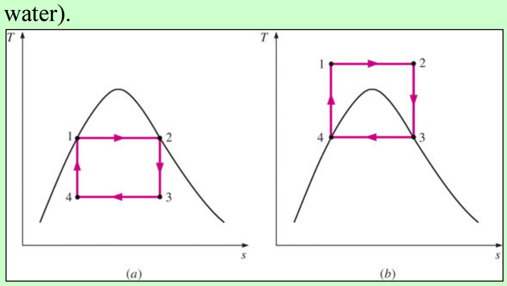
Chapter 9:

Vapor and Combined Power Cycles

1

THE CARNOT VAPOR CYCLE

- The Carnot cycle is not a suitable model for vapor power cycles.
-
- Consider a steady-flow *Carnot cycle* executed within the saturation dome Fig (a).
- Several impracticalities are associated with this cycle:
  - Limiting the heat transfer processes to two-phase systems will severely limits the maximum temperature that can be used in the cycle (under the critical-point value, which is 374°C for water).
  - The turbine has to handle steam with low quality (high moisture content). The impingement of liquid droplets on the turbine blades causes erosion and is a major source of wear (not less than about 90 percent quality).
  - It is not practical to design a compressor that handles two phases.



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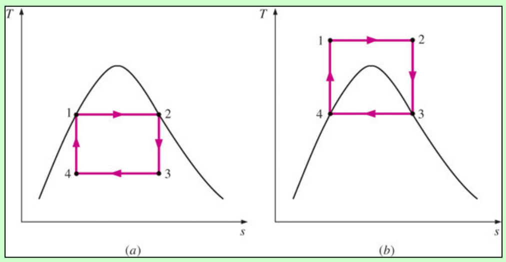
THE CARNOT VAPOR CYCLE

- Some of these problems could be eliminated by executing the Carnot cycle in a different way, as shown Fig (b).
- This cycle, however, presents other problems such as isentropic compression to extremely high pressures and isothermal heat transfer at variable pressures.
- Thus we conclude that the Carnot cycle cannot be approximated in actual devices and is not a realistic model for vapor power cycles.



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RANKINE CYCLE: THE IDEAL CYCLE FOR VAPOR POWER CYCLES

- 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, as shown schematically on a *T-s* diagram.
- 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 and consists of the following four processes:
  - 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,

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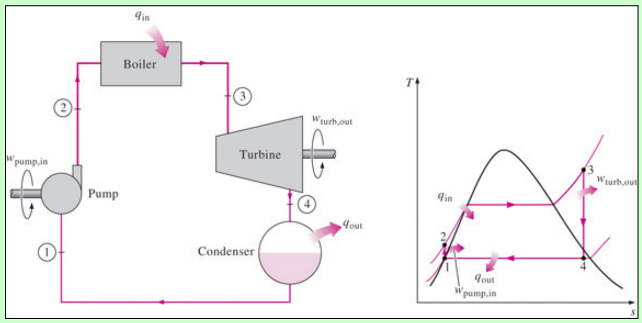
RANKINE CYCLE: THE IDEAL CYCLE FOR VAPOR POWER CYCLES

- Water enters the *pump* at state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler.
- The water temperature 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 called the *steam generator*.
- The superheated vapor at state 3 enters the *turbine*, where it expands isentropically and produces work by rotating the shaft connected to an electric generator.



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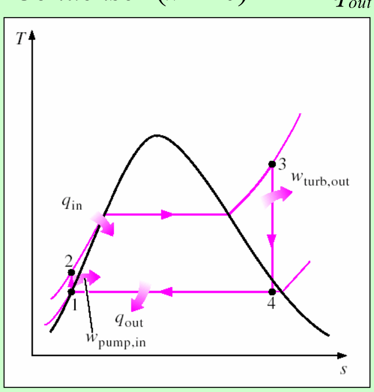
Energy Analysis of the Ideal Rankine Cycle

