



Thermodynamics I

Vapor Power Cycles

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Content

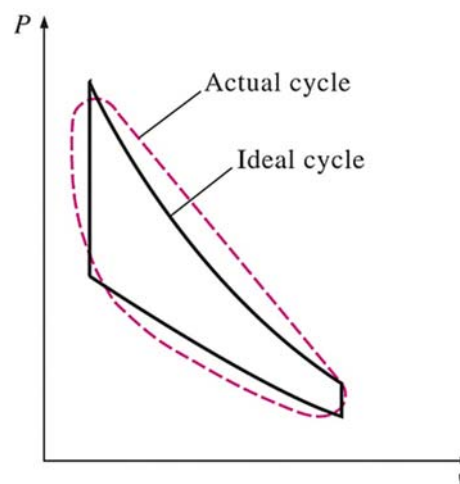


- Introduction
- Work in HE
- Carnot HE
- Rankine Cycle
 - Deviation for Rankine Cycle
 - Increasing the efficiency of Rankine Cycle



Introduction

- Two important areas of application for thermodynamics are power generation and refrigeration.
- Both are usually accomplished by systems that operate on a thermodynamic cycle. Thermodynamic cycles can be divided into two general categories:
 - i. *power cycles*
 - ii. *refrigeration cycles*
- Most power-producing devices operate on cycles.
- **Ideal cycle:** A cycle that resembles the actual cycle closely but is made up totally of internally reversible processes is called an.
- **Reversible cycles** such as **Carnot cycle** have the highest thermal efficiency of all heat engines operating between the same temperature levels. Unlike ideal cycles, they are totally reversible, and unsuitable as a realistic model.



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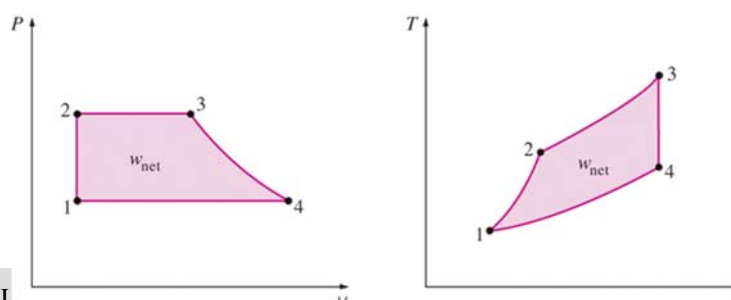
Introduction

On a T - s diagram, the ratio of the area enclosed by the cyclic curve to the area under the heat-addition process curve represents the thermal efficiency of the cycle. **Any modification that increases the ratio of these two areas will also increase the thermal efficiency of the cycle.**

The idealizations and simplifications in the analysis of power cycles:

1. The cycle does not involve any *friction*. Therefore, the working fluid does not experience any pressure drop as it flows in pipes or devices such as heat exchangers.
2. All expansion and compression processes take place in a *quasi-equilibrium* manner.
3. The pipes connecting the various components of a system are well insulated, and *heat transfer* through them is negligible.

- On both P - v and T - s diagrams, the area enclosed by the process curve represents the net work of the cycle.



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Work in HE

- Cyclic heat engines consisting of four separate processes.
- The engines can be operated as steady-state devices involving shaft work and have a working fluid that changes phase during the processes in the cycle, or may have a single-phase working fluid throughout
- Or as cylinder/piston devices involving boundary-movement work normally have a gaseous working fluid throughout the cycle.
- For a reversible steady-state process involving negligible kinetic and potential energy changes, the shaft work per unit mass is given

$$w = - \int v dP$$

- There is no work involved in a constant-pressure process,

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Work in HE

- For a reversible process involving a simple compressible substance, the boundary movement work per unit mass is given

$$w = \int P dv$$

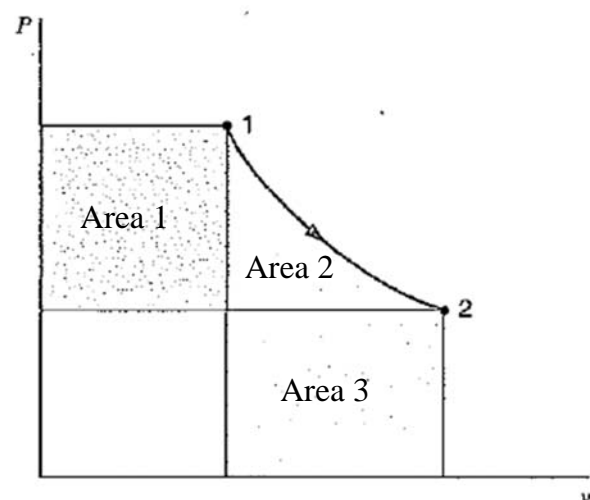
- There is no work involved in a constant-volume process.

