Lecture 4: Ideal Rankine Cycle

Course: MECH-422 – Power Plants

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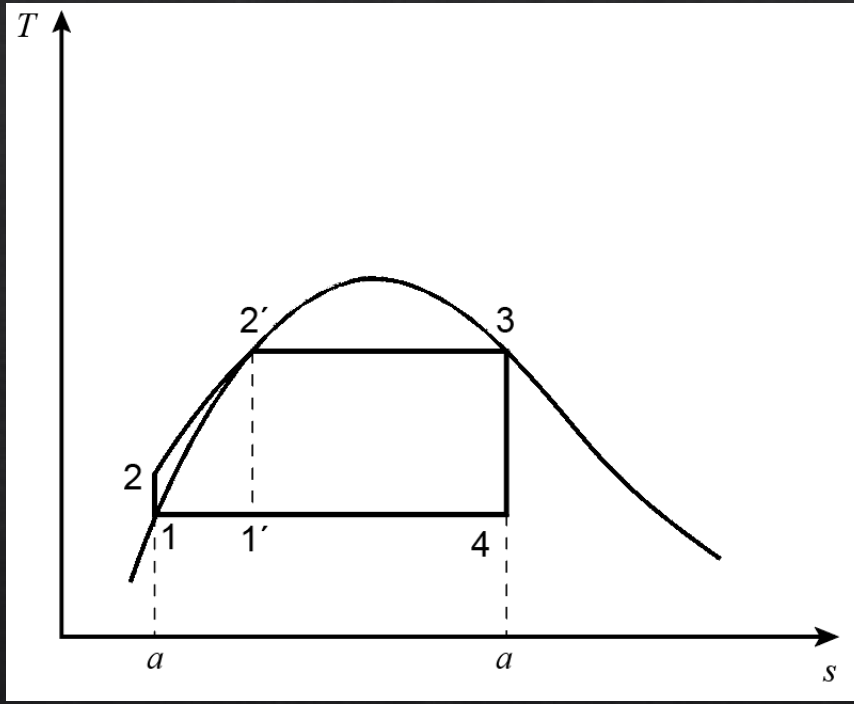
BUITEMS – DEPARTMENT OF MECHANICAL ENGINEERING

Ideal Rankine Cycle

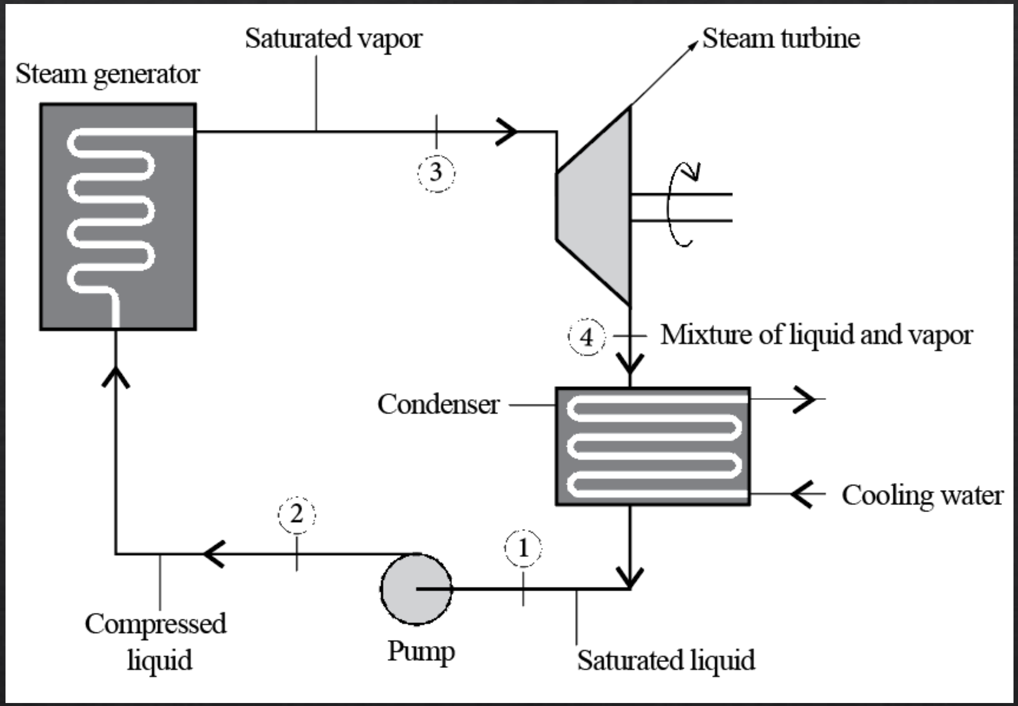
- The ideal Rankine cycle provides a simple setting to study aspects of vapor power plant performance. The ideal cycle adheres to additional modeling assumptions:
  - Frictional pressure drops are absent during flows through the boiler and condenser. Thus, these processes occur at constant pressure.
  - Flows through the turbine and pump occur adiabatically ***and*** without irreversibility. Thus, these processes are isentropic.

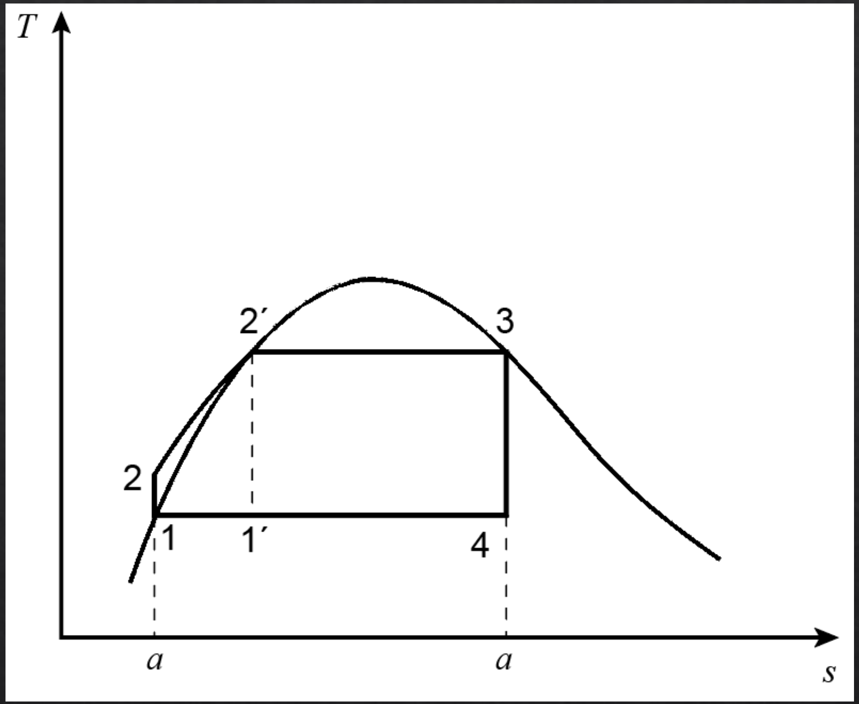
Ideal Rankine cycle

- Process 1-2: a reversible adiabatic (thus constant entropy or isentropic) compression process in a pump
- Process 2-3: a reversible constant-pressure process involving heat transfer at high temperature in a steam generator
- Process 3-4: a reversible adiabatic (thus constant entropy or isentropic) expansion process in a turbine
- Process 4-1: a reversible constant-pressure heat transfer from the working fluid to the surrounding at low temperature in a condenser



Ideal Rankine cycle





An ideal Rankine cycle, a) the schematic of the cycle, b) the T-s diagram of the Rankine cycle