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

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

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

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



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

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

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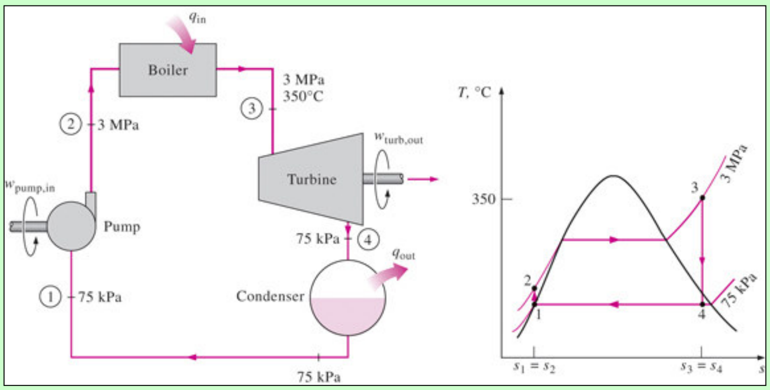
EXAMPLE 9–1

The Simple Ideal Rankine Cycle

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



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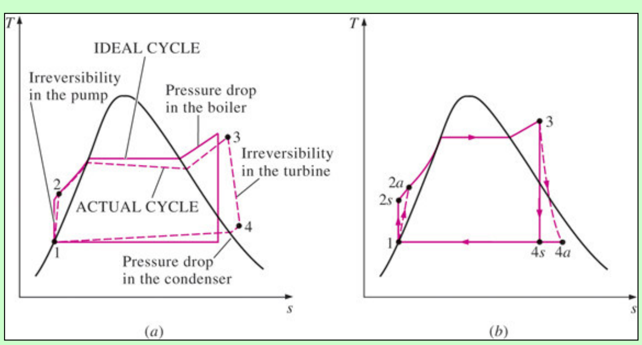
DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES

- The actual vapor power cycle differs from the ideal Rankine cycle, as a result of irreversibilities in various components.
- *Fluid friction* causes pressure drops in the boiler, the condenser, and the piping between various components.
- *Heat loss* from the steam to the surroundings as the steam flows through various components.



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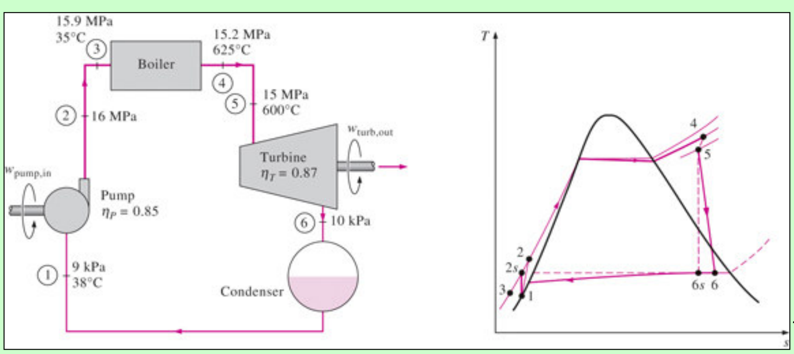
DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES

- Other factors also need to be considered in the analysis of actual vapor power cycles.
- In actual condensers, for example, 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.
- Finally, 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.

EXAMPLE 9–2

An Actual Steam Power Cycle

- A steam power plant operates on the cycle shown in Fig. 10–5. If the isentropic efficiency of the turbine is 87 percent and the isentropic efficiency of the pump is 85 percent, determine
- (*a*) the thermal efficiency of the cycle and
- (*b*) the net power output of the plant for a mass flow rate of 15 kg/s.



HOW CAN WE INCREASE THE EFFICIENCY OF THE RANKINE CYCLE?

- Steam power plants are responsible for the production of most electric power in the world, and even small increases in thermal efficiency can mean large savings from the fuel requirements.
- Therefore, every effort is made to improve the efficiency of the cycle on which steam power plants operate.
- The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same:
- *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.*
- That is, the average fluid temperature should be as high as possible during heat addition and as low as possible during heat rejection.
- Next we discuss three ways of accomplishing this for the simple ideal Rankine cycle.