$$w = - \int v dP = \text{Area 1} + \text{Area 2}$$

$$w = \int P dv = \text{Area 2} + \text{Area 3}$$

Thermal efficiency of heat engines

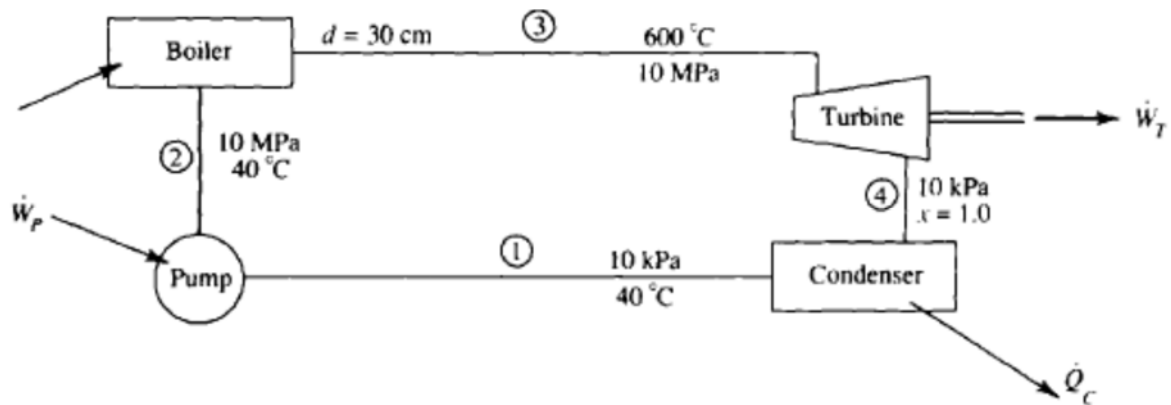
$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad \text{or} \quad \eta_{th} = \frac{w_{net}}{q_{in}}$$



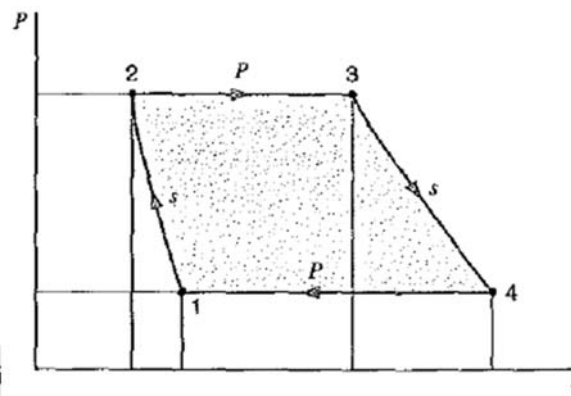
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Work in HE



- The two heat-transfer processes (boiler and condenser) constant-pressure processes involving no work.
- The turbine and pump processes are both adiabatic, such that they are therefore isentropic processes



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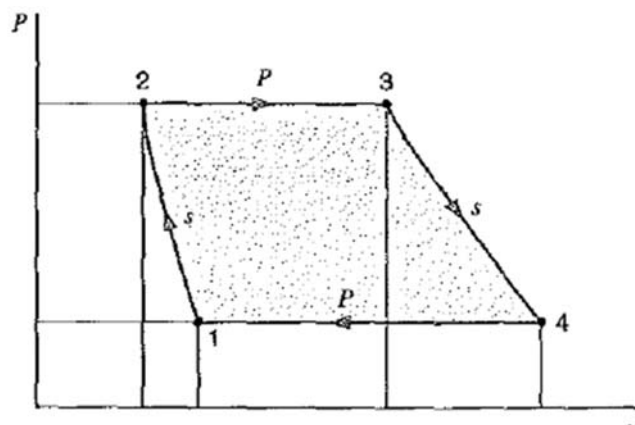
Work in HE



$$w_{\text{net}} = -\int_1^2 v dP + 0 - \int_3^4 v dP + 0 = -\int_1^2 v dP + \int_4^3 v dP$$

- $P_2 = P_3$ and also $P_1 = P_4$, the system produces a net work output because the specific volume is larger during the expansion from 3 to 4 than it is during the compression from 1 to 2.

$$\int_1^2 v dP \text{ Area} < \int_4^3 v dP \text{ Area}$$



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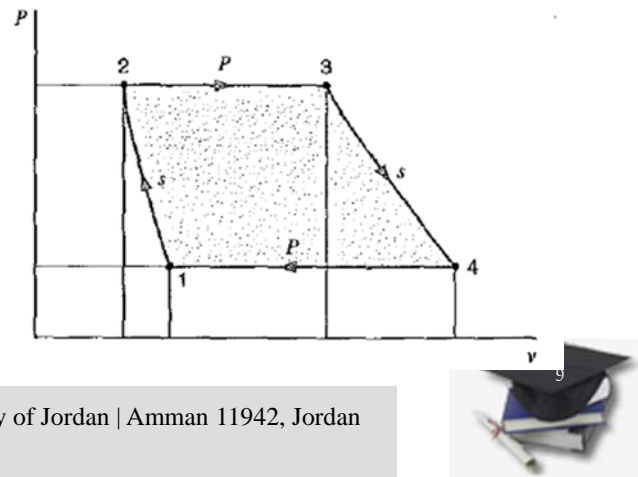


Work in HE

- If the four-process cycle shown were accomplished in a cylinder/piston system involving boundary-movement work, then the net work output for this power system is

$$w_{\text{net}} = \int_1^2 P dv + \int_2^3 P dv + \int_3^4 P dv + \int_4^1 P dv$$

