

# **Chapter 8**

## **Vapor Power Systems**

# Learning Outcomes

- ▶ Demonstrate an understanding of the basic principles of vapor power plants.
- ▶ Develop and analyze thermodynamic models of vapor power plants based on the Rankine cycle and its modifications, including:
  - ▶ sketching schematic and accompanying  $T$ - $s$  diagrams.
  - ▶ evaluating property data at principal states in the cycle.
  - ▶ applying mass, energy, and entropy balances for the basic processes.
  - ▶ determining cycle performance, thermal efficiency, net power output, and mass flow rates.
- ▶ Explain the effects on Rankine cycle performance of varying key parameters.
- ▶ Discuss the principal sources of exergy destruction and loss in vapor power plants.

# Introducing Power Generation

▶ To meet our national power needs there are **challenges** related to

- ▶ Declining economically recoverable supplies of **nonrenewable** energy resources.
- ▶ Effects of global climate change and other environmental and human health and safety issues.
- ▶ Rapidly increasing demand for power owing to increasing population.

▶ Today we are **heavily dependent** on coal, natural gas, and nuclear, all of which are nonrenewable.

## Current U.S. Electricity Generation by Source

Coal	48.5%
Natural gas	21.6%
Nuclear	19.4%
Hydroelectric	5.8%
Other renewables	2.5%
Oil	1.6%
Others	0.6%

# Introducing Power Generation

► While coal, natural gas, and nuclear will continue to play important roles in years ahead, **contributions from** wind power, solar power, and other **renewable sources are expected to be increasingly significant** up to mid-century at least.

**Table 8.2**

<b>Large-Scale Electric Power Generation through 2050 from Renewable and Nonrenewable Sources</b>			
<b>Power Plant Type</b>	<b>Nonrenewable Source</b>	<b>Renewable Source</b>	<b>Thermodynamic Cycle</b>
Coal-fueled	Yes		Rankine
Natural gas-fueled	Yes		Brayton
Nuclear-fueled	Yes		Rankine
Oil-fueled	Yes		Rankine
Biomass-fueled		Yes	Rankine
Geothermal		Yes	Rankine
Solar-concentrating		Yes	Rankine
Hydroelectric		Yes	None
Wind		Yes	None
Solar-photovoltaic		Yes	None
Fuel cells	Yes		None
Currents, tides, and waves		Yes	None

# Introducing Power Generation

▶ Table 8.2 also shows that **thermodynamic cycles** are a **fundamental** aspect of several power plant types that employ renewable or nonrenewable sources.

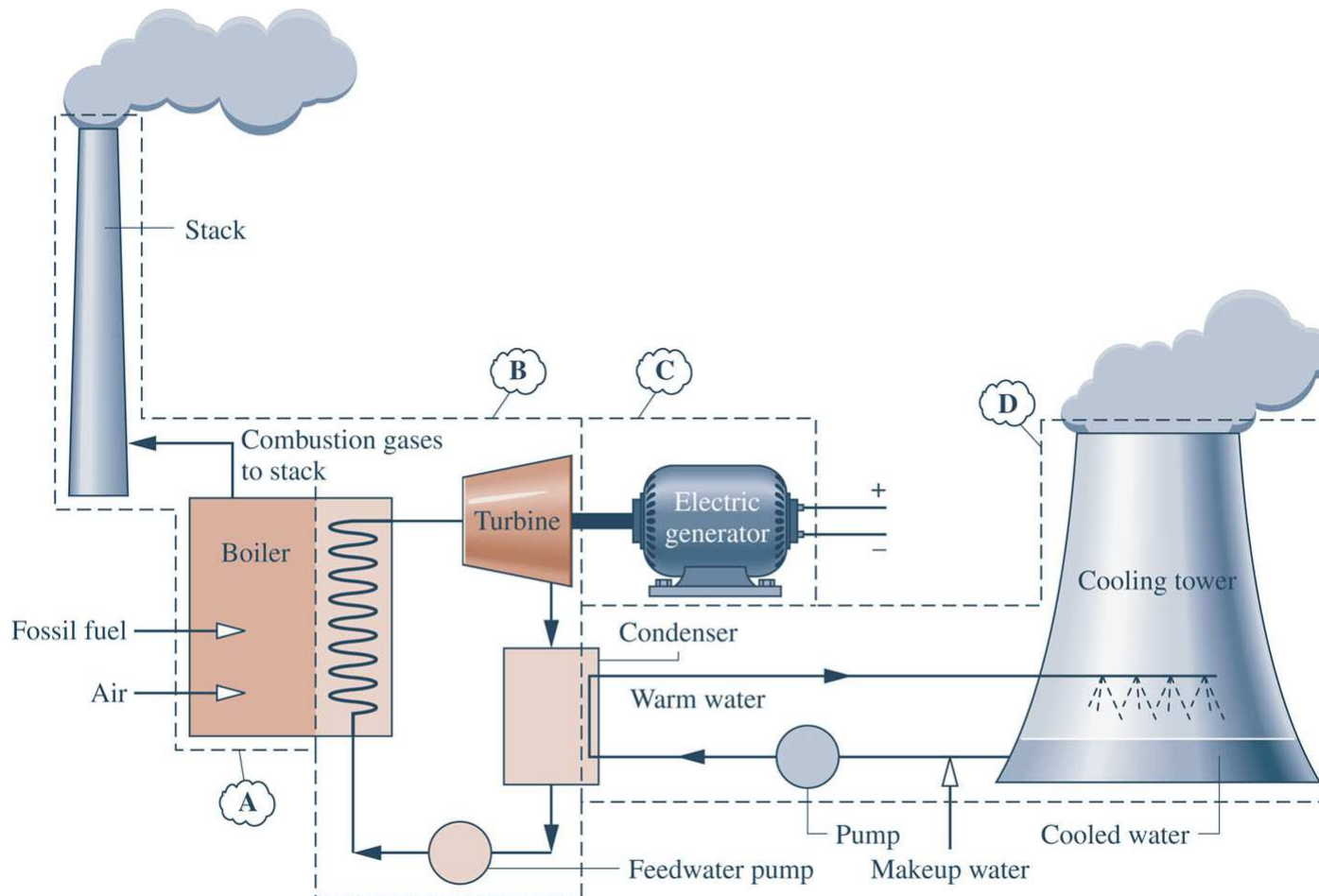
▶ In **Chapters 8** and **9**, vapor power systems, gas turbine power systems, and internal combustion engines are studied as thermodynamic cycles. Vapor power systems in which a working fluid is alternately vaporized and condensed is the focus of **Chapter 8**. The basic building block of vapor power systems is the ***Rankine cycle***.

# Introducing Vapor Power Plants

- ▶ The components of **four alternative vapor power plant configurations** are shown schematically in **Fig. 8.1**. They are
  - ▶ Fossil-fueled vapor power plants.
  - ▶ Pressurized-water reactor nuclear vapor power plants.
  - ▶ Concentrating solar thermal vapor power plants.
  - ▶ Geothermal vapor power plants.
- ▶ In each of the four types of vapor power plant, a **working fluid is alternately vaporized and condensed**. A key difference among the plants is the origin of the energy required to vaporize the working fluid.