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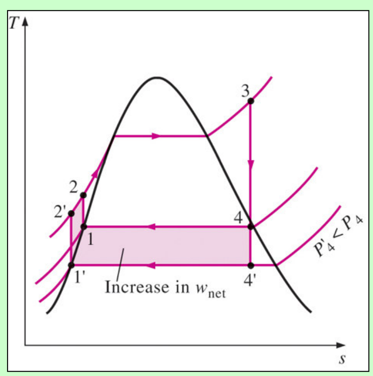
Lowering the Condenser Pressure (*Lowers* $T_{low,avg}$)

- Steam exists as a saturated mixture in the condenser at the saturation temperature corresponding to the pressure inside the condenser.
- Therefore, lowering the operating pressure of the condenser automatically lowers the temperature of the steam, and thus the temperature at which heat is rejected.
- The colored area on this diagram represents the increase in net work output as a result of lowering the condenser pressure from P_4 to $P_{4'}$.
- The heat input requirements also increase (represented by the area under curve 2'-2), but this increase is very small.
- Thus the overall effect of lowering the condenser pressure is an increase in the thermal efficiency of the cycle.



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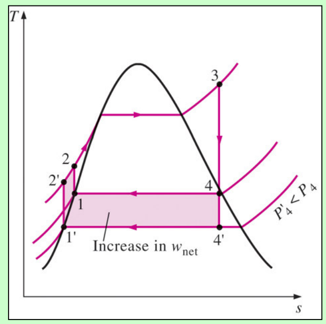
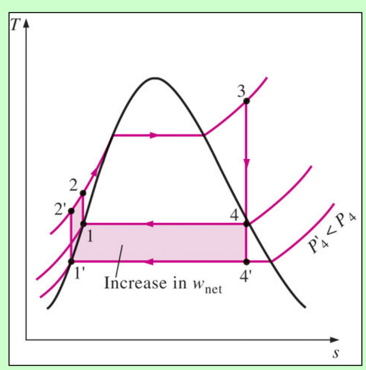
Lowering the Condenser Pressure (*Lowers $T_{low,avg}$*)

- To take advantage of the increased efficiencies at low pressures, the condensers of steam power plants usually operate well below the atmospheric pressure.
- This does not present a major problem since the vapor power cycles operate in 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.
- Consider, for example, a condenser that is to be cooled by a nearby river at 15°C.
- Allowing a temperature difference of 10°C for effective heat transfer, the steam temperature in the condenser must be above 25°C.
- Thus the condenser pressure must be above 3.2 kPa, which is the saturation pressure at 25°C.



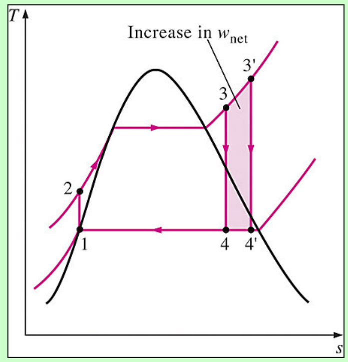
Lowering the Condenser Pressure (*Lowers $T_{low,avg}$*)

- Lowering the condenser pressure is not without any side effects.
- For one thing, it creates the possibility of air leakage into the condenser.
- More importantly, it increases the moisture content of the steam at the final stages of the turbine, as can be seen.
- The presence of large quantities of moisture is highly undesirable in turbines because it decreases the turbine efficiency and erodes the turbine blades.
- 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.
- Fortunately, this problem can be corrected, as discussed next.



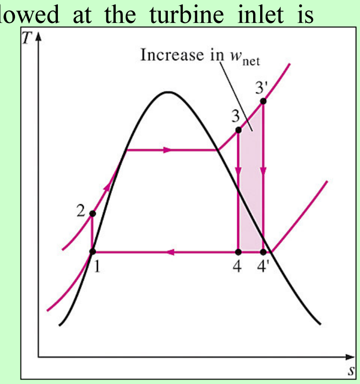
Superheating the Steam to High Temperatures (*Increases* $T_{high,avg}$)

- The average temperature at which heat is transferred to steam can be increased by 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.
- Thus 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, however, since the average temperature at which heat is added increases.
- Superheating the steam to higher temperatures has another very desirable effect: It decreases the moisture content of the steam at the turbine exit, (the quality at state 4' is higher than that at state 4).



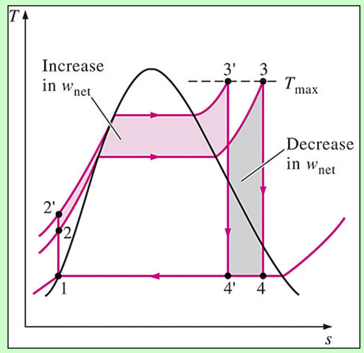
Superheating the Steam to High Temperatures (*Increases* $T_{high,avg}$)

- The temperature to which steam can be superheated is limited, however, by metallurgical considerations.
- Presently the highest steam temperature allowed at the turbine inlet is about 620°C (1150°F).
- 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.