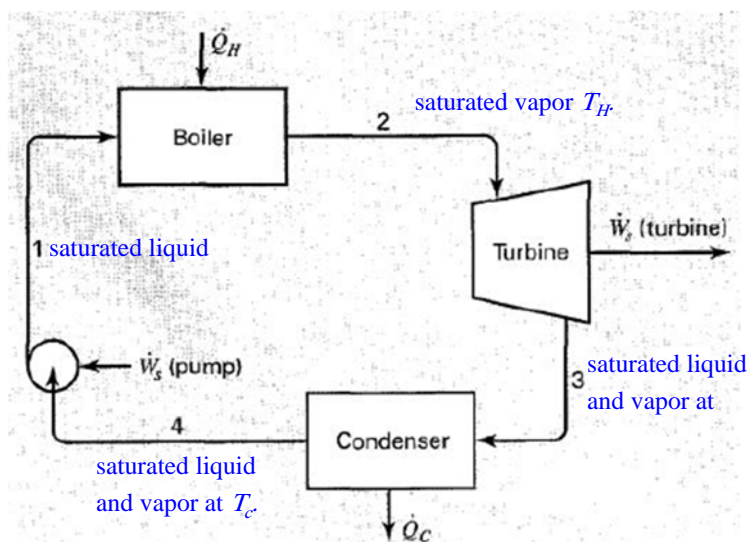
- The pressure is higher during any given change in volume in the two expansion processes than in the two compression processes, resulting in a net positive area and a net work output.
- The net work output of the cycle is equal to the area enclosed by the process lines 1-2-3-1, and this area is the same for both cases, even though the work terms for the four individual processes are different for the two cases



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Carnot HE

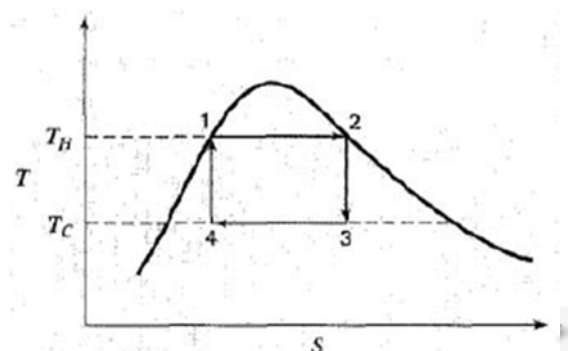


Simple steam power plant

$$\eta \equiv \frac{|W|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$

Isentropic expansion (W_s)

Carnot Cycle in T-S diagram



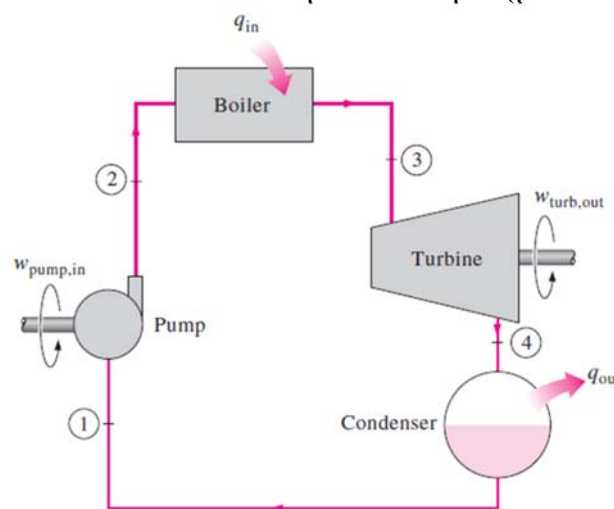
η increases as T_H increases and as T_C decreases.

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Rankine Cycle

- Severe practical difficulties attend the operation of equipment intended to carry out steps 2 to 3 and 4 to 1.
- Turbines that take in saturated steam produce an exhaust with high liquid content, which causes severe erosion problems.
- Even more difficult is the design of a pump that takes in a mixture of liquid and vapor (point 1) and discharges a saturated liquid (point 2).
- Rankine cycle, which is the ideal, four steady state process cycle, utilizing a phase change between vapor and liquid to maximize the difference in specific volume during expansion and compression.
- This is the idealized model for a steam power plant system.
- Equations pertaining to steady-flow systems should be used in the analysis of the Rankine cycle.



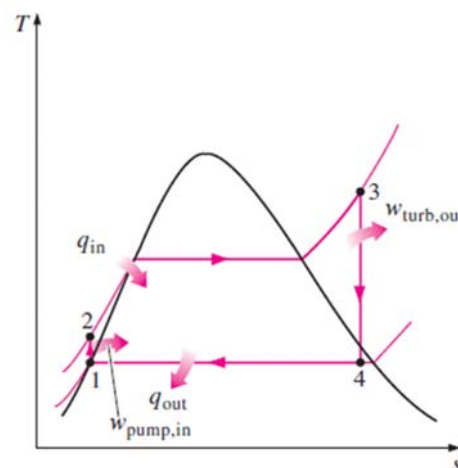
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Rankine Cycle

- 2 to 3: A constant-pressure heating process in a boiler. The step lies along an isobar (the pressure of the boiler), and consists of three sections:
 - Heating of subcooled liquid water to its saturation temperature,
 - Vaporization at constant temperature and pressure, and
 - Superheating of the vapor to a temperature well above its saturation temperature
- 3 to 4: Reversible, adiabatic (isentropic) expansion of vapor in a turbine to the pressure of the condenser. The step normally crosses the saturation curve, producing a wet exhaust.
- 4 to 1 **A constant-pressure, constant-temperature process in a condenser to produce saturated liquid at point 4.**
- 1 to 2: Reversible, adiabatic (isentropic) pumping of the saturated liquid to the pressure of the boiler, producing compressed (subcooled) liquid.