Example 2.4

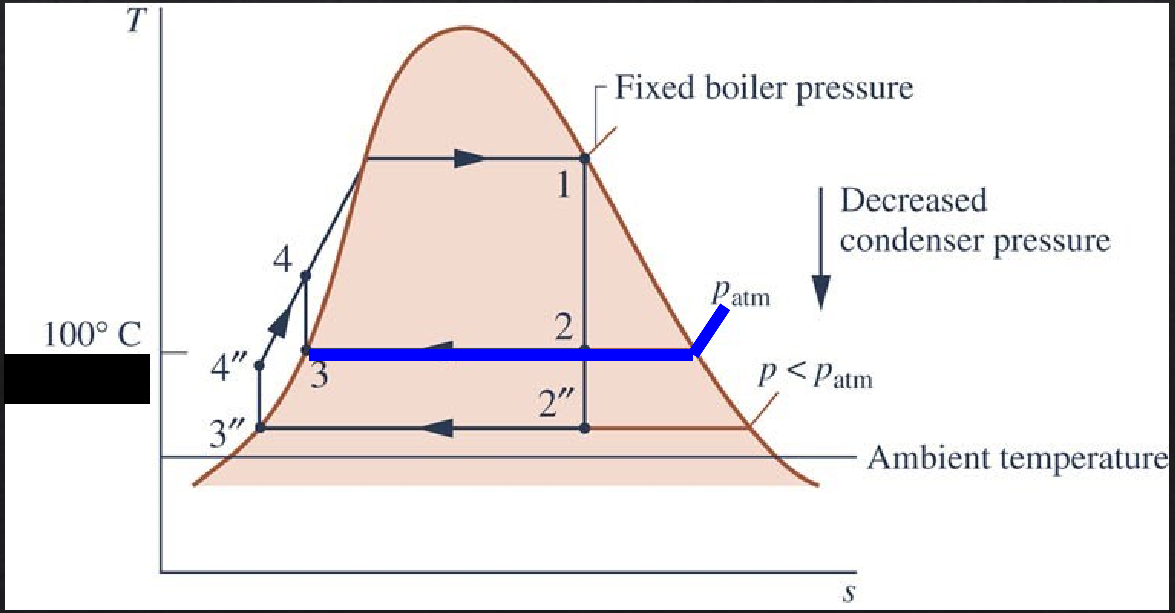
In a steam power plant that operates based on a Rankine cycle, the operating pressure of the steam generator and the condenser are 10,000 kPa and 10 kPa, respectively. If the turbine inlet stream is saturated vapor and the condenser outlet flow is saturated liquid, determine the specific heat transfers in the steam generator and the condenser, the specific work involved in the turbine and the pump, and the thermal efficiency and the back work ratio of the cycle. Also, if the power plant produces 250 MW power, determine the mass flow rate of the cycle's working fluid.

Summary of the results for Examples 2.3 and 2.4

Type of Cycle	$P_2 = P_3$ (kPa)	$P_1 = P_4$ (kPa)	x_4	q_{SG} (kJ/kg)	q_{Cond} (kJ/kg)	w_{Pump} (kJ/kg)	w_{Turb} (kJ/kg)	w_{Net} (kJ/kg)	η_{Th} (%)
Carnot cycle	10,000	10	0.662	1317.1	720.0	352.0	949.1	597.1	45.33
Simple Rankine –Turbine inlet: saturate steam	10,000	10	0.662	2522.8	1583.8	10.1	949.1	939.0	37.22

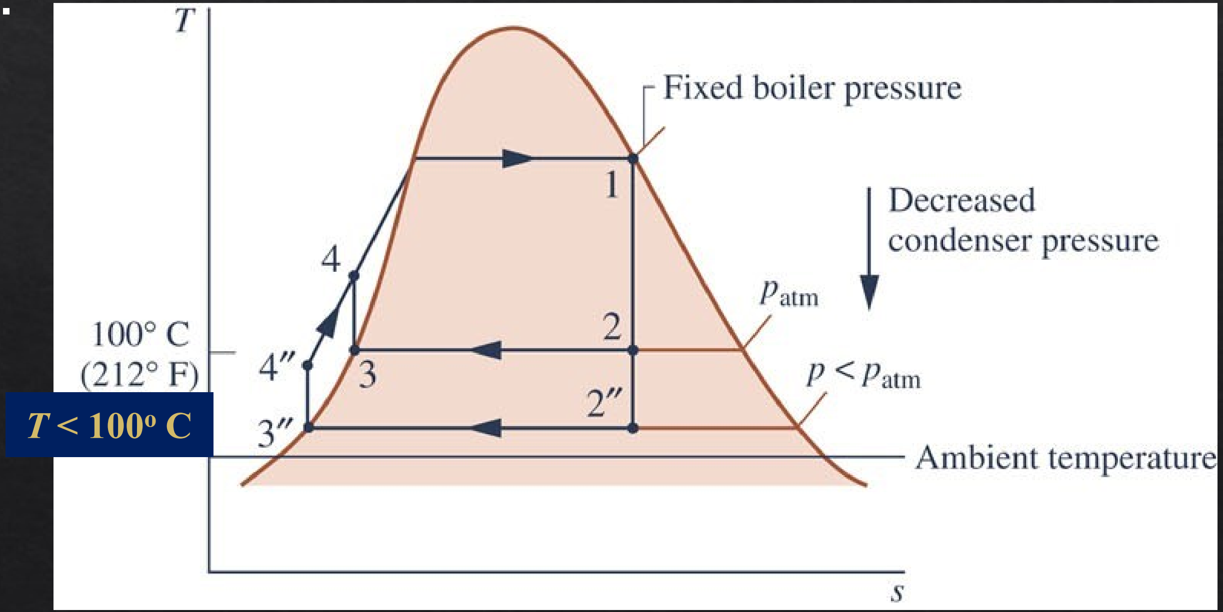
Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Condenser Pressure (1 of 4)

- The figure shows two cycles having the same boiler pressure but different condenser pressures:
  - one is at atmospheric pressure and
  - the other is at less than atmospheric pressure.



Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Condenser Pressure (2 of 4)

► Since the temperature of heat rejection for cycle 1-2″-3″-4″-1 is lower than for cycle 1-2-3-4-1, the cycle condensing below atmospheric pressure has the greater thermal efficiency. Reducing condenser pressure tends to increase thermal efficiency.



Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Condenser Pressure (3 of 4)

- Power plant condensers normally operate with steam condensing at a pressure well below atmospheric.

- For heat rejection to the surroundings the lowest feasible condenser pressure is the saturation pressure corresponding to the ambient temperature.

- A primary reason for including condensers in vapor power plants is the increase in thermal efficiency realized when the condenser operates at a pressure less than atmospheric pressure.
- Another is that the condenser allows the working fluid to flow in a closed loop and so demineralized water that is less corrosive than tap water can be used economically.