# Introducing Vapor Power Plants

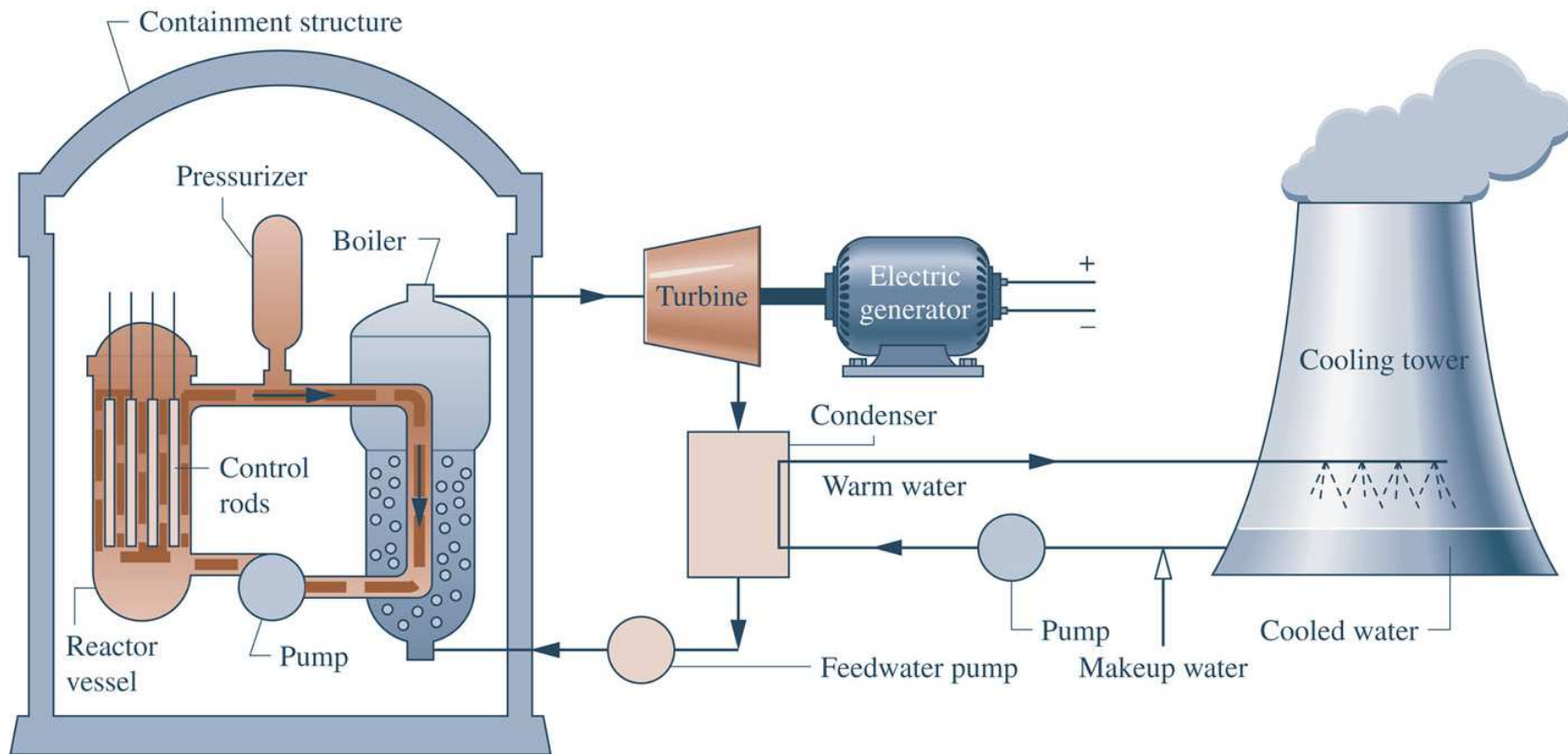
- ▶ In fossil-fueled plants, the energy required for vaporization originates in **combustion of the fuel**.



(a) Fossil-fueled vapor power plant.

# Introducing Vapor Power Plants

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

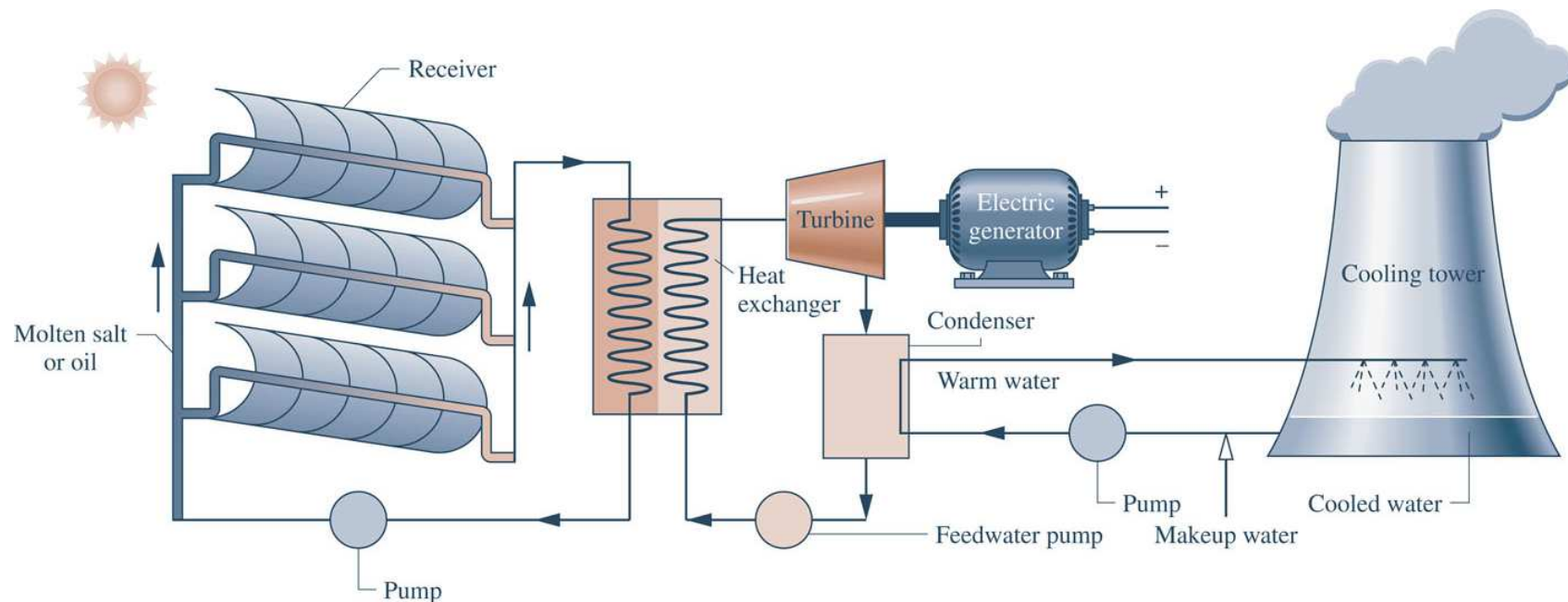


(b) Pressurized-water reactor nuclear vapor power plant.