Rankine Cycle

Pump ($q = 0$): $w_{\text{pump,in}} = h_2 - h_1 = \int_1^2 v \, dP \quad s_2 = s_1$

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

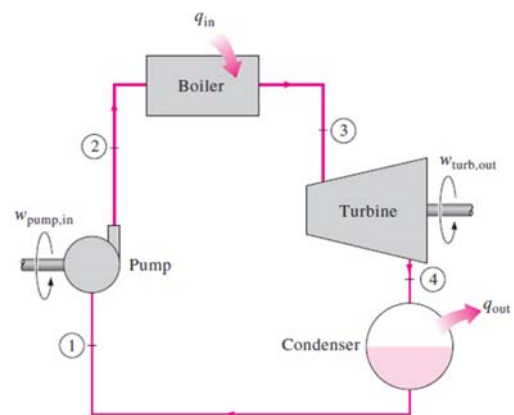
where

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

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

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

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



The thermal efficiency of the Rankine cycle is $\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$

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

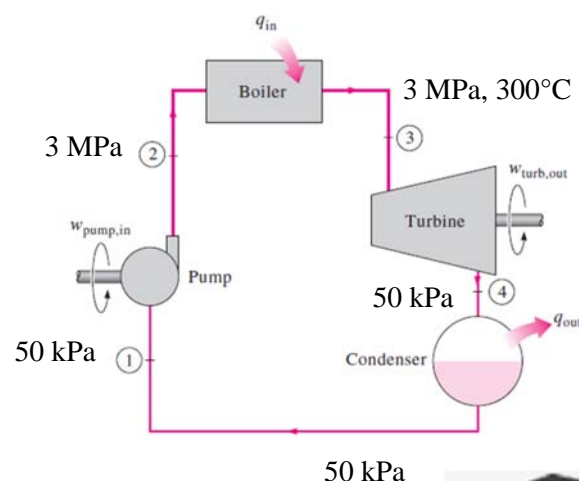
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Example

A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a T - s diagram with respect to saturation lines, and determine (a) the thermal efficiency of the cycle and (b) the net power output of the power plant.



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Example Cont.



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Example Cont.

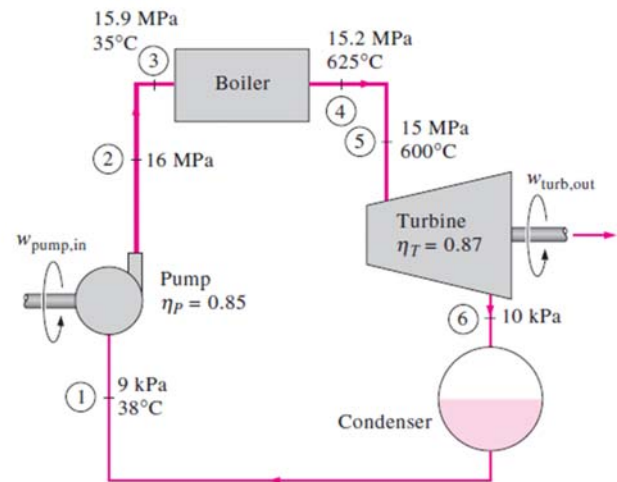


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Example

A steam power plant operates on the cycle shown. 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.



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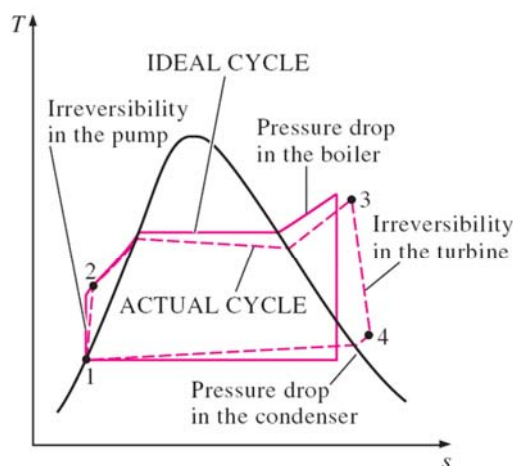
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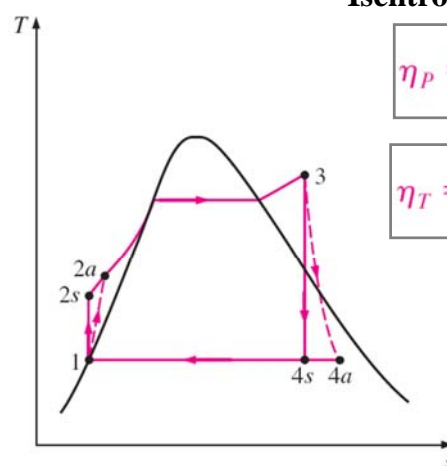


Deviation for Rankine Cycle

- The actual vapor power cycle differs from the ideal Rankine cycle as a result of irreversibilities in various components.
- **Fluid friction** and **heat loss to the surroundings** are the two common sources of irreversibilities.