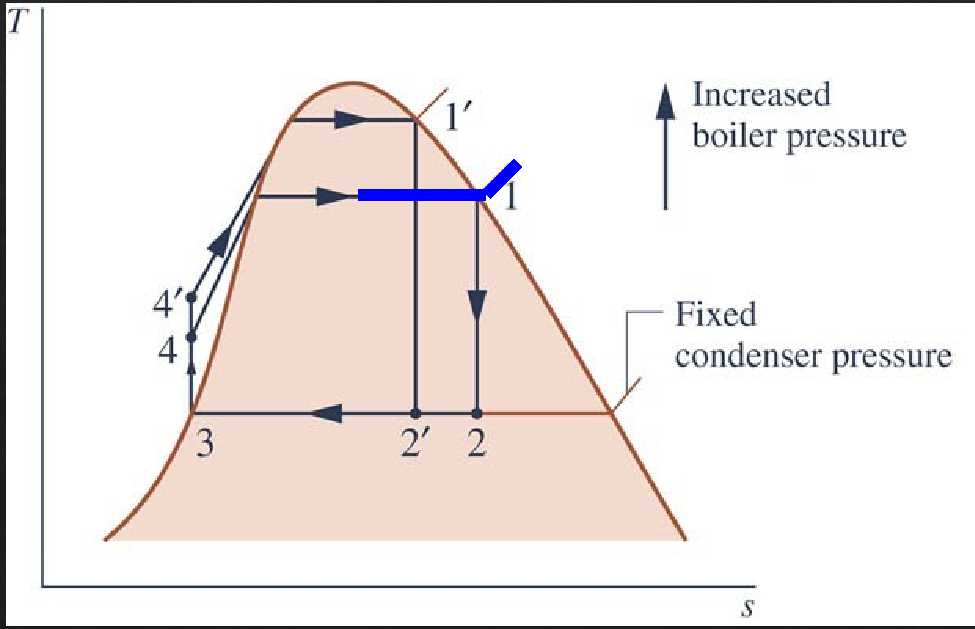
Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Condenser Pressure (4 of 4)

- As steam condenses, energy is discharged by heat transfer to cooling water flowing separately through the condenser.

- Although the cooling water carries away considerable energy, its utility is extremely limited because cooling water temperature is increased only by a few degrees above the ambient. Such warm cooling water has little thermodynamic or economic value.

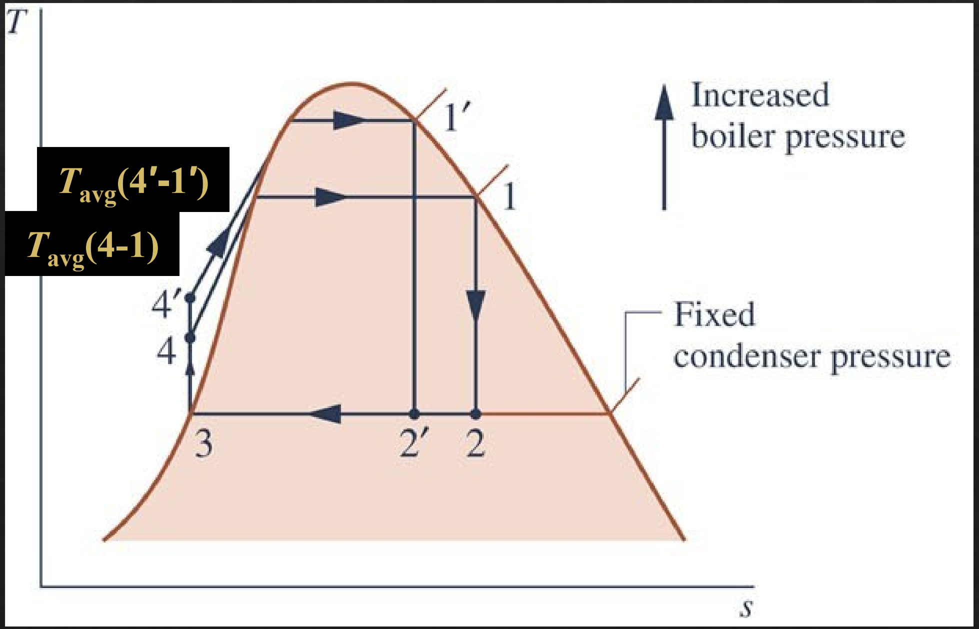
Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Boiler Pressure (1 of 4)

- The figure shows two cycles having the same condenser pressure but different boiler pressures:
  - one is at a given pressure and
  - the other is at higher than the given pressure.



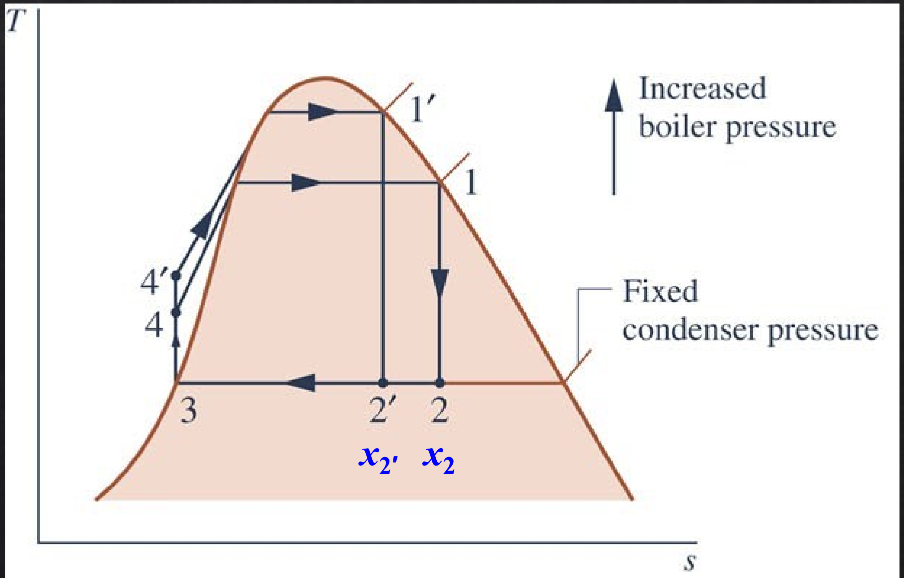
Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Boiler Pressure (2 of 4)

► Since the average temperature of heat addition for cycle 1′-2′-3-4′-1′ is greater than for cycle 1-2-3-4-1, the higher pressure cycle has the greater thermal efficiency. Increasing the boiler pressure tends to increase thermal efficiency.



Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Boiler Pressure (3 of 4)

- ►However, an increase in boiler pressure also results in a reduction of steam quality for the expansion through the turbine – compare the lower quality state $2'$ with state 2.
- ►If the quality of the expanding steam becomes too low, the impact of liquid droplets in the steam can erode the turbine blades and possibly diminish performance.

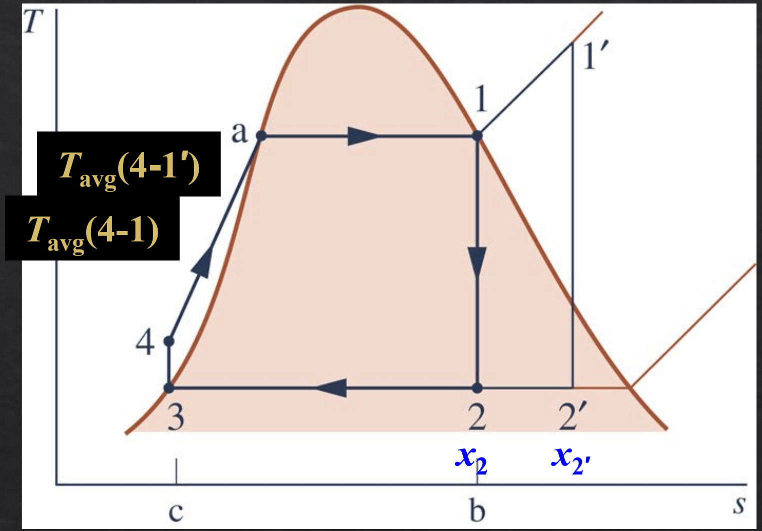


Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Boiler Pressure (4 of 4)

- Rankine cycle modifications known as **superheat** and **reheat** permit advantageous operating pressures in the boiler and condenser while avoiding low-quality steam in the turbine expansion. Another such modification is the **supercritical** cycle.
- considered next.