# Introducing Vapor Power Plants

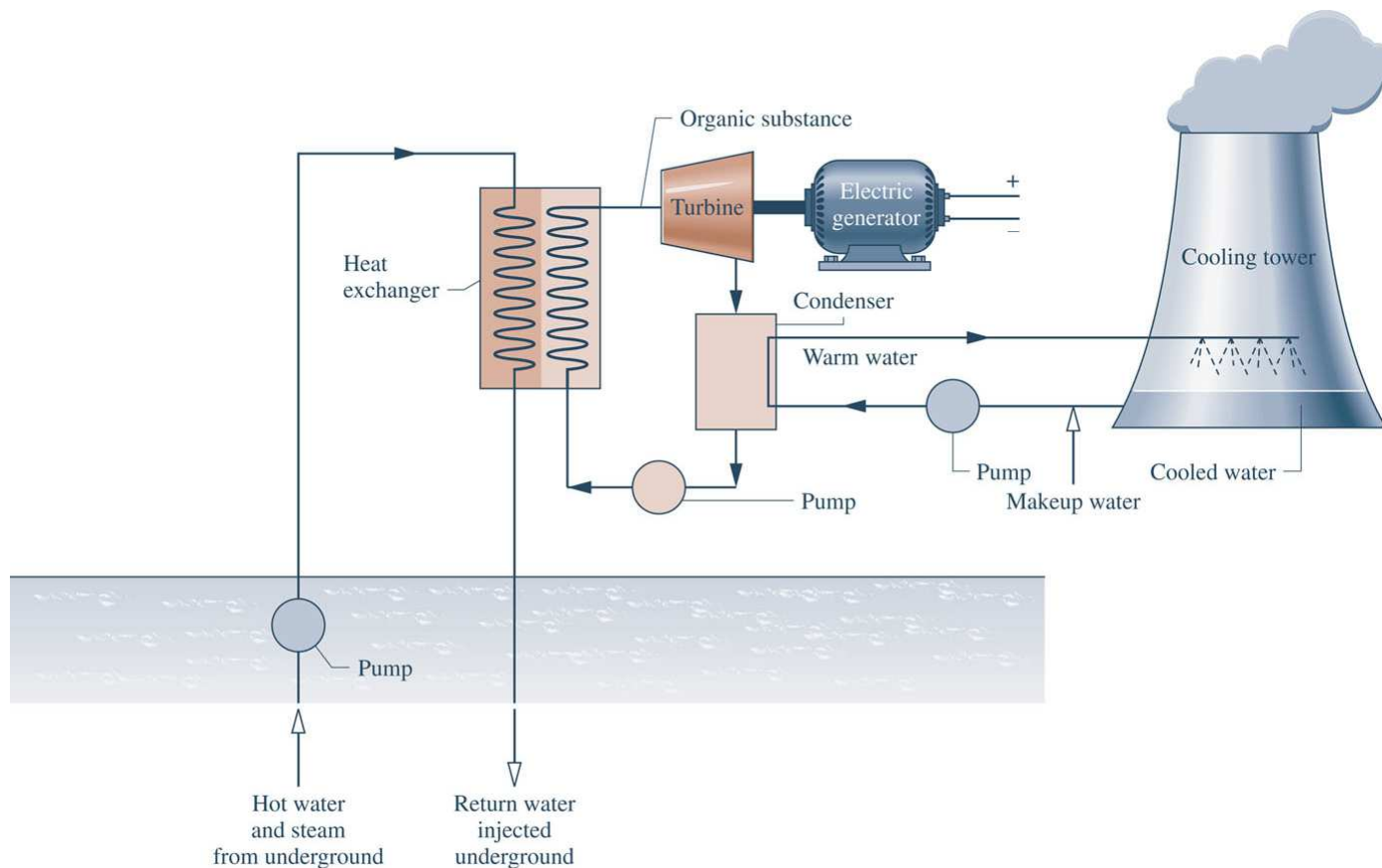
► In solar plants, the energy required for vaporization originates in **collected and concentrated solar radiation**.



(c) Concentrating solar thermal vapor power plant.

# Introducing Vapor Power Plants

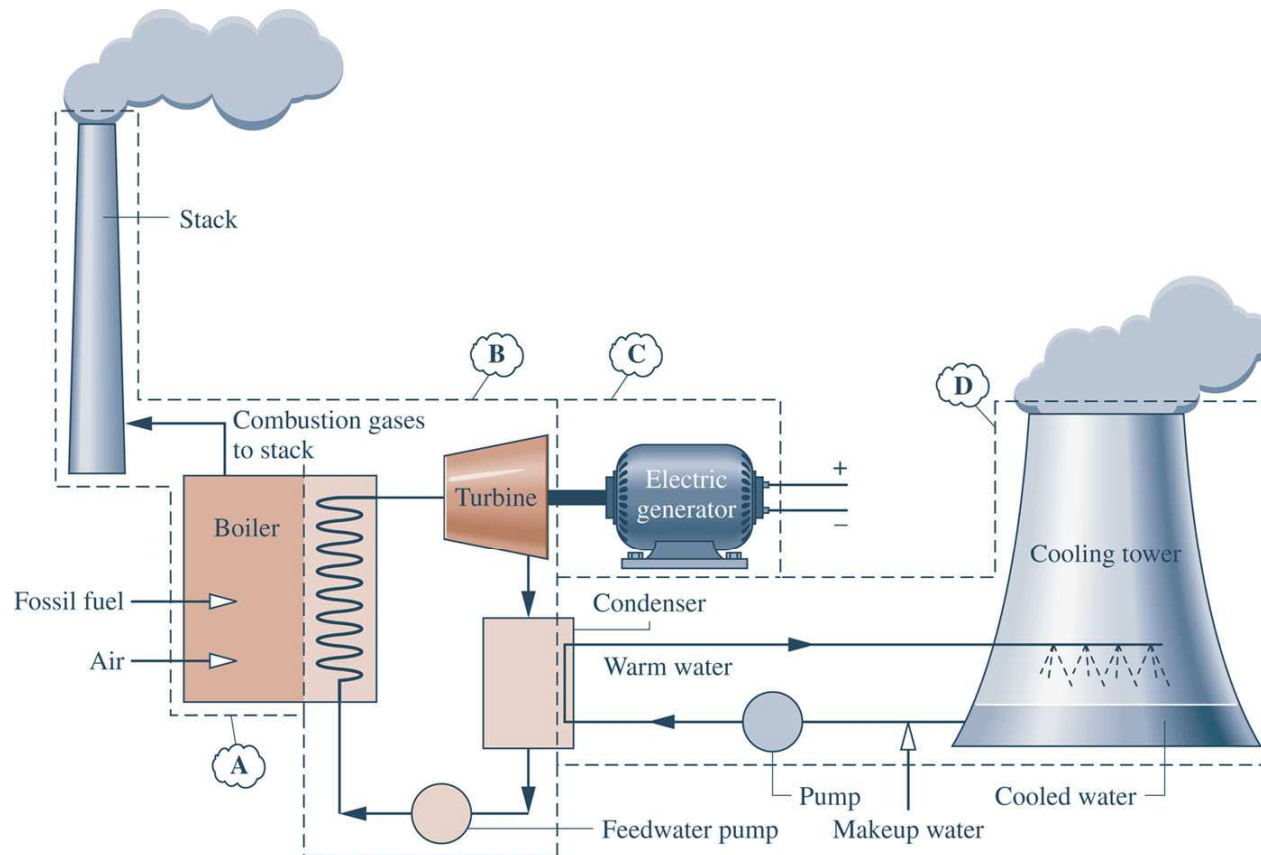
► In geothermal plants, the energy required for vaporization originates in **hot water and/or steam drawn from below the earth's surface.**



(d) Geothermal vapor power plant.

# Introducing Vapor Power Plants

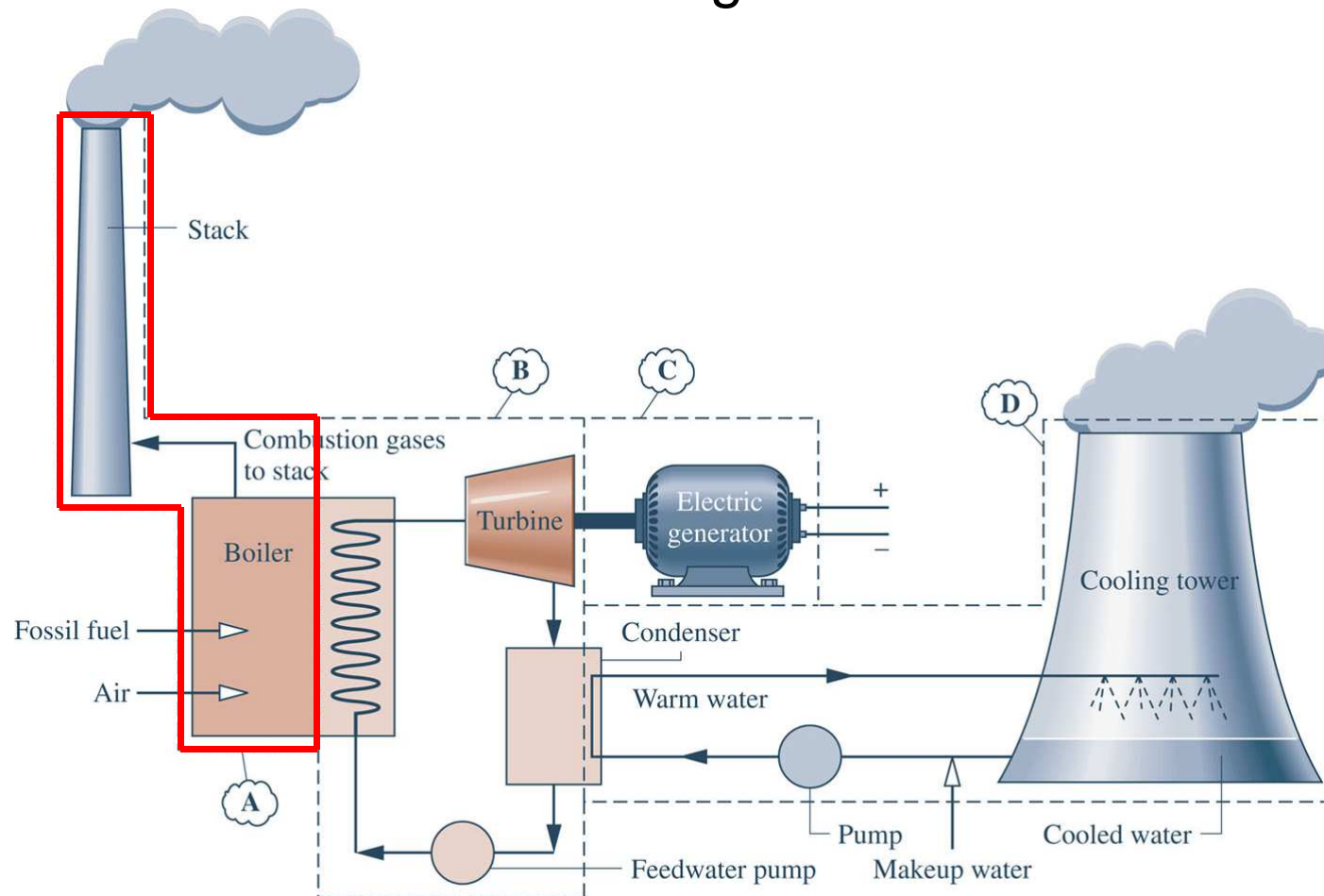
► The fossil-fueled vapor power plant of Fig. 8.1(a) will be considered as representative. The overall plant is broken into **four major subsystems** identified by **A**, **B**, **C**, and **D**. Water is the working fluid.



