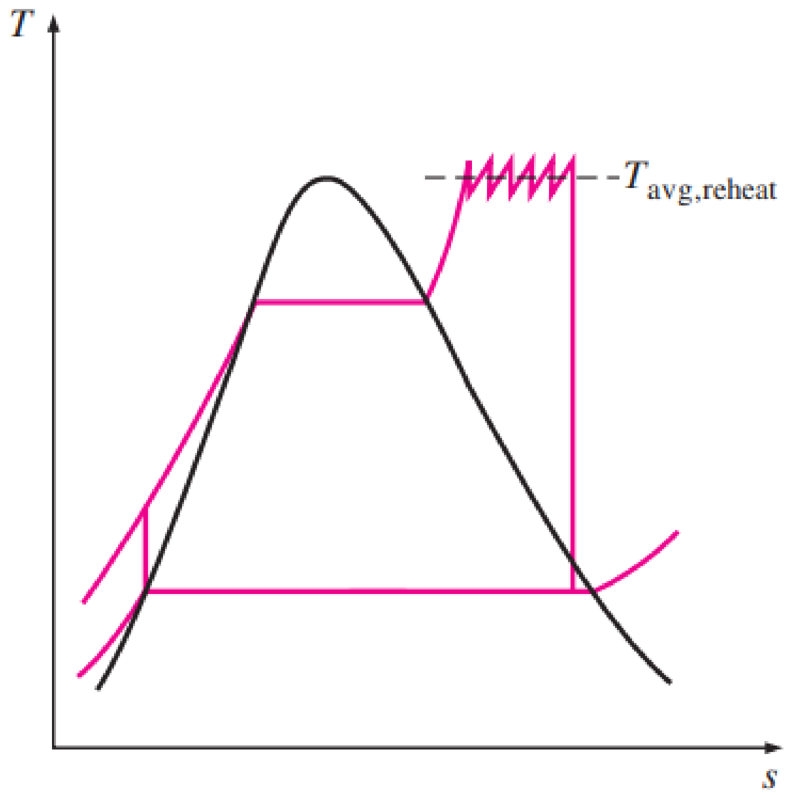


Reheat Rankine Cyle

- 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 of single reheat.

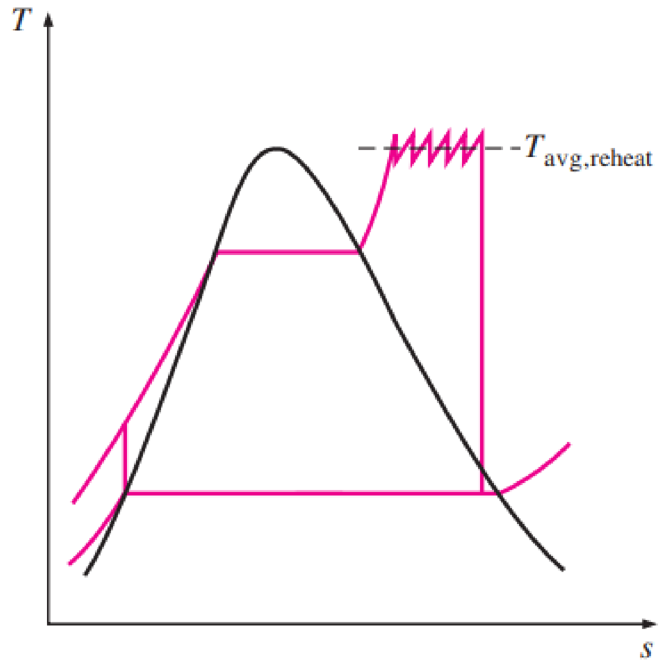
- If the turbine inlet pressure is not high enough, double reheat would result in superheated exhaust. This is undesirable as it would cause the average temperature for heat rejection to increase – decrease in efficiency

- Double reheat is used only on supercritical-pressure (P> 22.06 MPa) power plants. A third reheat gain is too small to justify the added cost and complexity.



Reheat Rankine Cyle

- Reheat cycle : introduced in the mid-1920s, but it was abandoned in the 1930s due to difficulties
- Increase in boiler pressures reintroduced single reheat in the late 1940s and double reheat in the early 1950s.
- The reheat temperatures are very close or equal to the turbine inlet temperature. The optimum reheat pressure is about one-fourth of the maximum cycle pressure.
- If we had materials that could withstand sufficiently high temperatures - no need for the reheat cycle.