(a)



(b)

Isentropic efficiencies

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

- (a) Deviation of actual vapor power cycle from the ideal Rankine cycle. (b) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

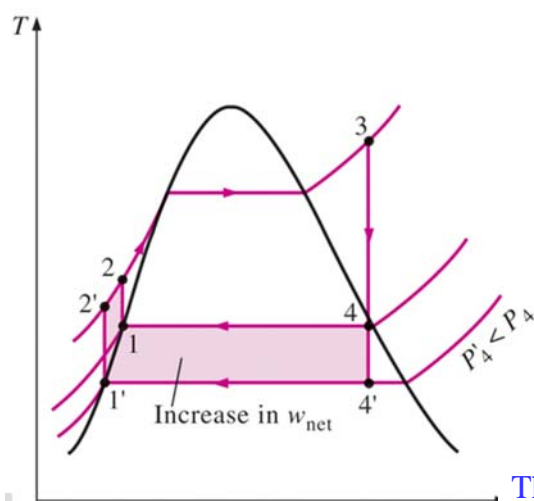
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Increasing the efficiency of Rankine Cycle

- 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.*

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



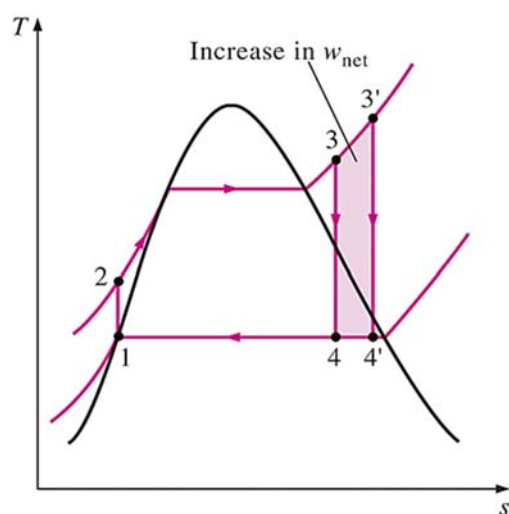
- To take advantage of the increased efficiencies at low pressures, the condensers of steam power plants usually operate well below the atmospheric pressure. There is a lower limit to this pressure depending on the temperature of the cooling medium
- **Side effect:** Lowering the condenser pressure increases the moisture content of the steam at the final stages of the turbine.

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

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Increasing the efficiency of Rankine Cycle

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



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

- Both the net work and heat input increase as a result of superheating the steam to a higher temperature. The overall effect is an increase in thermal efficiency since the average temperature at which heat is added increases.
- Superheating to higher temperatures decreases the moisture content of the steam at the turbine exit, which is desirable.
- The temperature is limited by metallurgical considerations. Presently the highest steam temperature allowed at the turbine inlet is about 620°C.

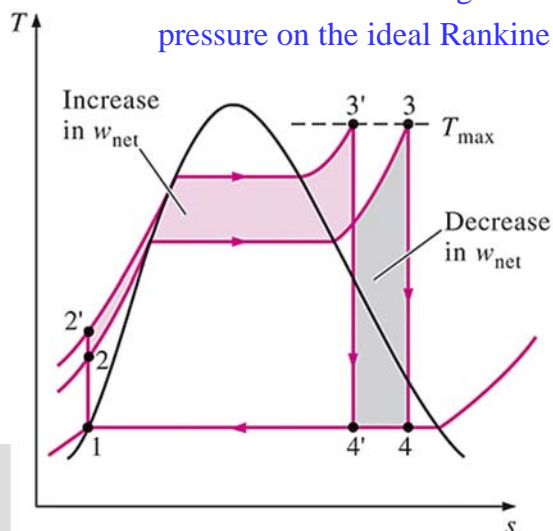


Increasing the efficiency of Rankine Cycle

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

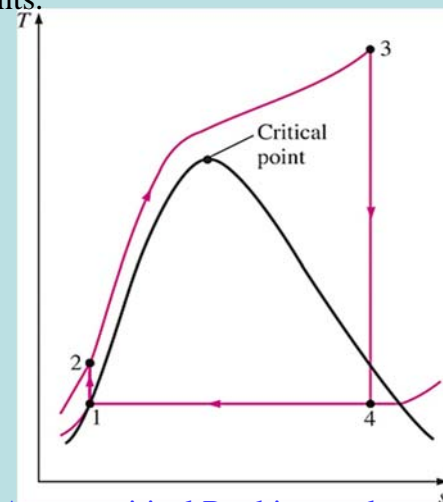
- For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases. This side effect can be corrected by reheating the steam.

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



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



A supercritical Rankine cycle.

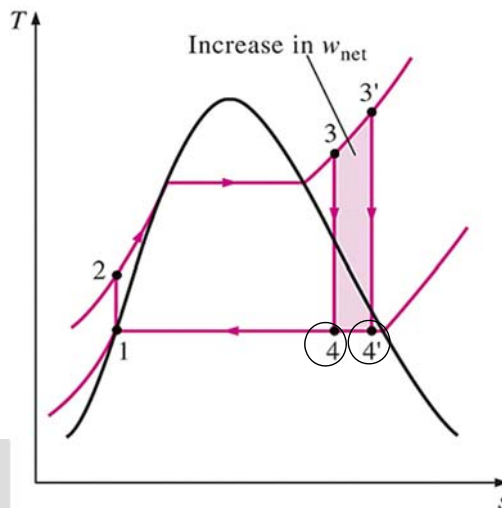
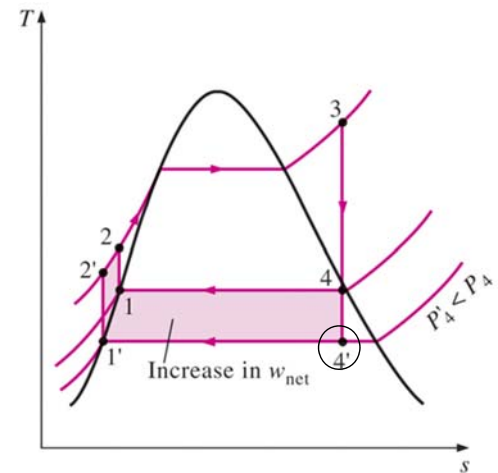
Summary

- The efficiency of the Rankine cycle can be increased by
 - Lowering the exhaust pressure,
 - Increasing the pressure during heat addition, and
 - Superheating the steam.
- The quality of the steam leaving the turbine is
 - Increased by superheating the steam and
 - Decreased by lowering the exhaust pressure and
 - Decreased by increasing the pressure during heat addition.