(a) Fossil-fueled vapor power plant.

# Introducing Vapor Power Plants

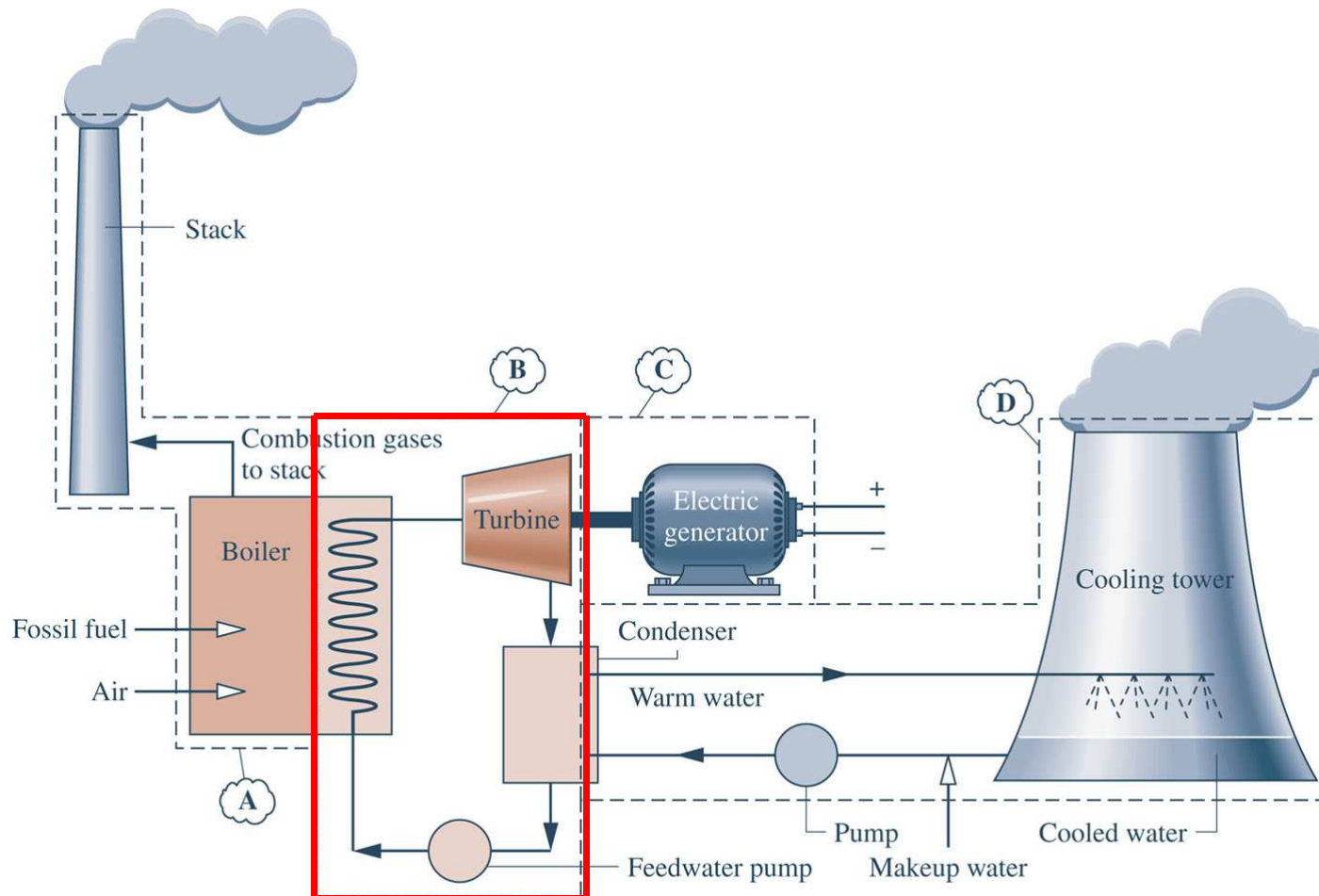
► **Subsystem A provides the heat transfer of energy** needed to vaporize water circulating in subsystem B. In fossil-fueled plants this heat transfer has its origin in the **combustion of the fuel**.



(a) Fossil-fueled vapor power plant.

# Introducing Vapor Power Plants

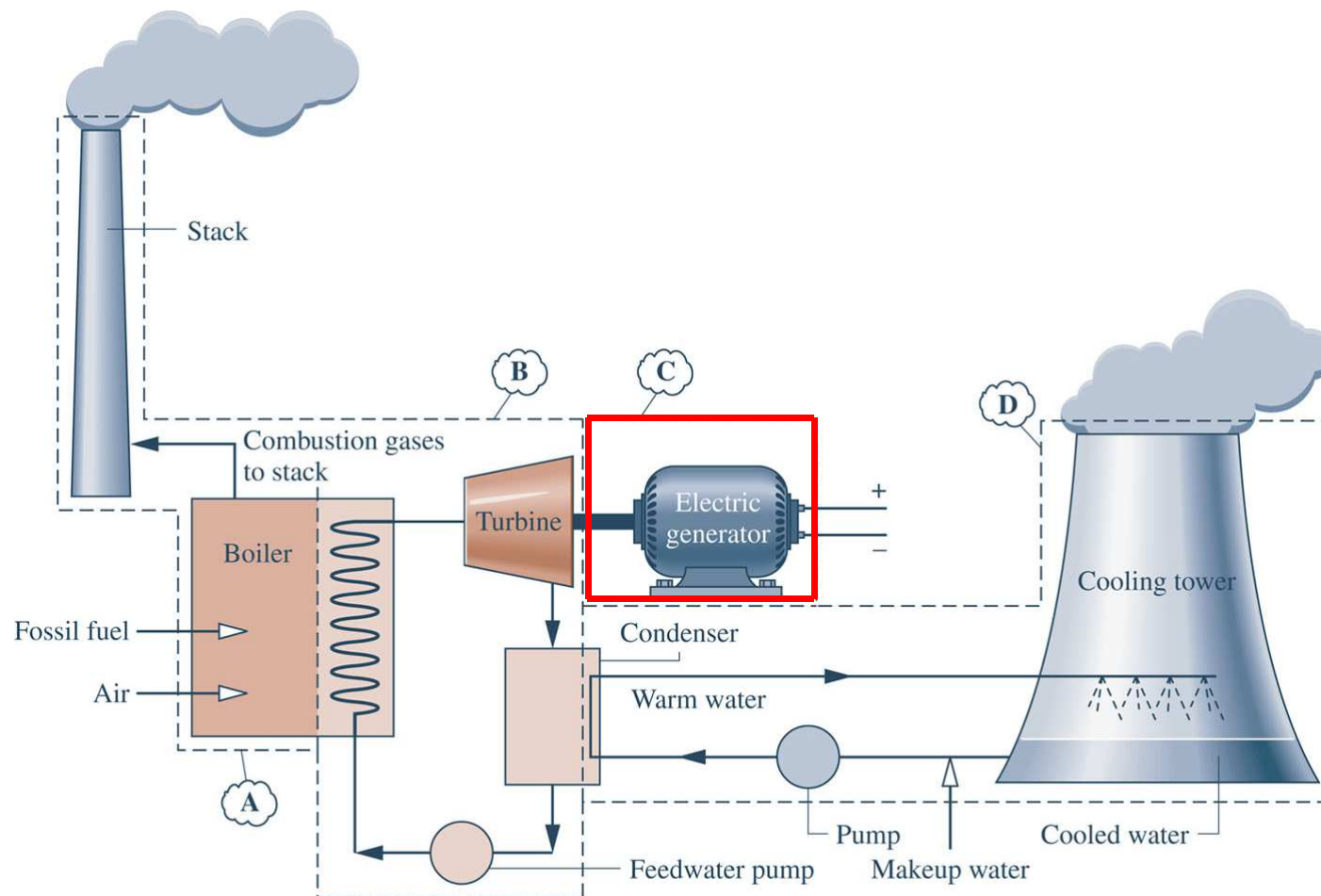
► In subsystem B, the water vapor expands through the turbine, developing power. The water then condenses and returns to the boiler.