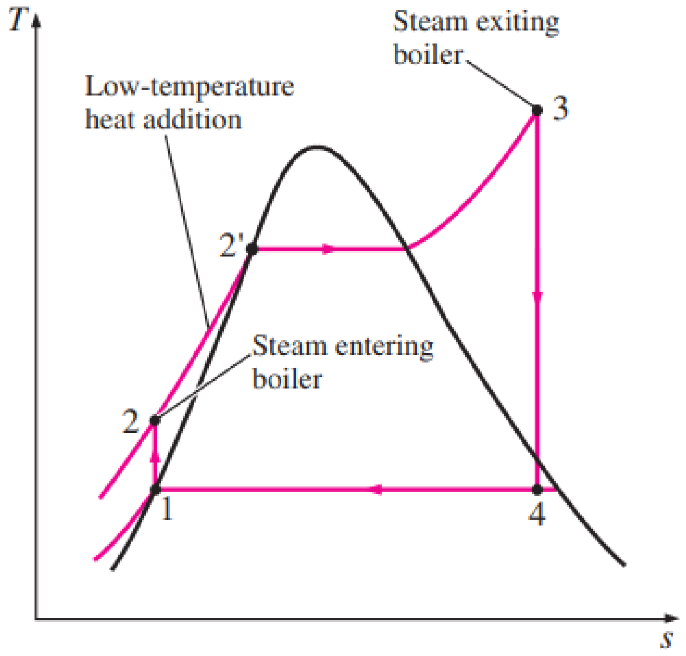
Regenerative Rankine Cyle

- 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

- The temperature of the liquid leaving the pump (called the feedwater) may be increased before it enters the boiler.

- Transfer heat to feedwater from the expanding steam in a counterflow heat exchanger -Regeneration

- Impractical solution as it is difficult to design such a heat exchanger : Also it would increase the moisture content of the steam at the final stages of the turbine

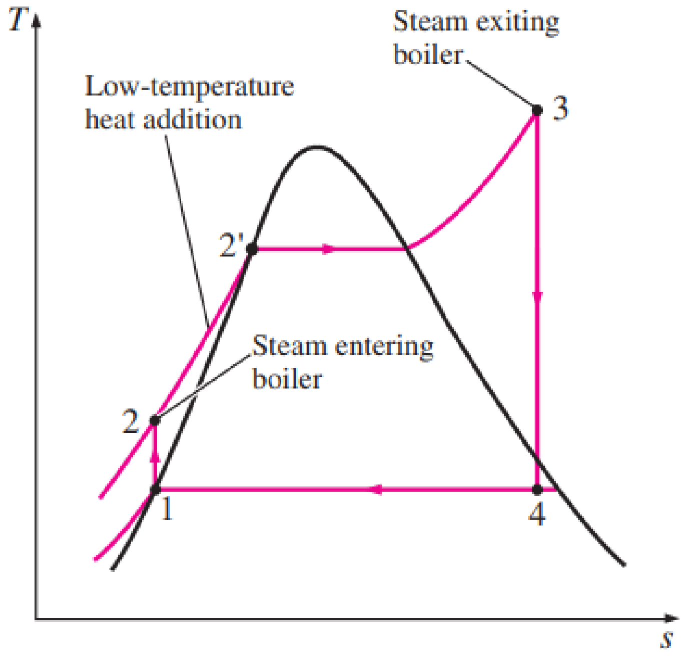


Regenerative Rankine Cyle

- A practical regeneration process in steam power plants is accomplished by extracting, or “bleeding,” steam 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).

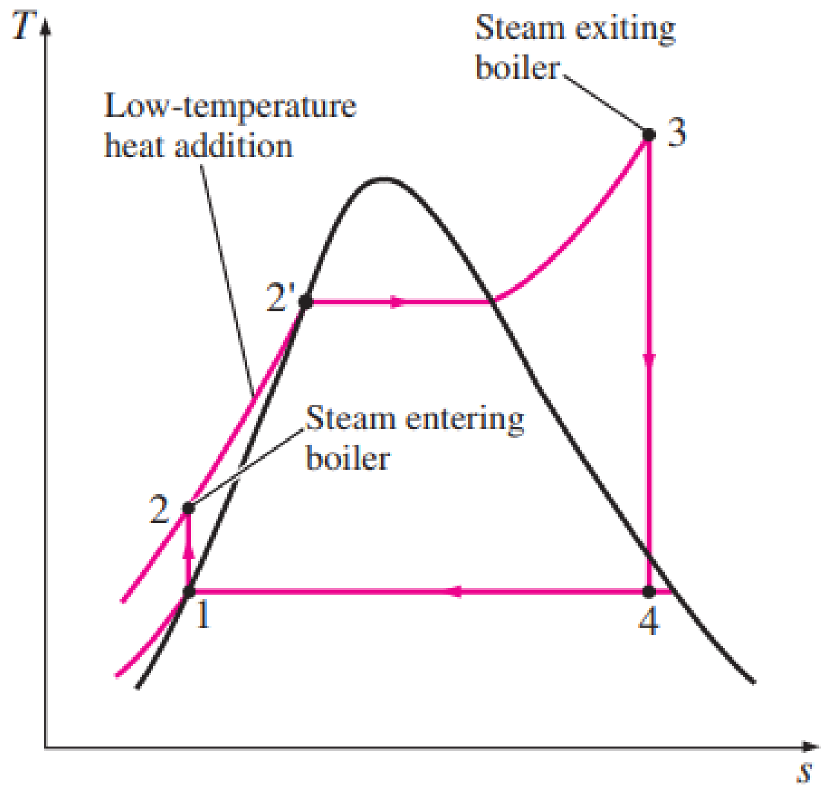
- Regeneration improves cycle efficiency, and also provides a convenient means of de-aerating the feedwater (removing the air that leaks in at the condenser) to prevent corrosion in the boiler.