The Ideal Reheat Rankine Cycle

- The increase in pressure also increases the moisture content of the steam in the low-pressure end of the turbine.
- To avoid this, Two possibilities come to mind
 - Superheat the steam to very high temperatures before it enters the turbine.



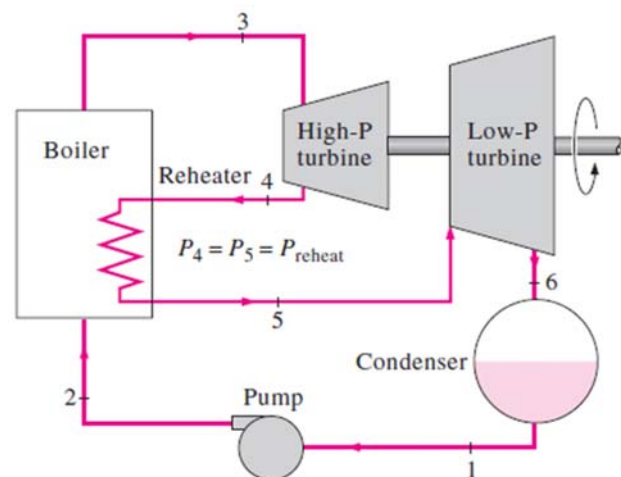
- This requires raising the steam temperature to metallurgically unsafe levels



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The Ideal Reheat Rankine Cycle

- The reheat cycle has been developed to take advantage of the increased efficiency with higher pressures, and yet avoid excessive moisture in the low-pressure stages of the turbine.
- The unique feature of this cycle is that the steam is expanded in the turbine in two stages, and reheat it in between.
- 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.

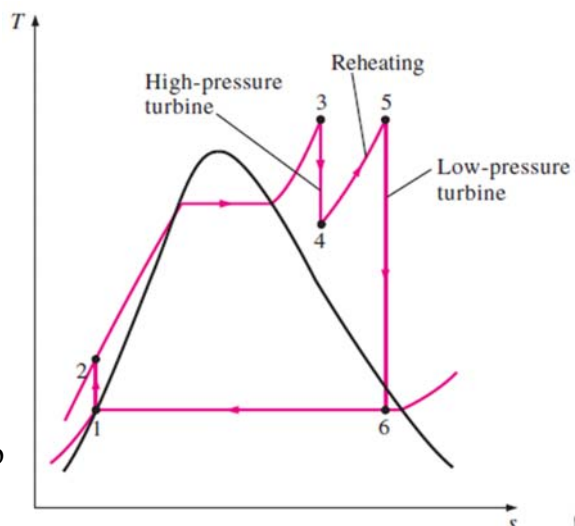


The Ideal Reheat Rankine Cycle

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

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

- 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.
- In an ideal reheat Rankine cycle.
 - The pump and the turbines are isentropic,
 - There are no pressure drops in the boiler and condenser, and
 - Steam leaves the condenser and enters the pump as saturated liquid at the condenser pressure.

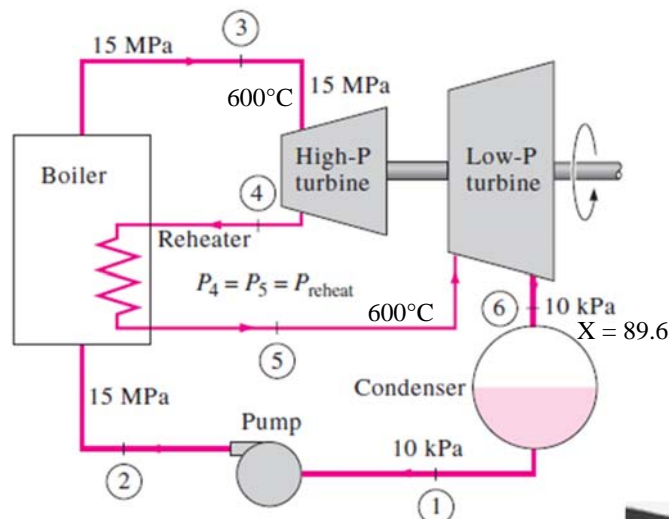


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Example

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.



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Example Cont.