(a) Fossil-fueled vapor power plant.

# Introducing Vapor Power Plants

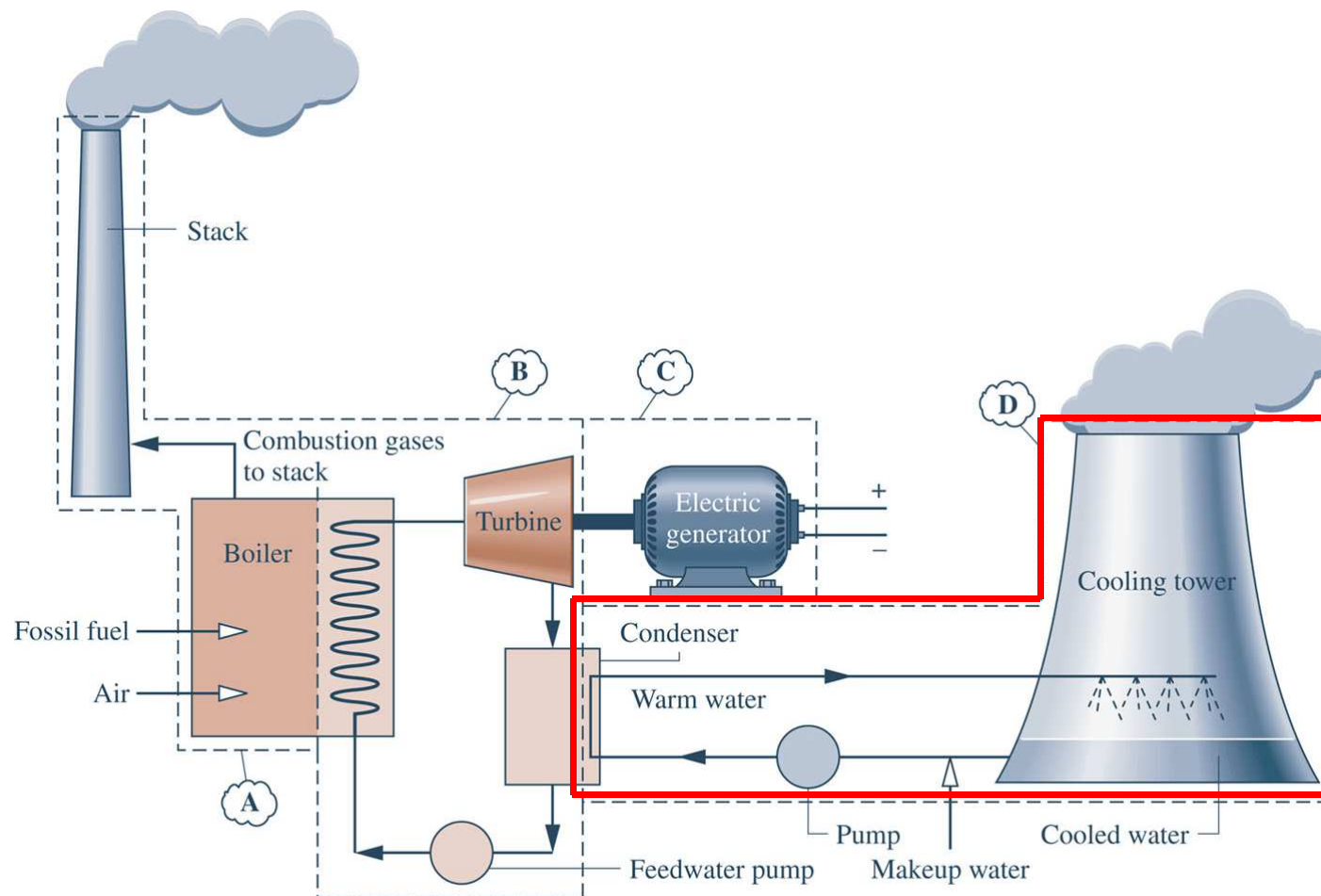
► In subsystem C, power developed by the turbine drives an electric generator.



(a) Fossil-fueled vapor power plant.

# Introducing Vapor Power Plants

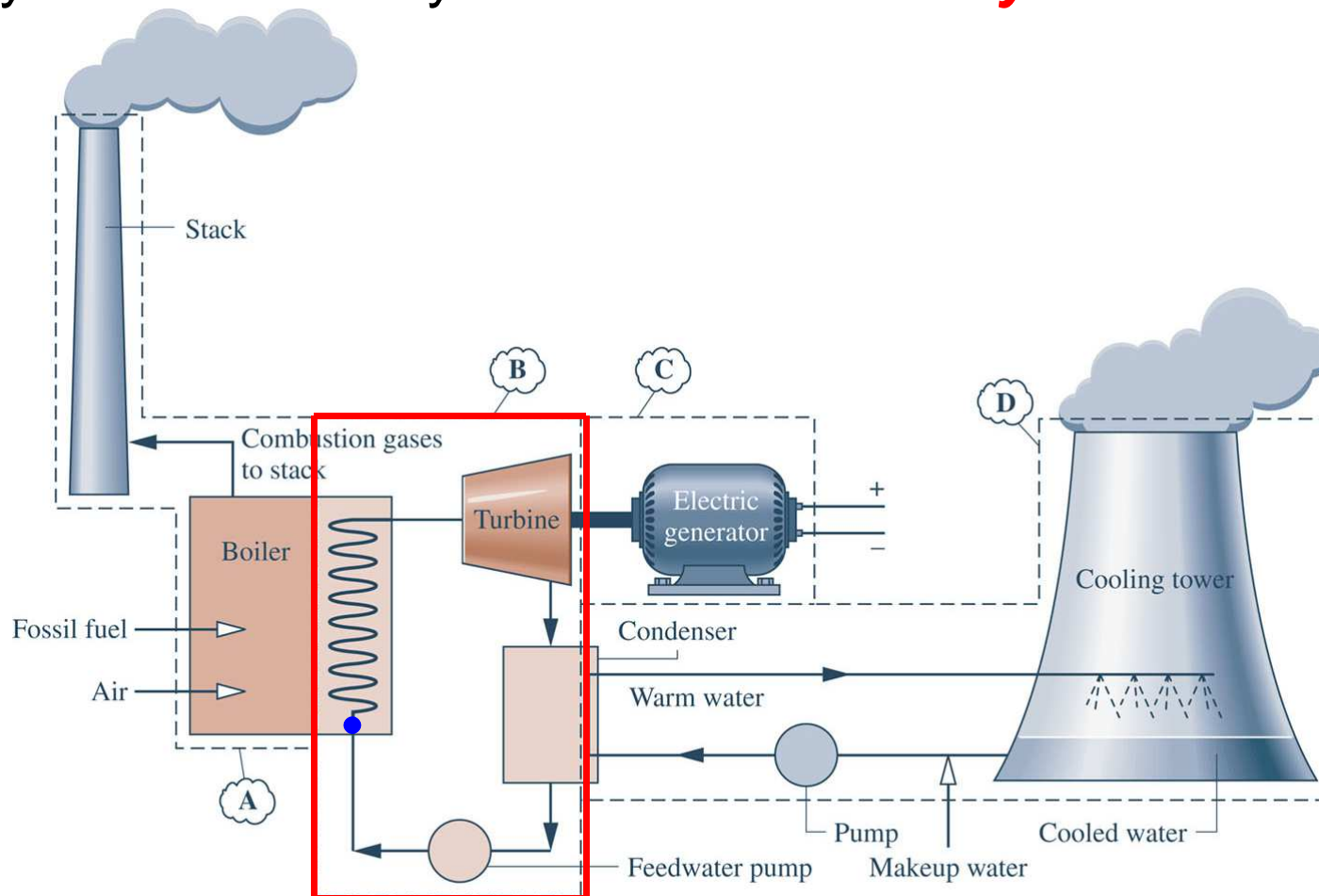
► **Subsystem D** removes energy by heat transfer arising from steam condensing in subsystem B.