Regenerative Rankine Cyle

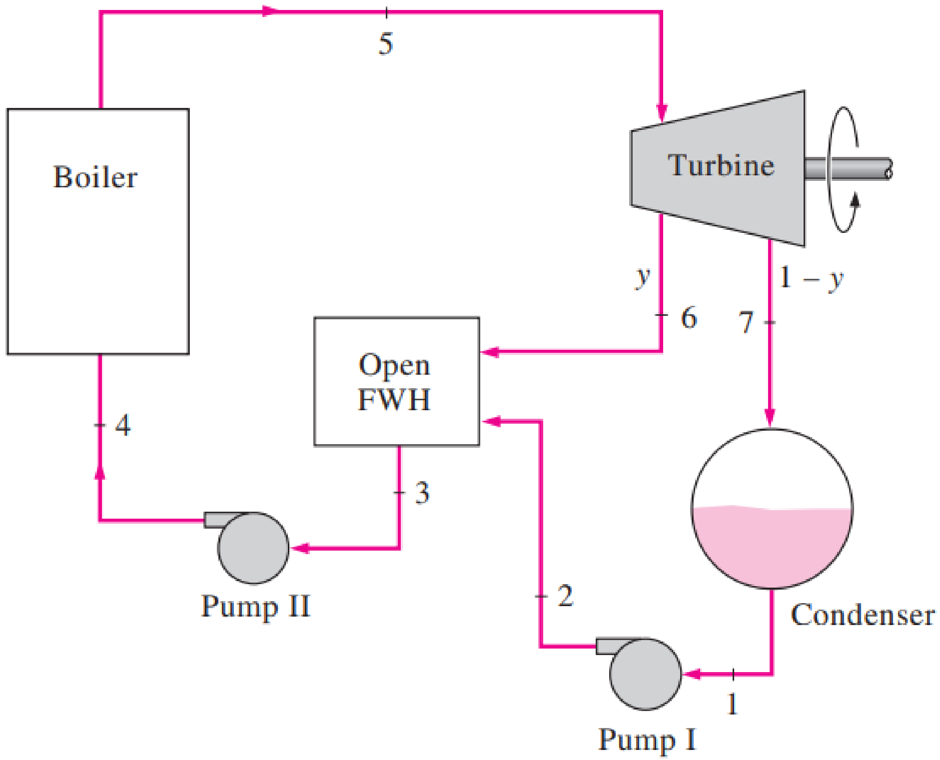
- Regeneration also helps control the large volume flow rate of the steam at the final stages of the turbine (due to the large specific volumes at low pressures). Therefore, regeneration has been used in all modern steam power plants.

- 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 Heater Rankine Cyle

- 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.
- In an ideal regenerative Rankine cycle, steam enters the turbine at the boiler pressure (state 5) and expands isentropically to an intermediate pressure, state 6.

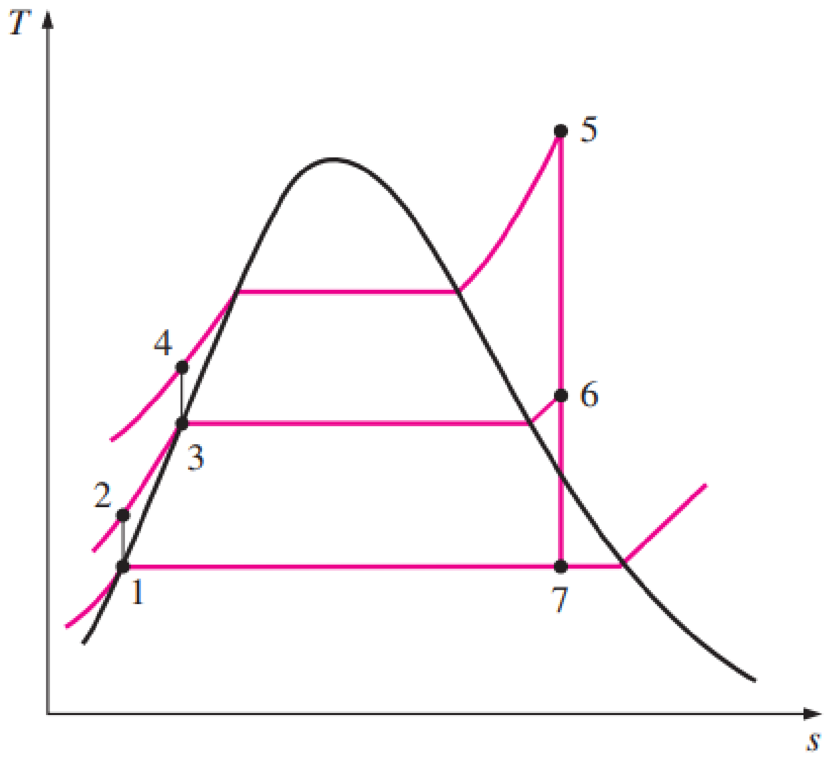


Open Feedwater Heater Rankine Cyle

- Some steam is extracted at this state and routed to the feedwater heater, while the remaining steam continues to expand isentropically to the condenser pressure (state 7).

- This steam leaves the condenser as a saturated liquid at the condenser pressure (state 1).

- The condensed water, which is also called the feedwater, then enters an isentropic pump, where it is compressed to the feedwater heater pressure (state 2) and is routed to the feedwater heater, where it mixes with the steam extracted from the turbine.