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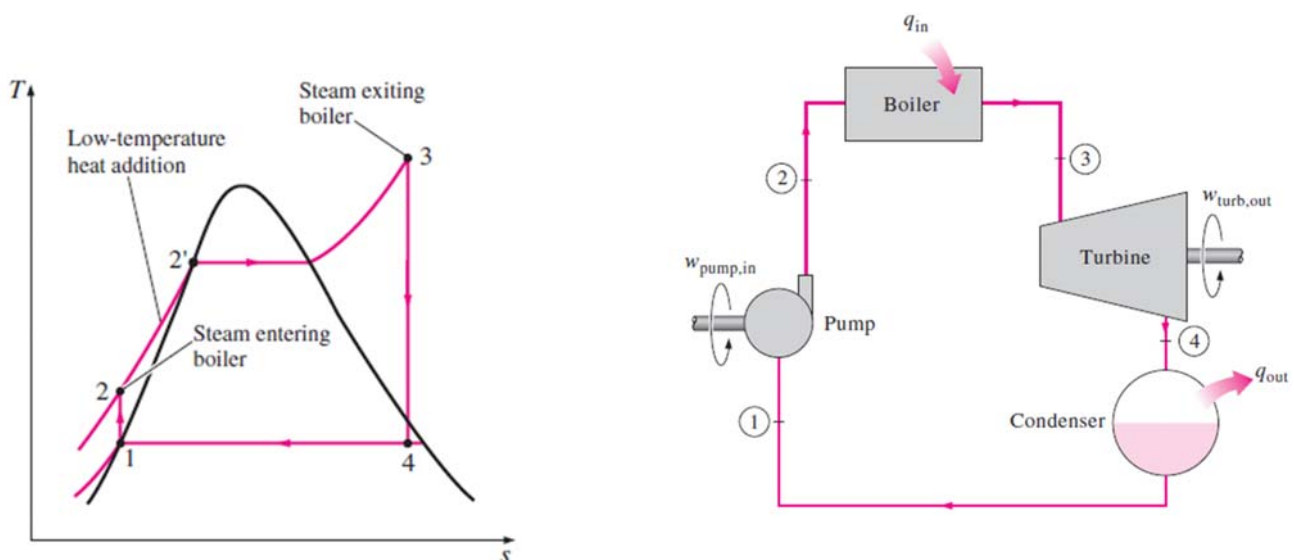


Example Cont.

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The Ideal Regenerative Rankine Cycle



- 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.

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The Ideal Regenerative Rankine Cycle

- To remedy this shortcoming, we look for ways to raise the temperature of the liquid leaving the pump (called the *feedwater*) before it enters the boiler.
- This is accomplished by
 - Extracting, or “bleeding,” steam from the turbine at various points.
 - This steam 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)**.

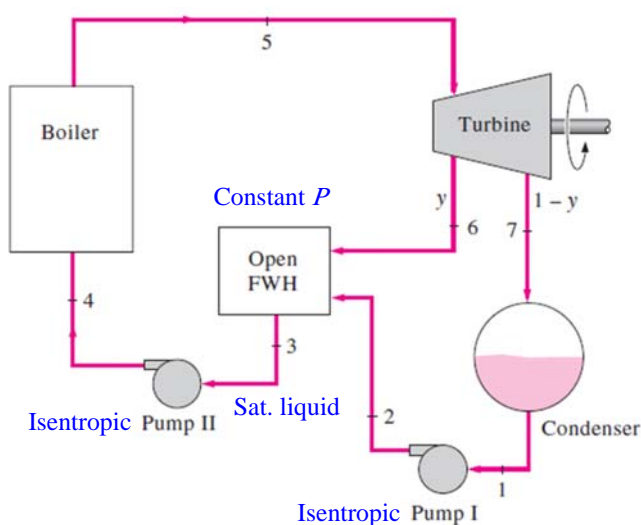
Regeneration

- Improves cycle efficiency,
- Provides a convenient means of deaerating the feedwater (removing the air that leaks in at the condenser) to prevent corrosion in the boiler.
- 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).

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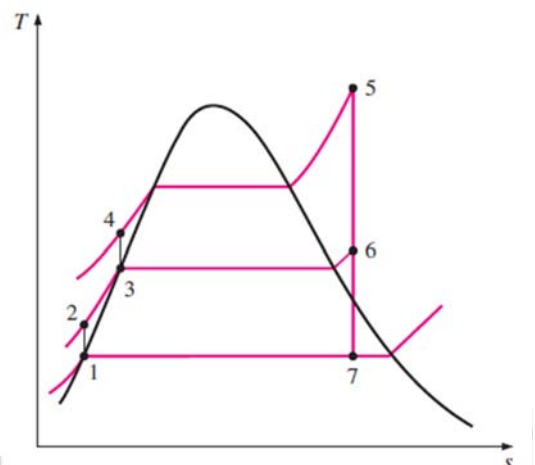
The Ideal Regenerative Rankine Cycle



The ideal regenerative Rankine cycle with an open feedwater heater

$$y = \dot{m}_6 / \dot{m}_5 \quad (\text{fraction of steam extracted})$$

- 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.
- The mixture leaves the heater as a saturated liquid at the heater pressure.