(a) Fossil-fueled vapor power plant.

# Introducing Vapor Power Plants

- ▶ Each unit of mass of water periodically undergoes a thermodynamic cycle as it circulates through the components of subsystem B. This cycle is the **Rankine cycle**.



(a) Fossil-fueled vapor power plant.



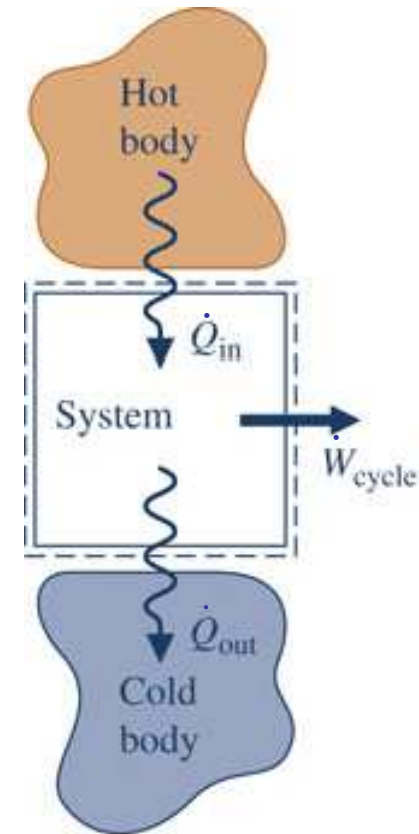
# Power Cycle Review

▶ The first law of thermodynamics requires the **net work developed** by a system undergoing a power cycle to **equal the net energy added by heat transfer** to the system:

$$\dot{W}_{\text{cycle}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$$

▶ The **thermal efficiency** of a power cycle is

$$\eta = \frac{\dot{W}_{\text{cycle}}}{\dot{Q}_{\text{in}}}$$



# Power Cycle Review

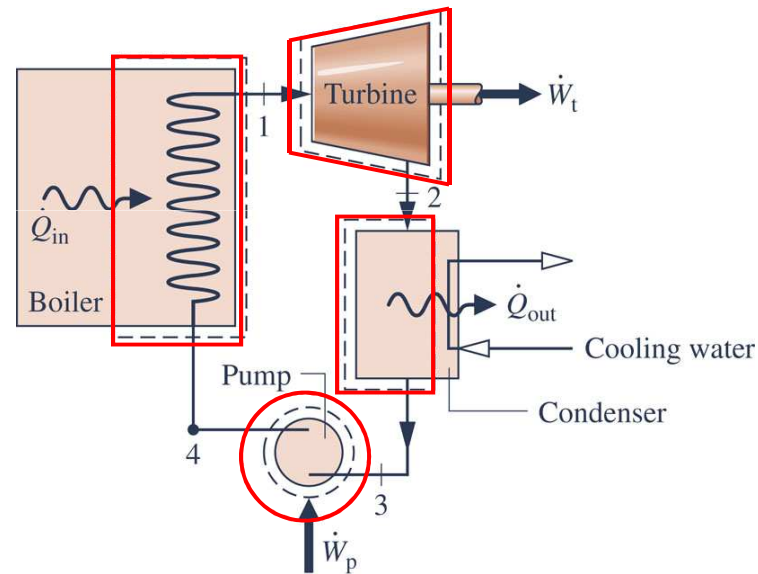
- ▶ The second law of thermodynamics requires the thermal efficiency to be less than 100%. Most of today's vapor power plants have thermal efficiencies ranging up to about 40%.
- ▶ Thermal efficiency tends to increase as the average temperature at which energy is added by heat transfer increases and/or the average temperature at which energy is rejected by heat transfer decreases.
- ▶ Improved thermodynamic performance of power cycles, as measured by increased thermal efficiency, for example, also accompanies the reduction of irreversibilities and losses.
- ▶ The extent of improved power cycle performance is limited, however, by constraints imposed by thermodynamics *and* economics.

# The Rankine Cycle

▶ Each unit of mass of water circulating through the interconnected components of **Subsystem B of Fig. 8.1(a)** undergoes a thermodynamic cycle known as the Rankine cycle.

▶ There are **four principal control volumes** involving these components:

- ▶ Turbine
- ▶ Condenser
- ▶ Pump
- ▶ Boiler



**All energy transfers** by work and heat **are taken as positive in the directions of the arrows** on the schematic and energy balances are written accordingly.

# The Rankine Cycle

▶ The processes of the Rankine cycle are

Process 1-2: vapor expands through the turbine developing work

Process 2-3: vapor condenses to liquid through heat transfer to cooling water

Process 3-4: liquid is pumped into the boiler requiring work input

Process 4-1: liquid is heated to saturation and evaporated in the boiler through heat transfer from the energy source

# The Rankine Cycle

- ▶ **Engineering model:**
  - ▶ Each component is analyzed as a control volume at **steady state**.
  - ▶ The **turbine** and **pump** operate **adiabatically**.
  - ▶ Kinetic and **potential energy changes** are **ignored**.

# The Rankine Cycle

▶ Applying mass and energy rate balances

Turbine

$$\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$$

**(Eq. 8.1)**

Condenser

$$\frac{\dot{Q}_{\text{out}}}{\dot{m}} = h_2 - h_3$$

**(Eq. 8.2)**

Pump

$$\frac{\dot{W}_p}{\dot{m}} = h_4 - h_3$$

**(Eq. 8.3)**

Boiler

$$\frac{\dot{Q}_{\text{in}}}{\dot{m}} = h_1 - h_4$$

**(Eq. 8.4)**

# The Rankine Cycle

## ► Performance parameters

### Thermal Efficiency

$$\eta = \frac{\dot{W}_{\text{cycle}}}{\dot{Q}_{\text{in}}} = \frac{\dot{W}_t / \dot{m} - \dot{W}_p / \dot{m}}{\dot{Q}_{\text{in}} / \dot{m}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)} \quad \text{(Eq. 8.5a)}$$

### Back Work Ratio

$$\text{bwr} = \frac{\dot{W}_p / \dot{m}}{\dot{W}_t / \dot{m}} = \frac{(h_4 - h_3)}{(h_1 - h_2)} \quad \text{(Eq. 8.6)}$$

Back work ratio is characteristically **low for vapor power plants**. For instance, in **Example 8.1**, the power required by the pump is less than 1% of the power developed by the turbine.

# The Rankine Cycle

- ▶ Provided states 1 through 4 are fixed, **Eqs. 8.1** through **8.6** can be **applied to** determine performance of simple vapor power plants adhering to the **Rankine cycle**.
- ▶ Since **these equations** are developed from mass and energy balances, they **apply equally when irreversibilities are present and for idealized performance** in the absence of such effects.