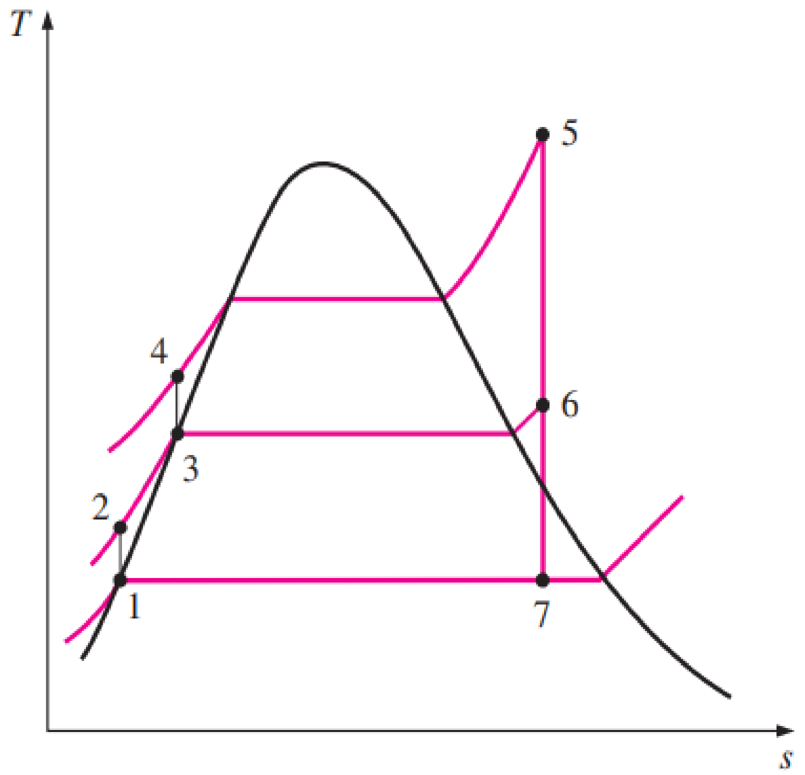
Open Feedwater Heater Rankine Cyle

- The fraction of the steam extracted is such that the mixture leaves the heater as a saturated liquid at the heater pressure (state 3).

- A second pump raises the pressure of the water to the boiler pressure (state 4).

- The cycle is completed by heating the water in the boiler to the turbine inlet state (state 5).

- For each 1 kg of steam leaving the boiler, y kg expands partially in the turbine and is extracted at state 6. The remaining (1-y) kg expands completely to the condenser pressure.



Open Feedwater Heater Rankine Cyle – Energy analysis

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

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

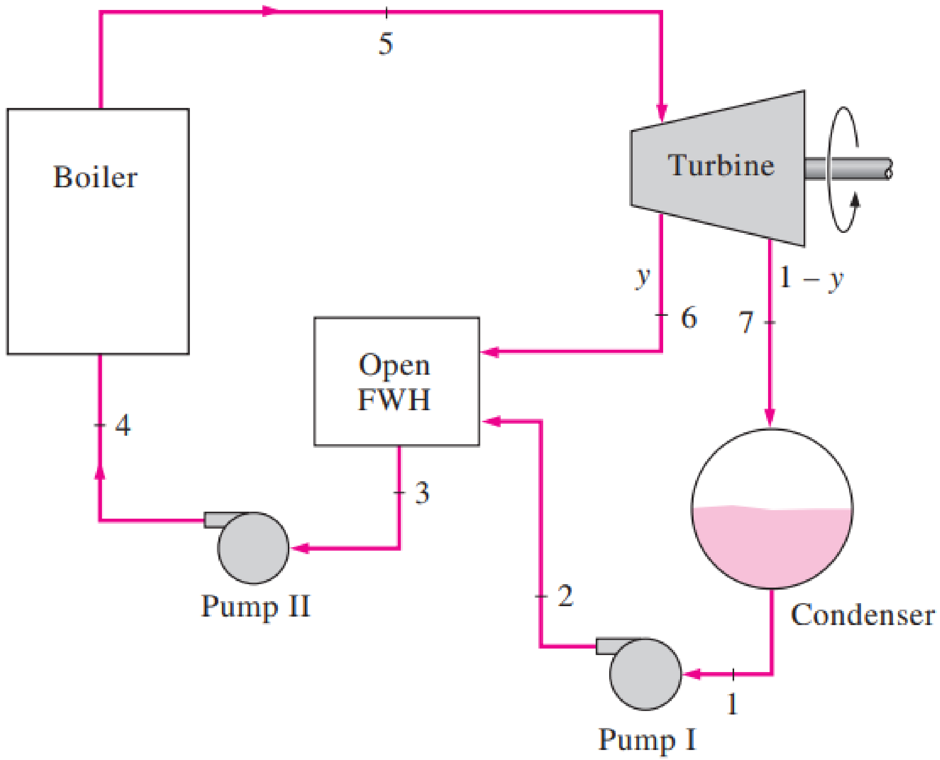
$$w_{turb,out} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