Ideal Rankine Cycle with Superheat

► The figure shows a Rankine cycle with superheated vapor at the turbine inlet: cycle 1′-2′-3-4-1′.

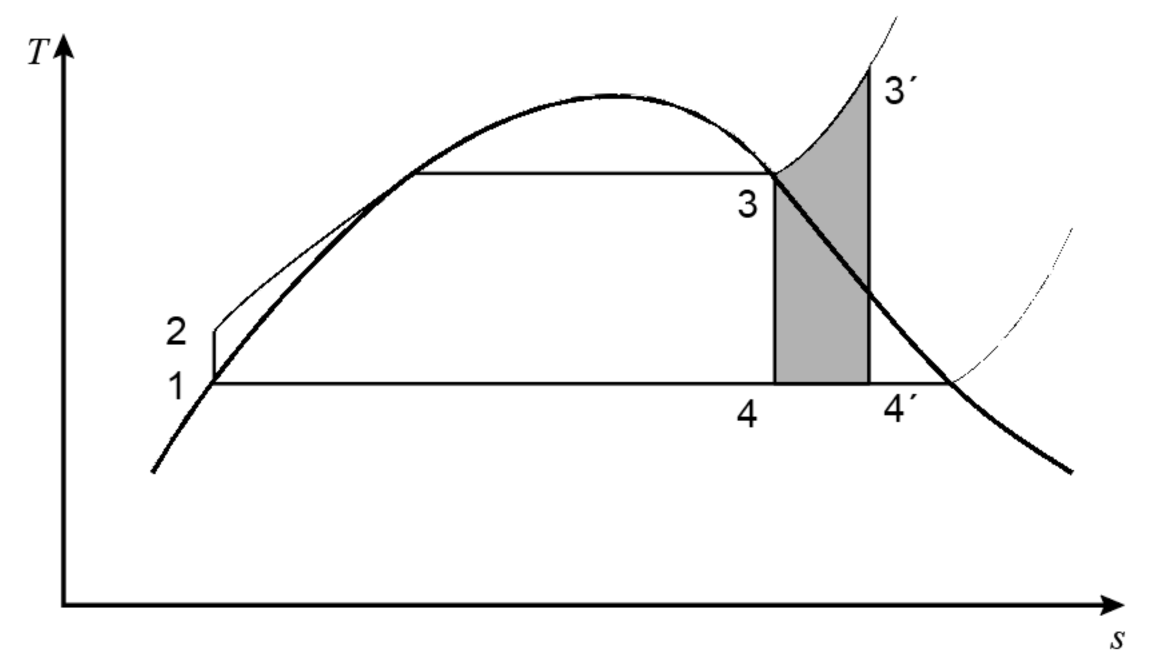


► The cycle with superheat has a higher average temperature of heat addition than cycle 1-2-3-4-1 without superheat, and thus has a higher thermal efficiency.

► Moreover, with superheat the quality at the turbine exit, state 2′, is greater than at state 2, the turbine exit without superheat.

► A combined boiler-superheater is called a ***steam generator***.

Effects of superheating steam in steam generator



Effect of superheating steam in the steam generator on Rankine cycle performance

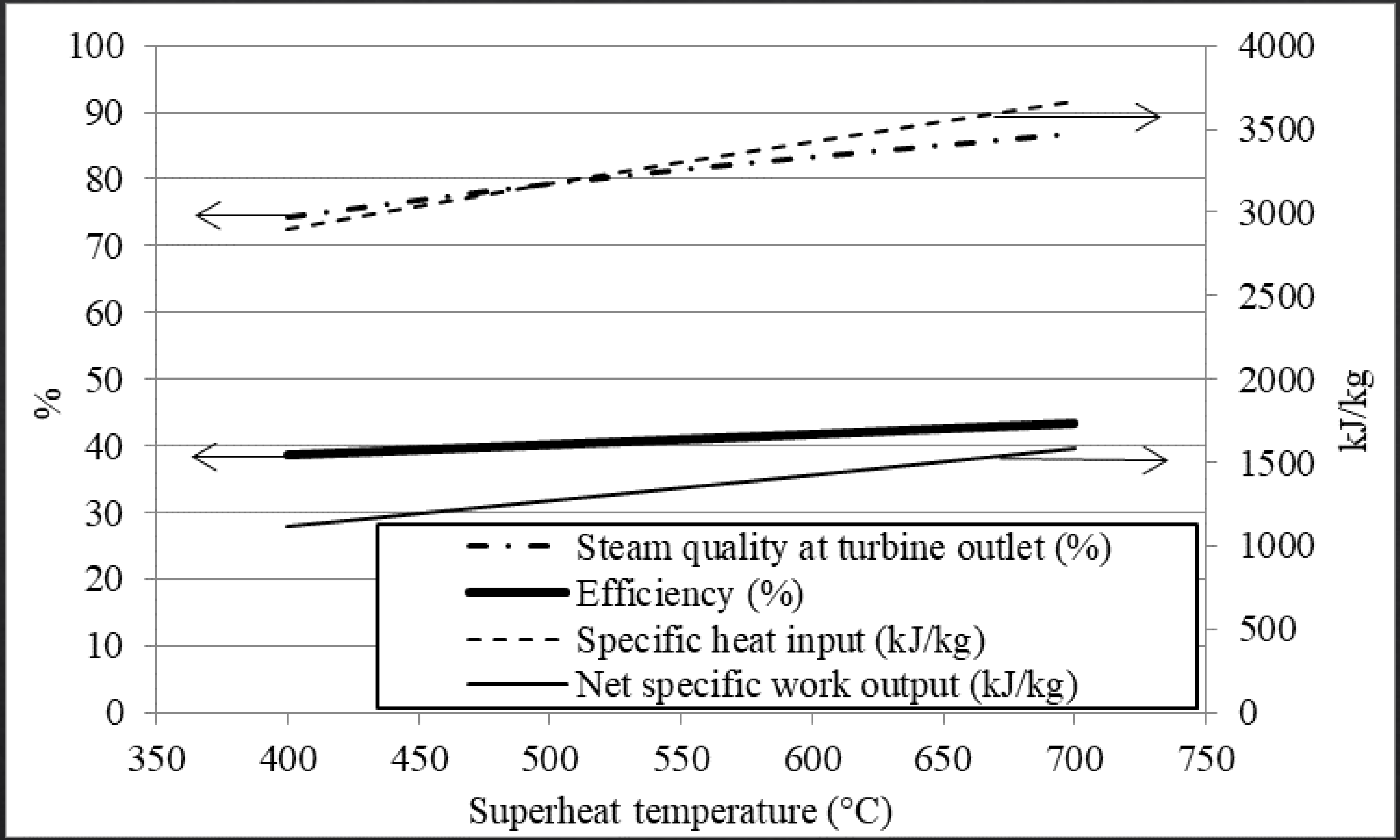
Example 2.6

In Example 2.4, the outlet steam from the steam generator is superheated to the pressure and temperature of 10,000 kPa and 600°C, respectively. The condenser outlet flow is saturated liquid at the pressure of 10 kPa. Determine the specific heat transfers in the steam generator and the condenser, the specific work involved in the turbine and the pump, and the thermal efficiency of the cycle. Also, if the power plant produces 250 MW (net power output), determine the mass flow rate of the cycle's working fluid.

Note: This steam power plant is expressed as 100/600 (100 bar/600°C, steam generator pressure/turbine inlet temperature).