# 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

► The ideal Rankine cycle consists of four internally reversible processes:

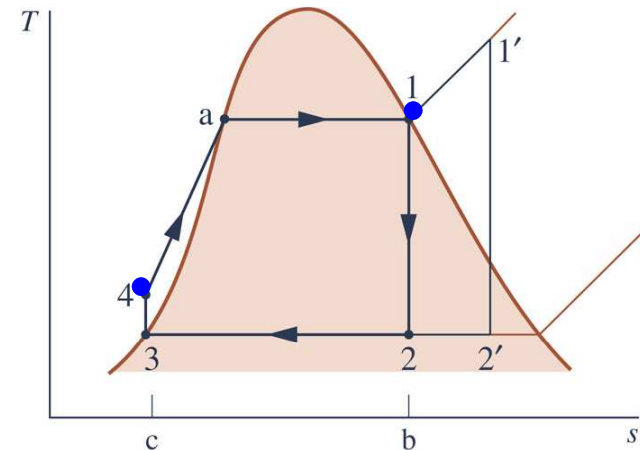
Process 1-2: Isentropic expansion through the turbine

Process 2-3: Heat transfer *from* the working fluid passing through the condenser at constant pressure

Process 3-4: Isentropic compression in the pump

Process 4-1: Heat transfer *to* the working fluid passing through the boiler at constant pressure

Possible variations of this cycle include: turbine inlet state is **superheated vapor, State 1'**; pump inlet, **State 3**, falls in the liquid region.



# Ideal Rankine Cycle

- ▶ Since the ideal Rankine cycle involves internally reversible processes, results from **Sec. 6.13** apply.
- ▶ Applying **Eq. 6.51c**, the pump work input per unit of mass flowing is evaluated as follows

$$\left( \frac{\dot{W}_p}{\dot{m}} \right)_s \approx v_3 (p_4 - p_3) \quad \text{(Eq. 8.7b)}$$

**where**  $v_3$  is the **specific volume at the pump inlet** and the subscript  $s$  signals the **isentropic process** of the liquid flowing through the pump.

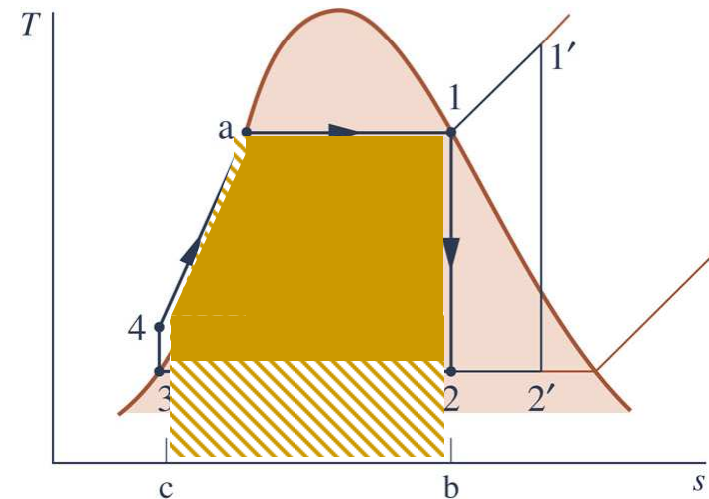
# Ideal Rankine Cycle

▶ Applying **Eq. 6.49**, areas under process lines on the  $T-s$  diagram can be interpreted as heat transfers, each per unit of mass flowing:

▶ Area **1-b-c-4-a-1** represents heat transfer to the water flowing through the boiler

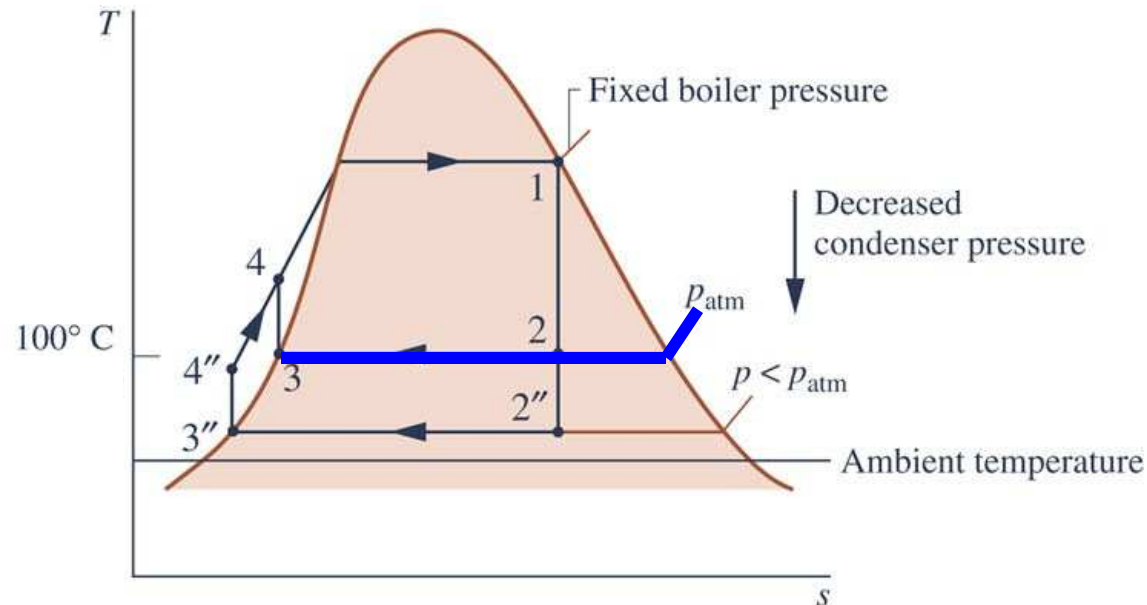
▶ Area **2-b-c-3-2** represents heat transfer from the water flowing through the condenser.

▶ Enclosed area **1-2-3-4-a-1** represents the net heat input or equivalently the net work developed by the cycle.



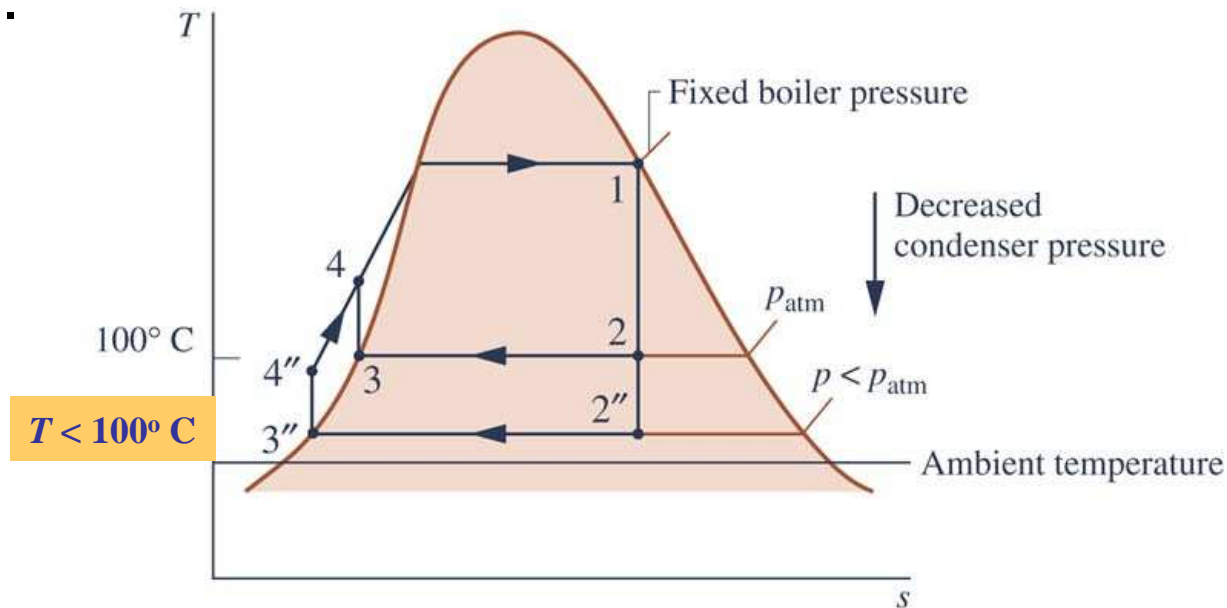
# Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Condenser Pressure

- ▶ 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

- ▶ 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

- ▶ 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.