$$w_{pump,in} = (1 - y)w_{pump\ I,in} + w_{pump\ II,in}$$

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

$$w_{pump\ I,in} = v_1(P_2 - P_1)$$

$$w_{pump\ II,in} = v_3(P_4 - P_3)$$



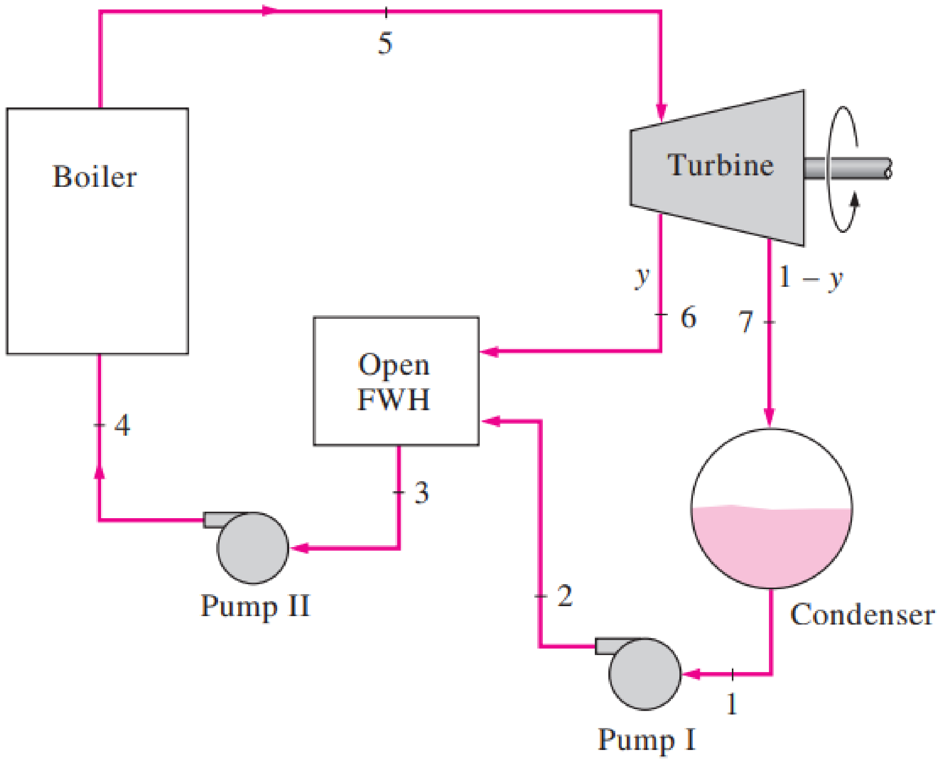
Open Feedwater Heater Rankine Cyle

- The thermal efficiency of the Rankine cycle increases as a result of regeneration.

- The cycle efficiency increases further as the number of feedwater heaters is increased.

- Many large plants in operation today use as many as eight feedwater heaters. The optimum number of feedwater heaters is determined from economical considerations.

- Use of an additional feedwater heater cannot be justified unless it saves more from the fuel costs than its own cost.