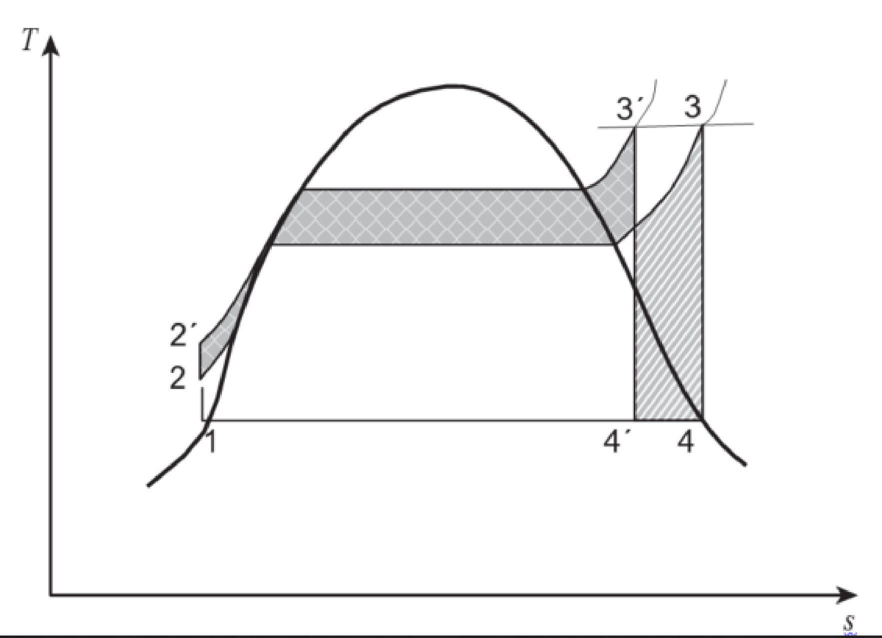
Effects of the superheated steam temperature of the turbine inlet flow on the performance of the cycle in Example 2.6

Type of Cycle	$P_2 = P_3$ (kPa)	$P_1 = P_4$ (kPa)	x_4	q_{SG} (kJ/kg)	q_{Cond} (kJ/kg)	w_{Pump} (kJ/kg)	w_{Turb} (kJ/kg)	w_{Net} (kJ/kg)	η_{Th} (%)
Simple Rankine – Turbine inlet: saturate steam (Example 2.4)	10,000	10	0.662	2522.8	1583.8	10.1	949.1	939.0	37.22
Superheated at 400°C	10,000	10	0.742	2894.6	1774.5	10.1	1130.2	1120.1	38.70
Superheated at 500°C	10,000	10	0.793	3171.3	1896.8	10.1	1284.7	1274.6	40.19
Superheated at 600°C (Example 2.6)	10,000	10	0.834	3423.4	1994.9	10.1	1438.6	1428.5	41.73
Superheated at 700°C	10,000	10	0.869	3668.6	2079.7	10.1	1599.0	1588.9	43.31



Efficiency, specific net work output, specific heat input, and quality of the flow at the outlet of the turbine as a function of the temperature of the superheated steam inlet to the turbine in Example 2.6

Effects of Steam Generator Pressure



Effect of the steam generator operating pressure at the constant temperature of the steam turbine inlet flow

- This increases the thermal efficiency of the cycle.
- However, the maximum temperature of the steam inlet to the steam turbine (and indeed the maximum temperature in the entire cycle) is limited by the material and design of both the steam generator and the early stages of the turbine blades.
- Therefore, to realistically study the effects of the operating pressure of the steam generation on the performance of the cycle, the maximum temperature of the inlet flow to the turbine should be kept constant.

Example 2.7

In a Rankine cycle, similar to the one in Examples 2.4 and 2.6, the inlet steam to the turbine is superheated steam at the temperature of 600°C and the pressure of 20,000 kPa. If the outlet stream of the condenser is saturated water at the pressure of 10 kPa, determine the specific heat transfers in the steam generator and the condenser, the specific work involved in the turbine and the pump, and the thermal efficiency of the cycle.

Given: Similar to Example 2.6.

Find: Similar to Example 2.6.

Assumptions: Similar to Example 2.6.

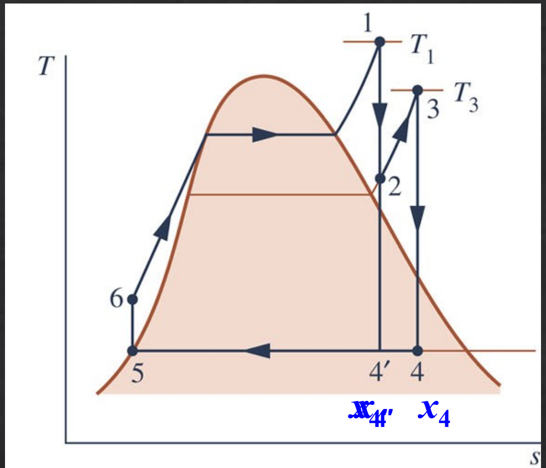
Effects of the steam generator operating pressure at the constant turbine inlet temperature on the performance of the cycle in Example 2.7

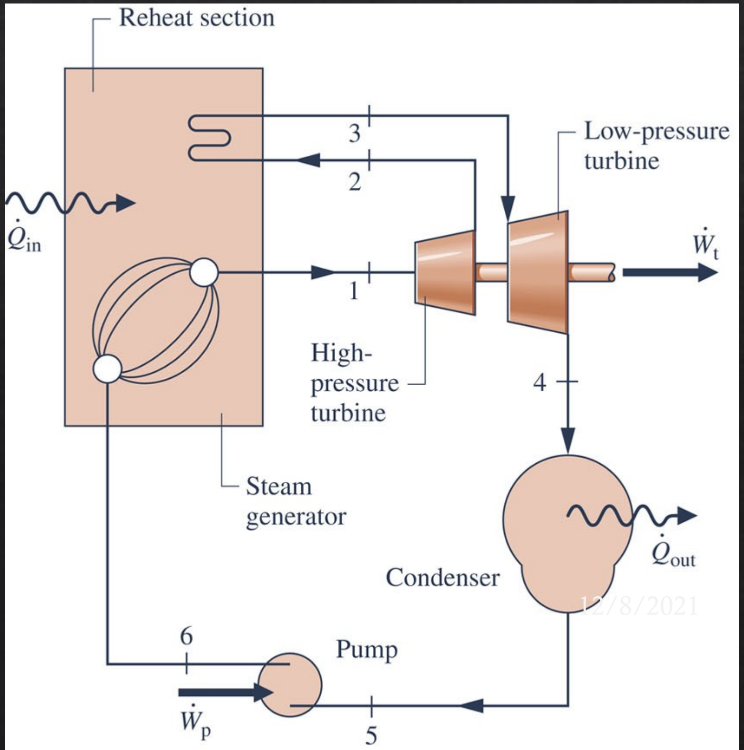
Type of Cycle: Simple Rankine–Turbine Inlet:	$P_2' = P_3'$ (kPa)	$P_1 = P_4'$ (kPa)	x_4'	q_{SG} (kJ/kg)	q_{Cond} (kJ/kg)	w_{Pump} (kJ/kg)	w_{Turb} (kJ/kg)	w_{Net} (kJ/kg)	η_{Th} (%)
Superheated at 4000 kPa	4000	10	0.896	3478.5	2143.5	4.0	1339.0	1335.0	38.38
Superheated at 10,000 kPa (Example 2.6)	10,000	10	0.834	3423.4	1994.9	10.1	1438.6	1428.5	41.73
Superheated at 12,000 kPa	12,000	10	0.820	3404.4	1963.3	12.1	1453.2	1441.1	42.33
Superheated at 16,000 kPa	16,000	10	0.799	3365.5	1911.0	16.2	1470.7	1454.5	43.22
Superheated at 20,000 kPa (Example 2.7)	20,000	10	0.781	3325.6	1867.9	20.2	1477.9	1457.7	43.83
Superheated at 24,000 kPa	24,000	10	0.765	3284.6	1830.5	24.2	1478.4	1454.1	44.27

Ideal Reheat Cycle (1 of 3)

►The reheat cycle is another Rankine cycle modification that takes advantage of the increased thermal efficiency resulting from a high average temperature of heat addition and yet avoids low-quality steam during expansion through the turbine.