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The Ideal Regenerative Rankine Cycle

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

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

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

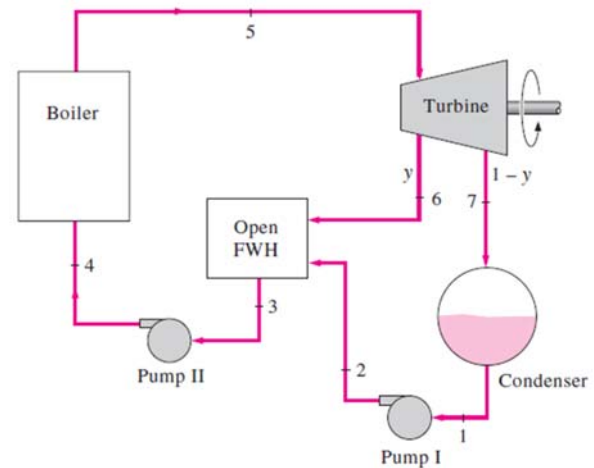
$$w_{\text{pump,in}} = (1 - y)w_{\text{pump I,in}} + w_{\text{pump II,in}}$$

where

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

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

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



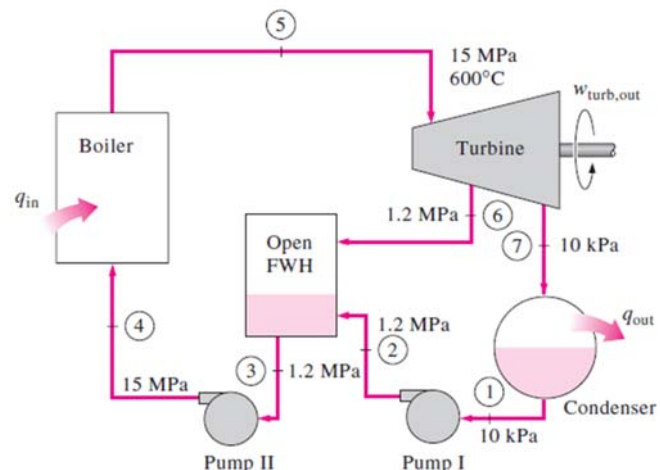
- The thermal efficiency of the Rankine cycle increases because regeneration raises the average temperature at which heat is transferred to the steam in the boiler by raising the temperature of the water before it enters the boiler

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Example

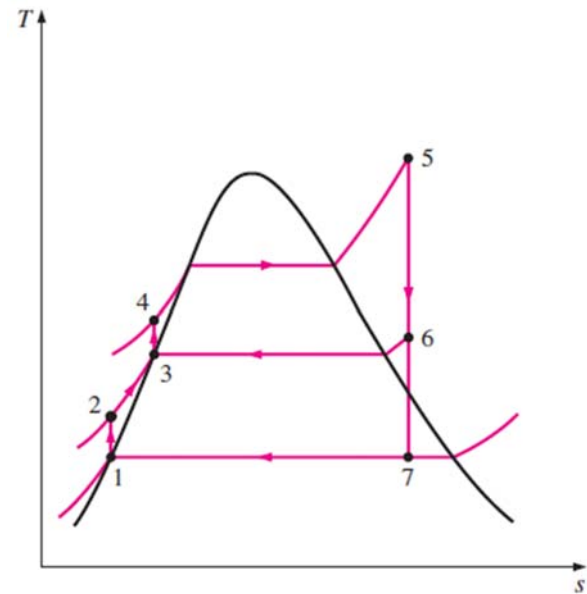
Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feedwater heater. Steam enters the turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. Some steam leaves the turbine at a pressure of 1.2 MPa and enters the open feedwater heater. Determine the fraction of steam extracted from the turbine and the thermal efficiency of the cycle



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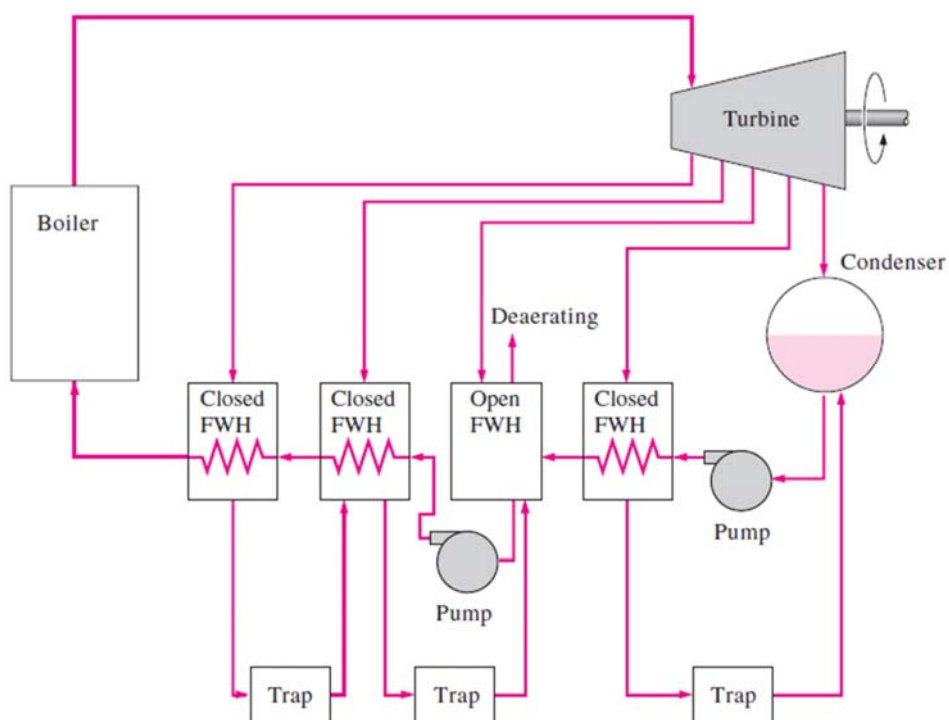
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The Ideal Regenerative Rankine Cycle



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