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

- Another way of increasing the average temperature during the heat-addition process is to increase the operating pressure of the boiler, which automatically raises the temperature at which boiling takes place.
- This, in turn, raises the average temperature at which heat is transferred to the steam and thus raises the thermal efficiency of the cycle.
- The effect of increasing the boiler pressure on the performance of vapor power cycles is illustrated on a *T-s* diagram.
- Notice that 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, as discussed in the next section.



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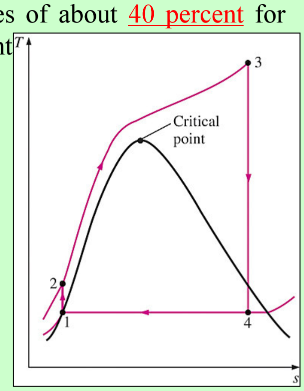
Increasing the Boiler Pressure (*Increases* $T_{high,avg}$)

- Operating pressures of boilers have gradually increased over the years from about 2.7 MPa (400 psia) in 1922 to over 30 MPa (4500 psia) today, generating enough steam to produce a net power output of 1000 MW or more in a large power plant.
- Today many modern steam power plants operate at supercritical pressures (P > 22.06 MPa) and have thermal efficiencies of about 40 percent for fossil-fuel plants and 34 percent for nuclear plants.
- There are over 150 supercritical-pressure steam power plants in operation in the United States.
- The lower efficiencies of nuclear power plants are due to the lower maximum temperatures used in those plants for safety reasons.
- The effects of lowering the condenser pressure, superheating to a higher temperature, and increasing the boiler pressure on the thermal efficiency of the Rankine cycle are illustrated below with an example.



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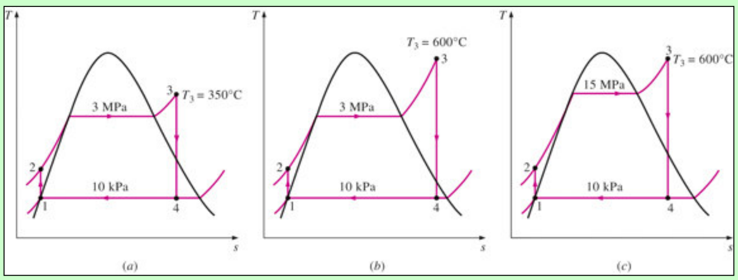
EXAMPLE 9–3

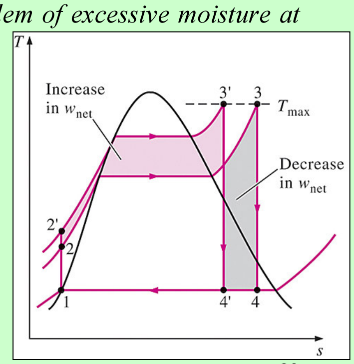
Effect of Boiler Pressure and Temperature on Efficiency

- Consider a steam power plant operating on the ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 10 kPa. Determine:
- (*a*) the thermal efficiency of this power plant,
- (*b*) the thermal efficiency if steam is superheated to 600°C instead of 350°C, and
- (*c*) the thermal efficiency if the boiler pressure is raised to 15 MPa while the turbine inlet temperature is maintained at 600°C.



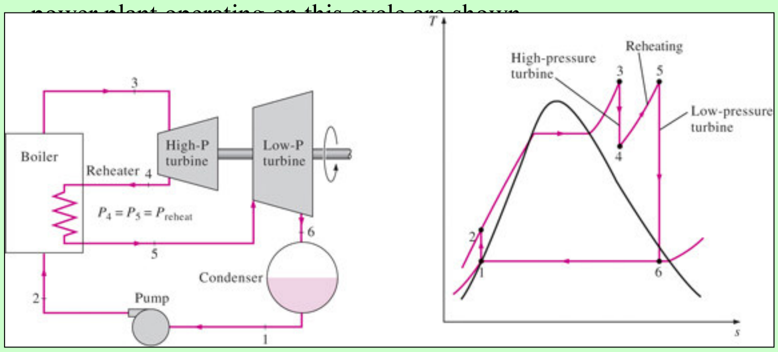
THE IDEAL REHEAT RANKINE CYCLE

- We noted in the last section that increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels. Then it is natural to ask the following question:
- *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?*
- Two possibilities come to mind:
- 1. Superheat the steam to very high temperatures before it enters the turbine. This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency. This is not a viable solution, however, since it requires raising the steam temperature to metallurgically unsafe levels.