►With reheat, the steam quality at the turbine exit, state 4, is greater than at state 4′, the turbine exit without reheat.

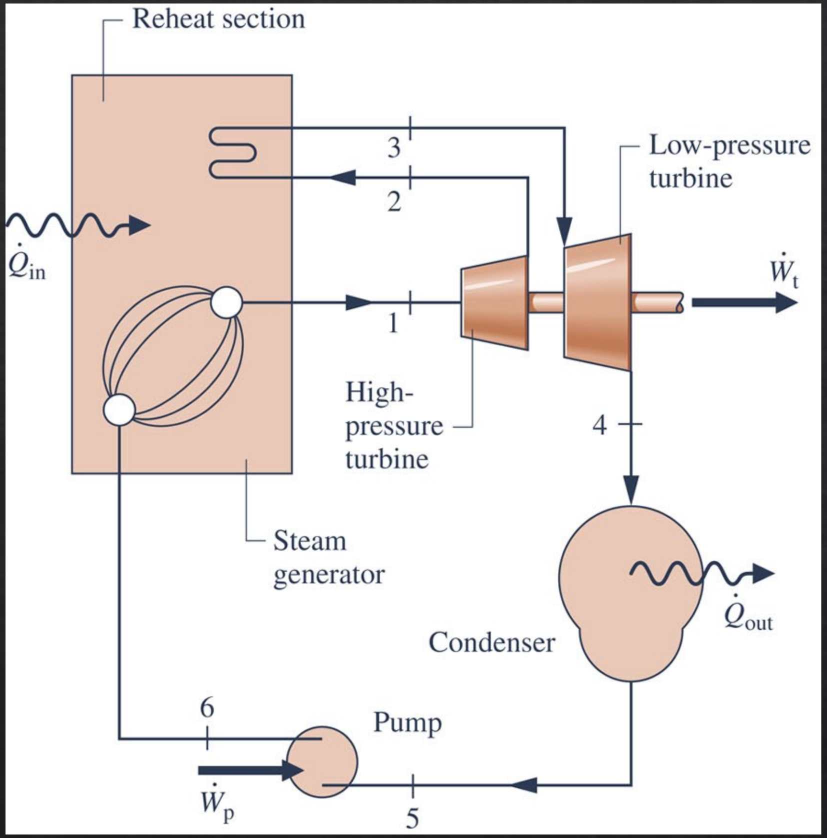




Ideal Reheat Cycle (2 of 3)

► Departures of the reheat cycle from the simple vapor power cycle considered thus far include

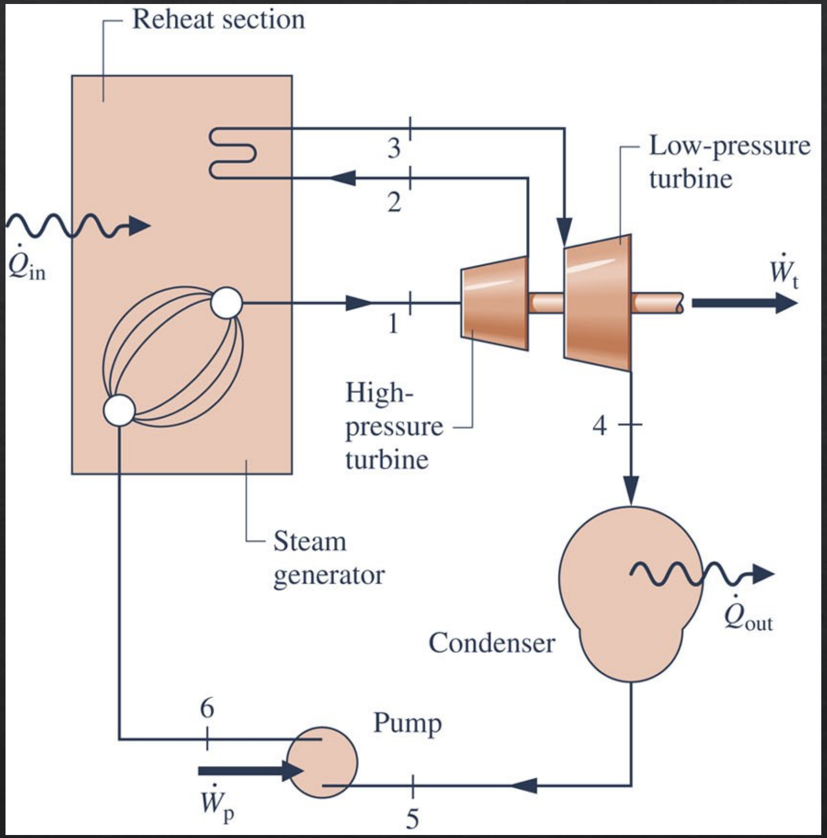
- **Process 1-2**. Steam expands through the high-pressure turbine stage.
- **Process 2-3**. Steam is reheated in the steam generator.
- **Process 3-4**. Steam expands through the low-pressure turbine stage.



Ideal Reheat Cycle (3 of 3)

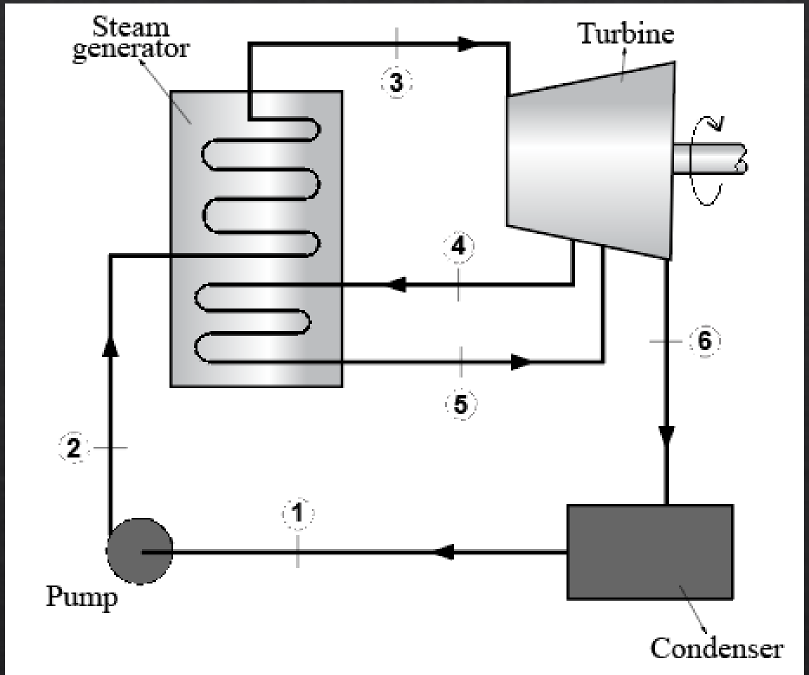
► When computing the thermal efficiency of a reheat cycle it is necessary to account for the