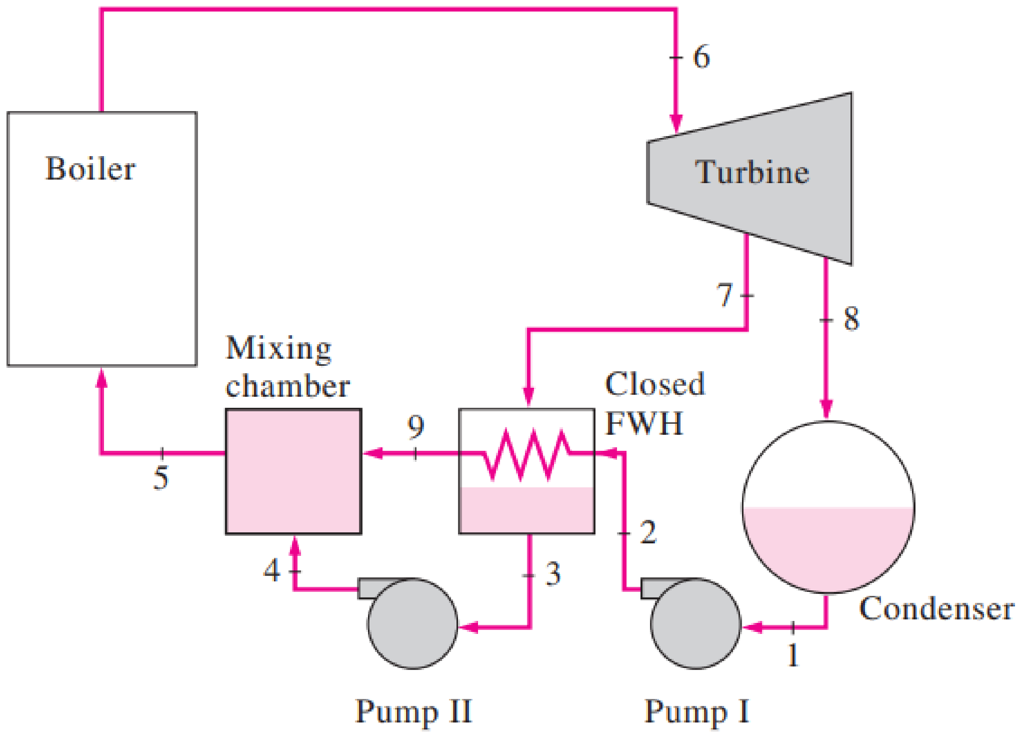


Closed Feedwater Heater Rankine Cyle

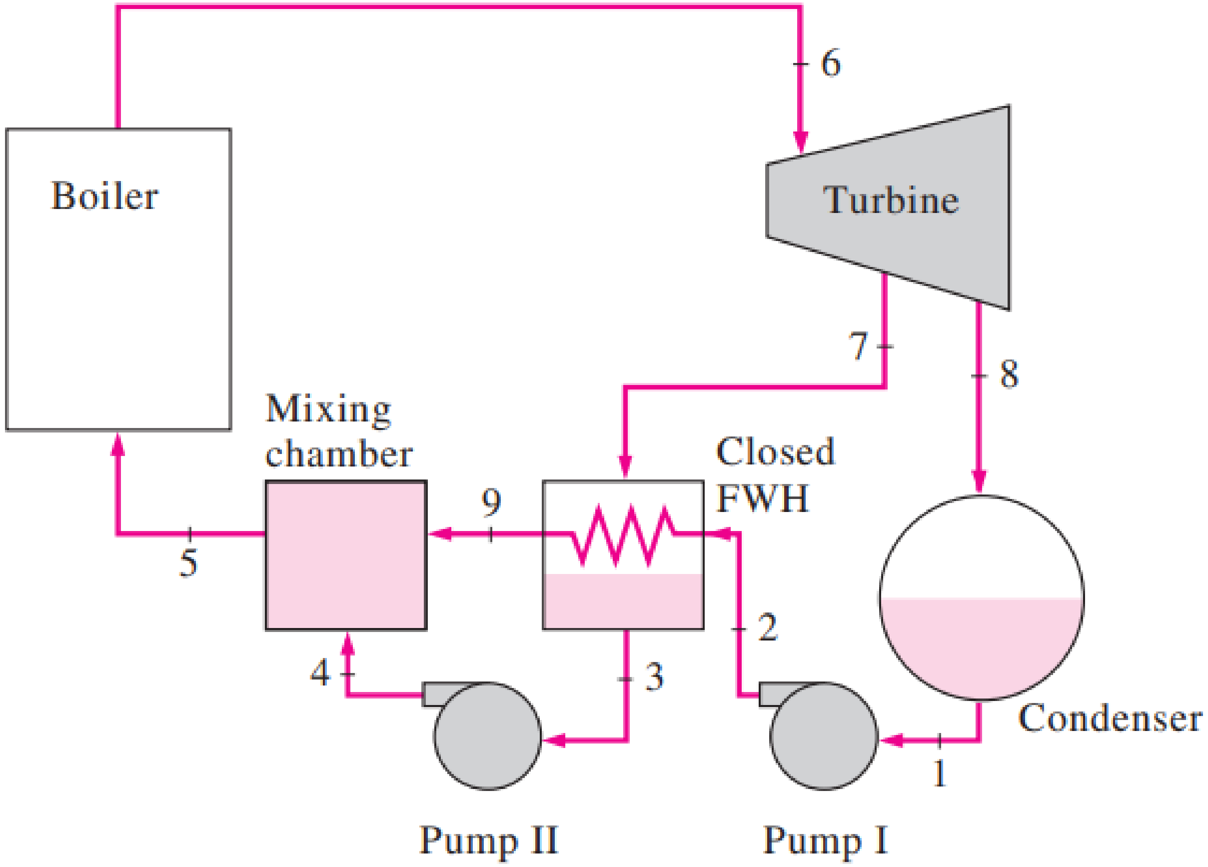
- In the Closed feedwater heaters, heat is transferred from the extracted steam to the feedwater without any mixing taking place.

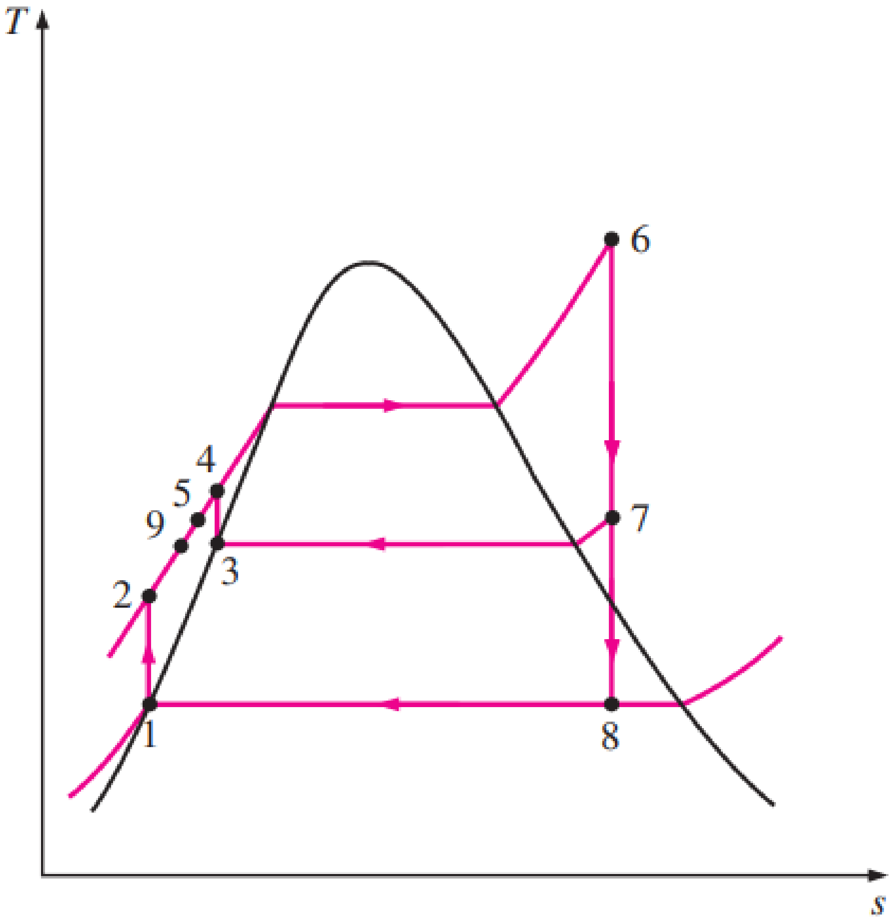
- The two streams now can be at different pressures, since they do not mix.