THE IDEAL REHEAT RANKINE CYCLE

- 2. Expand the steam in the turbine in two stages, and reheat it in between.
- In other words, modify the simple ideal Rankine cycle with a **reheat** process.
- Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.
- The *T-s* diagram of the ideal reheat Rankine cycle and the schematic of the



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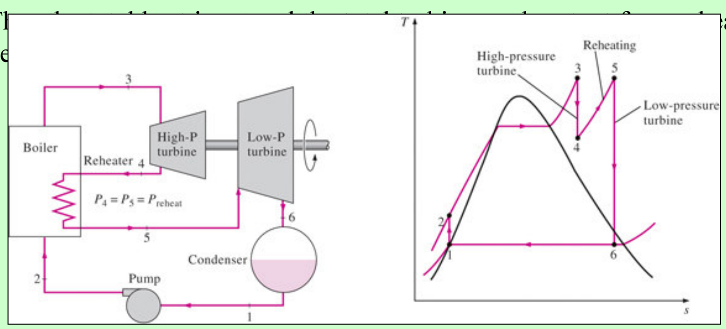
THE IDEAL REHEAT RANKINE CYCLE

- The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages.
- In the first stage (the high pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated 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.
- Th … at cycle be



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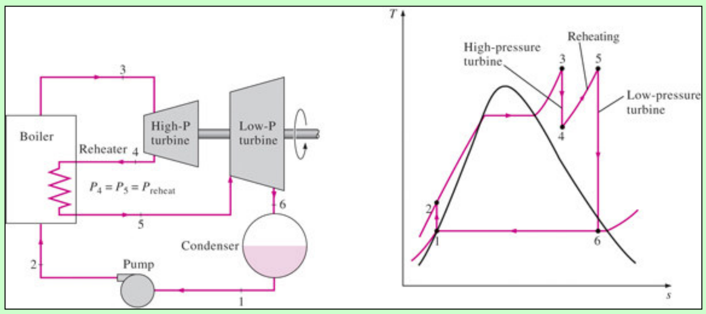
THE IDEAL REHEAT RANKINE CYCLE

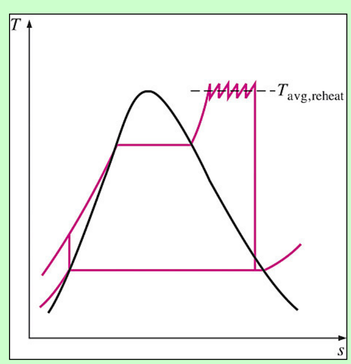
- Thus the first law of thermodynamics analysis for a reheat cycle become:

Component	**Process**	**First Law Result**
Boiler	Const. P	$q_{in} = (h_3 - h_2) + (h_5 - h_4)$
Turbine	Isentropic	$w_{out} = (h_3 - h_4) + (h_5 - h_6)$
Condenser	Const. P	$q_{out} = (h_6 - h_1)$
Pump	Isentropic	$w_{in} = (h_2 - h_1) = v_1(P_2 - P_1)$



THE IDEAL REHEAT RANKINE CYCLE

- The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent.
- As the number of stages is increased, the expansion and reheat processes approach an isothermal process at the maximum temperature, as shown.
- The use of more than two reheat stages, however, is not practical.
- The theoretical improvement in efficiency from the second reheat is about half of that which results from a single reheat.
- This gain is too small to justify the added cost and complexity.



EXAMPLE 9–4

The Ideal Reheat Rankine Cycle

- Consider a steam power plant operating on the ideal reheat Rankine cycle. Steam enters the high-pressure turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. If the moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10.4 percent, determine:
- (*a*) the pressure at which the steam should be reheated and
- (*b*) the thermal efficiency of the cycle.
- Assume the steam is reheated to the inlet temperature of the high-pressure turbine.