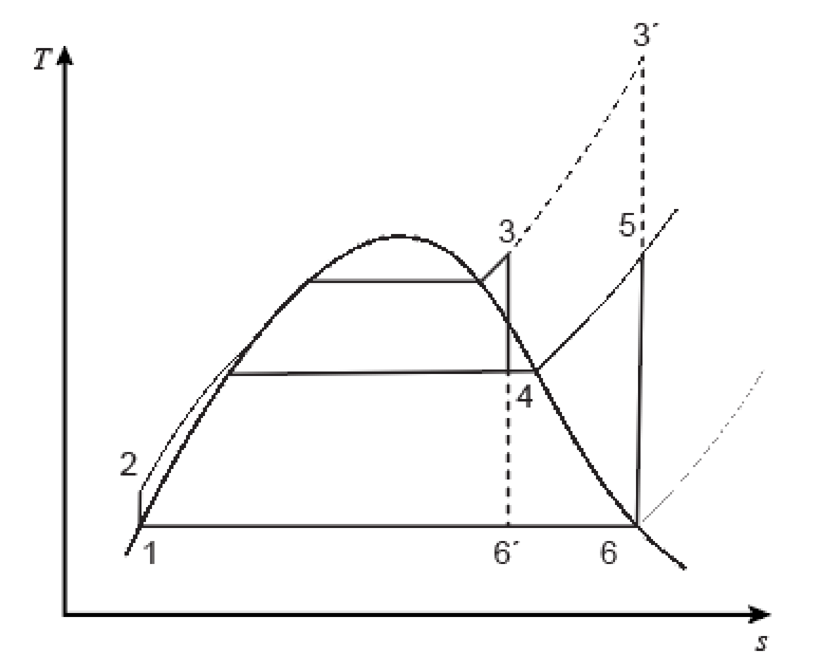
- ► **Total work developed in the two turbine stages**: processes 1-2 and 3-4.
- ► **Total heat added during vaporization/superheating and reheating**: processes 6-1 and 2-3.



$$\eta = \frac{\dot{W}_{t_{HP}} + \dot{W}_{t_{LP}} - \dot{W}_p}{\dot{Q}_{6\text{-}1} + \dot{Q}_{2\text{-}3}}$$

Reheat Rankine cycle





A reheat Rankine cycle

Example 2.9

Reconsider the Rankine cycle in Example 2.6, where the operating pressure of the steam generator and the condenser are 10,000 and 10 kPa, respectively, and the turbine inlet steam is superheated at the temperature of 600°C. If the expansion process occurs in two stages with a reheater with the pressure of 1,000 kPa in between, determine the specific heat transfers in the steam generator and the condenser, the specific work involved in the turbine and the pump, and the thermal efficiency of the cycle. The outlet flows of the steam generator and the reheater are at the same temperature.

Note: This steam power plant is sometimes expressed as 100/600/600 (100 bar/600°C/600°C, steam generator pressure/high pressure turbine inlet temperature/low pressure turbine inlet temperature).

Effects of the reheater on the performance of the cycle in Examples 2.6 and 2.9

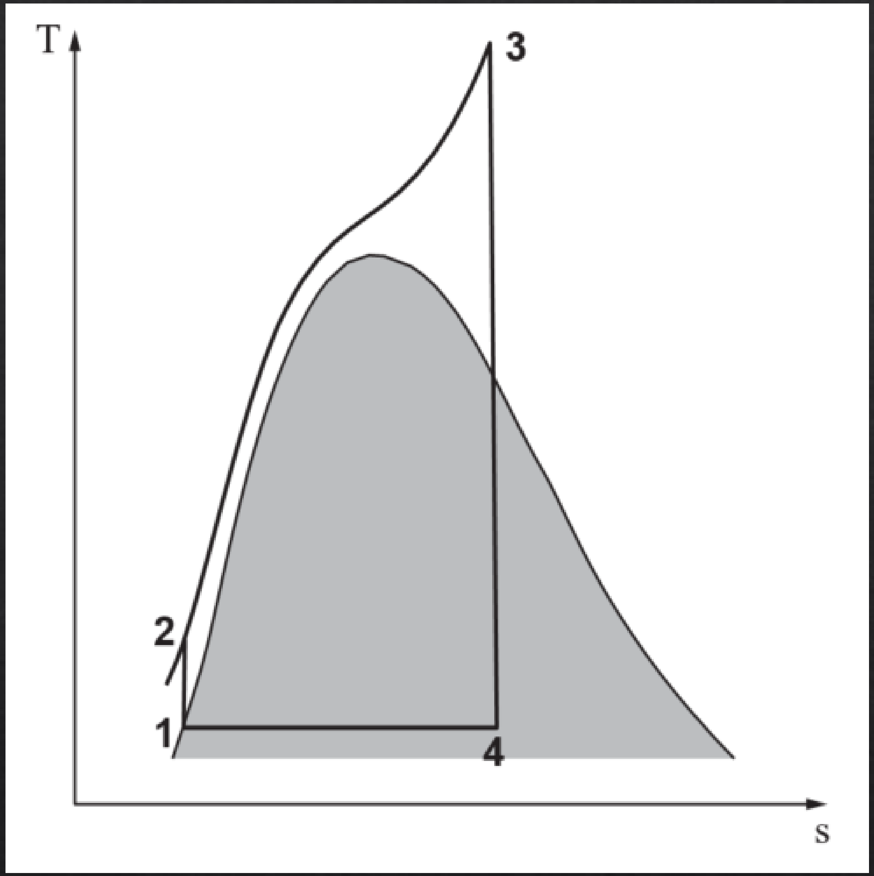
Type of Cycle: Rankine Cycle	$P_2 = P_3$ (kPa)	$P_1 = P_6$ (kPa)	x_4 or x_6	q_{SG} (kJ/kg)	q_{Cond} (kJ/kg)	w_{Pump} (kJ/kg)	w_{Turb} (kJ/kg)	w_{Net} (kJ/kg)	η_{Th} (%)
Without reheater (Example 2.6)	10,000	10	0.834	3423.4	1994.9	10.1	1438.6	1428.5	41.73
With reheater (Example 2.9)	10,000	10	0.984	4189.5	2354.1	10.1	1845.5	1835.4	43.81

Note: A double-reheat steam power plant is expressed as: steam generator pressure/high pressure turbine inlet temperature/intermediate pressure turbine inlet temperature/low pressure turbine inlet temperature.

Effects of the reheater pressure on the performance of the cycle

Reheater Pressure at Rankine Cycle (kPa)	$P_2 = P_3$ (kPa)	$P_1 = P_6$ (kPa)	x_6	q_{SG} (kJ/kg)	q_{Cond} (kJ/kg)	w_{Pump} (kJ/kg)	w_{Turb} (kJ/kg)	w_{Net} (kJ/kg)	η_{Th} (%)
1000 (Example 2.9)	10,000	10	0.984	4189.5	2354.1	10.1	1845.5	1835.4	43.81
1500	10,000	10	0.958	4087.6	2293.4	10.1	1804.3	1794.2	43.89
2000	10,000	10	0.940	4008.6	2250.0	10.1	1768.8	1758.7	43.87
4000	10,000	10	0.896	3791.5	2143.5	10.1	1658.1	1648.0	43.46
8000	10,000	10	0.849	3523.6	2032.5	10.1	1501.2	1491.1	42.32

Supercritical steam power plant



T-s diagram of a supercritical Rankine cycle

Supercritical Ideal Reheat Cycle (1 of 2)

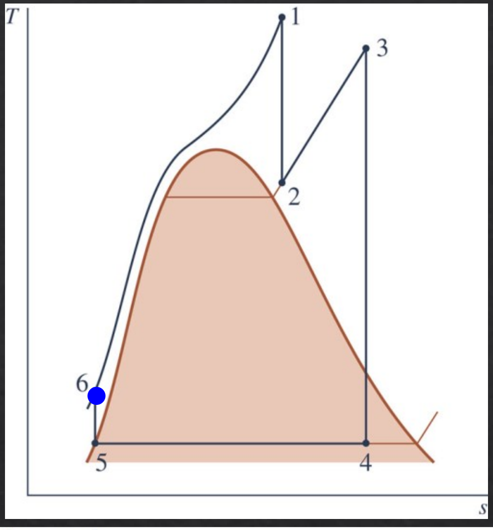
- Steady improvements over many decades in materials and fabrication methods have permitted significant increases in maximum allowed temperatures and steam generator pressures.
- These efforts are embodied in the ***supercritical*** reheat cycle.