- In an ideal case, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.



Closed Feedwater Heater Rankine Cyle



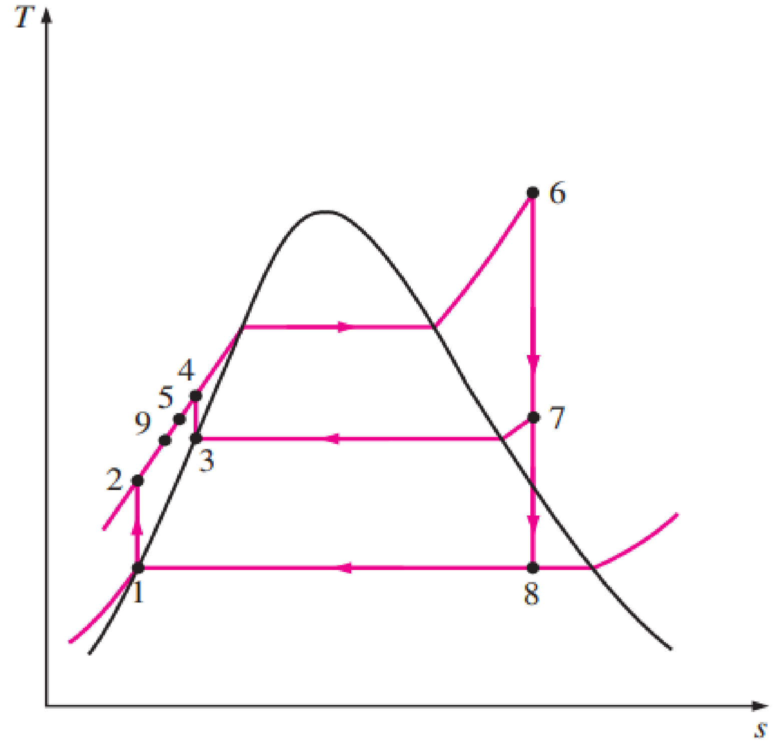


Closed Feedwater Heater Rankine Cyle

- In actual power plants, the feedwater leaves the heater below the exit temperature of the extracted steam because a temperature difference of at least a few degrees is required for any effective heat transfer to take place.

- The condensed steam is then either pumped to the feedwater line or routed to another heater or to the condenser through a device called a trap.

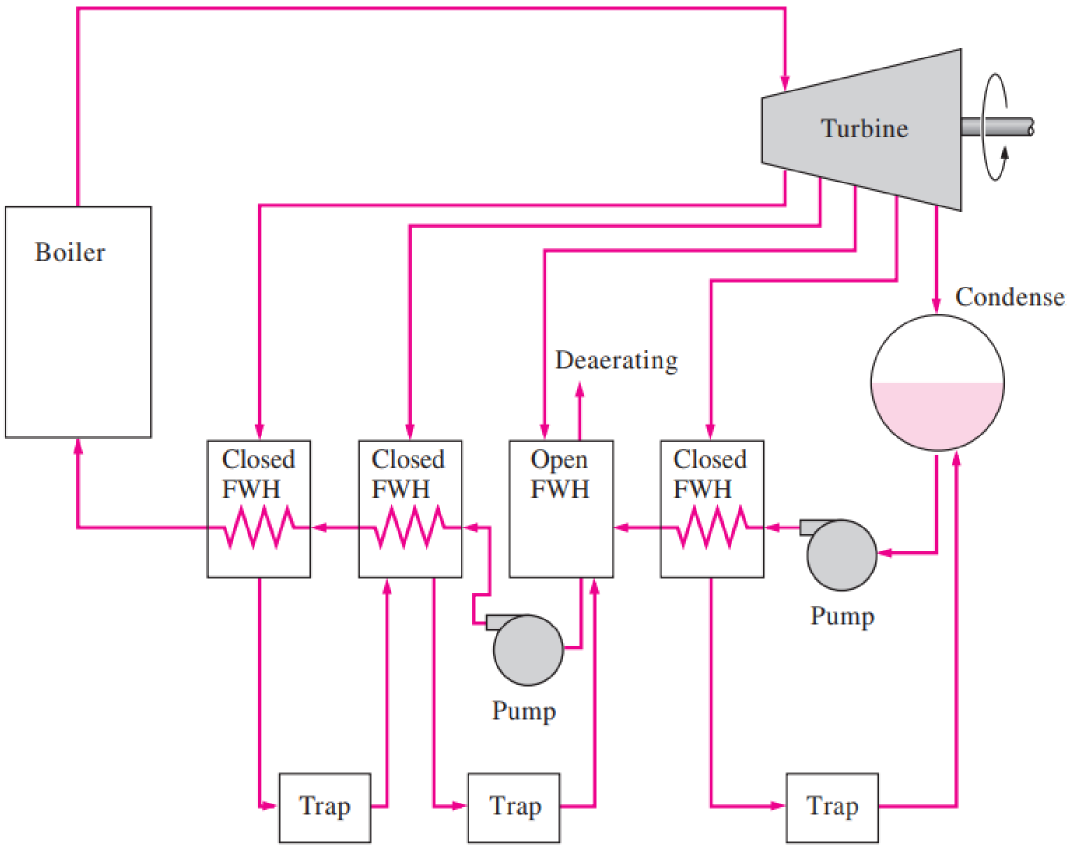
- A trap allows the liquid to be throttled to a lower pressure region but traps the vapor. The enthalpy of steam remains constant during this throttling process.