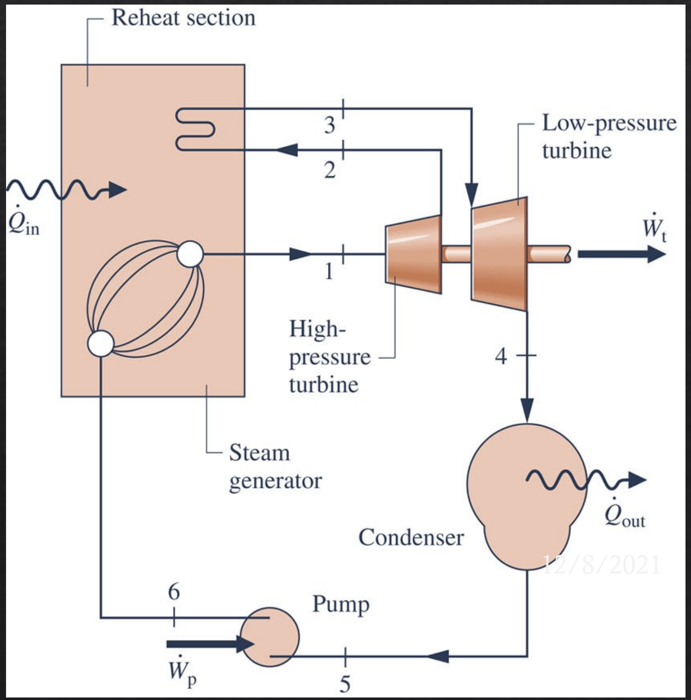
Supercritical Ideal Reheat Cycle (2 of 2)

► Steam generation occurs at a pressure greater than the critical pressure of water: Process 6-1.

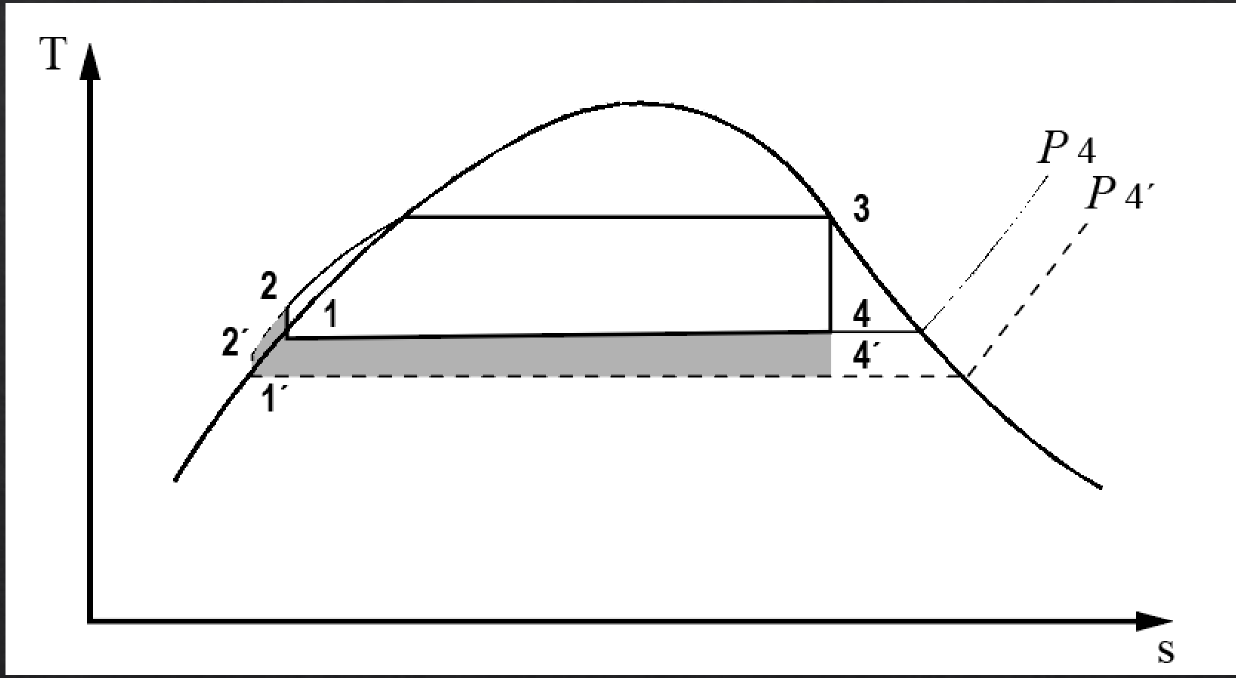
► No phase change occurs during process 6-1. Instead, water flowing through tubes is heated from liquid to vapor without the bubbling associated with boiling.

► Today's supercritical plants achieve thermal efficiencies up to 47%. ***Ultrasupercritical*** plants capable of operating at still higher temperatures and steam generator pressures will have thermal efficiencies exceeding 50%.





Effects of pressure and temperature of turbine exhaust



Effects of the operating temperature and pressure of the condenser on the performance of the cycle

Example 2.8

Similar to Example 2.6, in a Rankine cycle, the inlet flow to the turbine is superheated steam at the pressure of 10,000 kPa and the temperature of 600°C. If the outlet stream of the condenser is saturated water and the operating pressure of the condenser is 40 kPa, determine the specific heat transfers in the steam generator and the condenser, the specific work involved in the turbine and the pump, and the thermal efficiency of the cycle.

Given: Similar to Example 2.6.

Find: Similar to Example 2.6.

Assumptions: Similar to Example 2.6.

Effects of the operating pressure of the condenser on the performance of the cycle in Example 2.8

Type of Cycle: Simple Rankine– Condenser Pressure:	$P_2' = P_3$ (kPa)	$P_1' = P_4'$ (kPa)	x_4'	q_{SG} (kJ/kg)	q_{Cond} (kJ/kg)	w_{Pump} (kJ/kg)	w_{Turb} (kJ/kg)	w_{Net} (kJ/kg)	η_{Th} (%)
5 kpa	10,000	5	0.811	3478.8	1966.0	10.05	1522.8	1512.8	43.49
10 kPa (Example 2.6)	10,000	10	0.834	3423.4	1994.9	10.09	1438.6	1428.5	41.73
20 kPa	10,000	20	0.858	3363.7	2023.2	10.15	1350.7	1340.6	39.85
40 kPa (Example 2.8)	10,000	40	0.885	3297.5	2051.3	10.23	1256.4	1246.2	37.79
80 kPa	10,000	80	0.914	3223.3	2079.1	10.30	1154.5	1144.2	35.50
100 kPa	10,000	100	0.925	3197.5	2087.8	10.33	1120.0	1109.7	34.71

To summarize, the improvement of the net specific output power and efficiency of the cycle can be achieved by

- Superheating steam in the steam generator
- Increasing the operating pressure of the steam generator
- Lowering the operating pressure of the condenser
- Reheat

Increasing the quality of the steam leaving the turbine can be achieved by

- Superheating steam in the steam generator
- Decreasing the operating pressure of the steam generator
- Increasing the operating pressure of the condenser

End of Lecture!