Rankine Cycle steam power plant with one open and three closed feedwater heaters

- A trap allows the liquid to be throttled to a lower pressure region but traps the vapor. The enthalpy of steam remains constant during this throttling process.

- Open feedwater heaters are simple and inexpensive and have good heat transfer characteristics. They also bring the feedwater to the saturation state. For each heater, however, a pump is required to handle the feedwater.

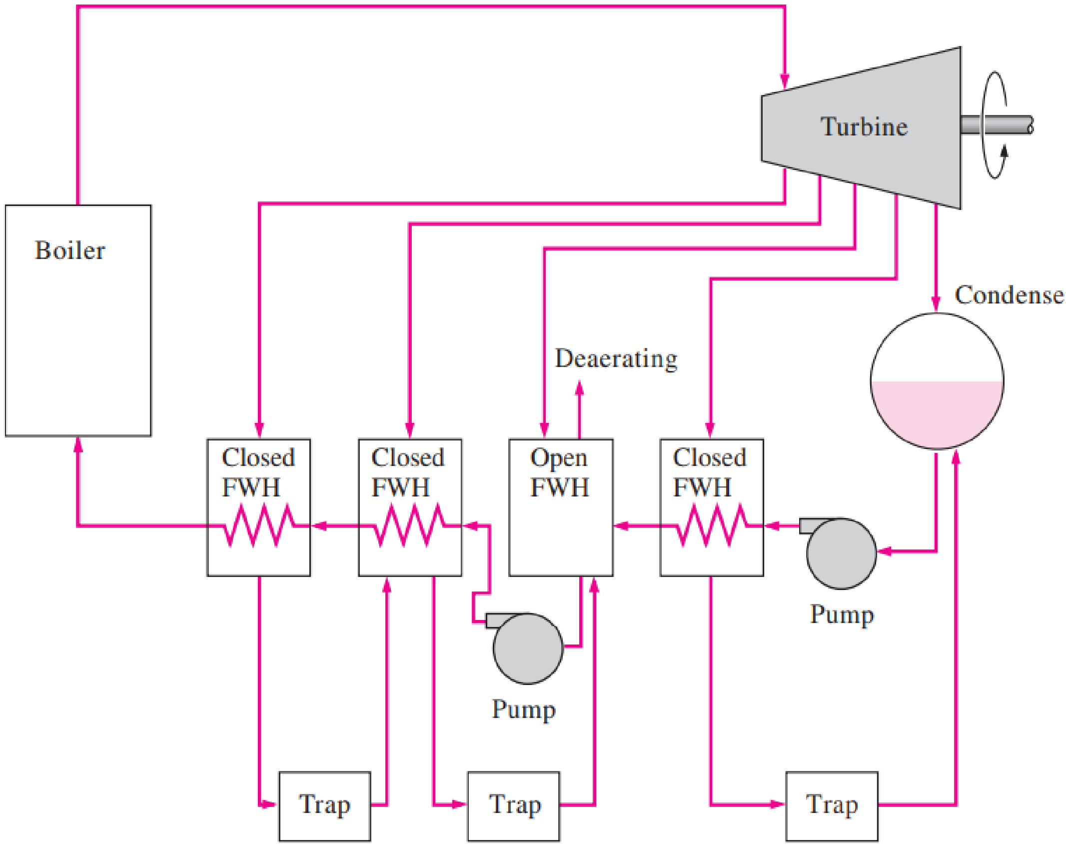


Rankine Cycle steam power plant with one open and three closed feedwater heaters

- The closed feedwater heaters are more complex because of the internal tubing network, and thus expensive. Heat transfer in closed feedwater heaters is also less effective since the two streams are not allowed to be in direct contact.

- However, closed feedwater heaters do not require a separate pump for each heater since the extracted steam and the feedwater can be at different pressures.

- Most steam power plants use a combination of open and closed feedwater heaters.



Reheat–Regenerative Rankine cycle with one open feedwater heater, one closed feedwater heater, and one reheater.