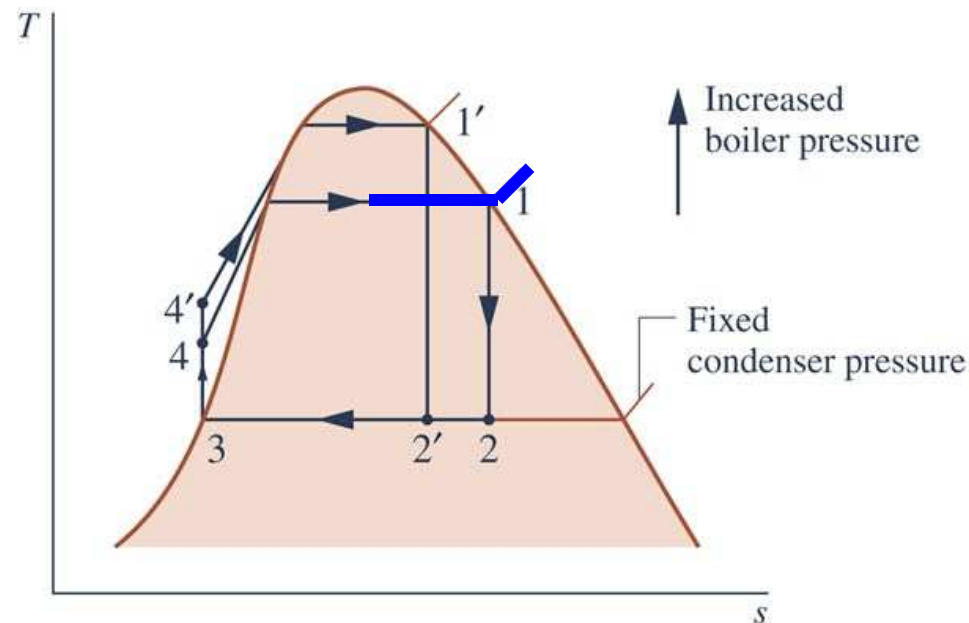
# Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Condenser Pressure

▶ 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

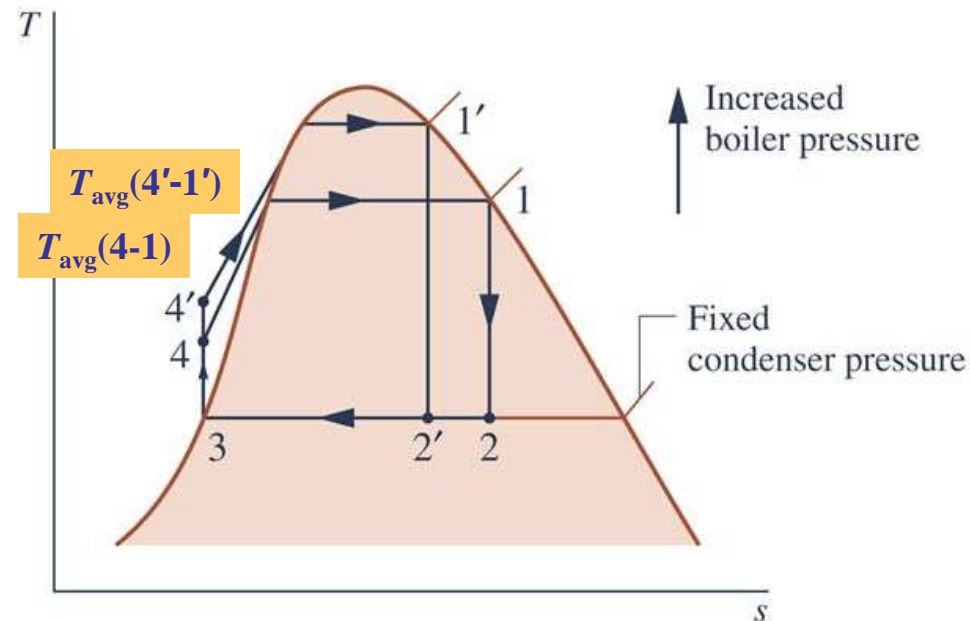
- ▶ The figure shows **two cycles** having the **same condenser pressure** but **different boiler pressures**:
  - ▶ one is at a **given pressure** and
  - ▶ the other is at **higher than the given pressure**.



# Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Boiler Pressure

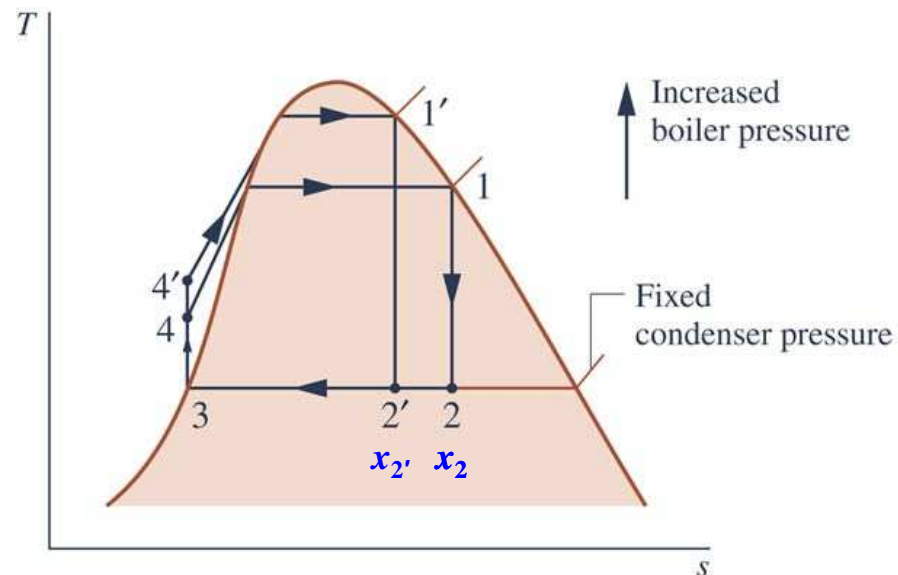
► Since the average temperature of heat addition for cycle  $1'-2'-3-4'-1'$  is greater than for cycle  $1-2-3-4-1$ , the higher pressure cycle has the greater thermal efficiency.

Increasing the boiler pressure tends to increase thermal efficiency.



# Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Boiler Pressure

- ▶ 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**.



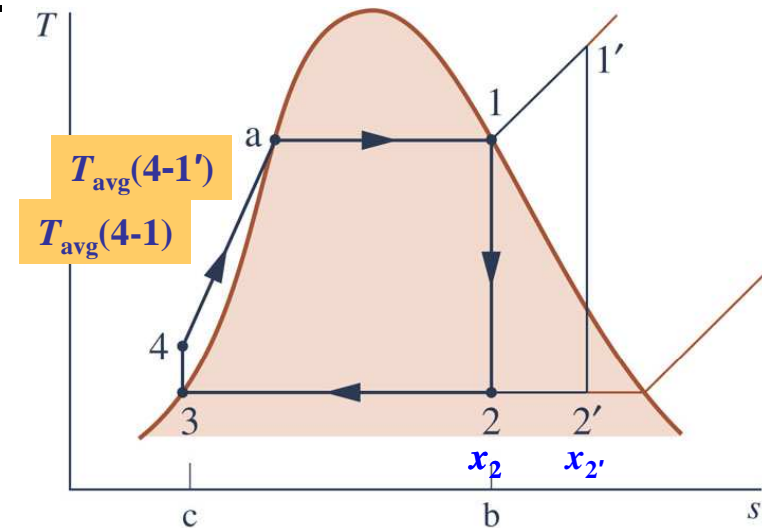
# Using the Ideal Rankine Cycle to Study the Effects on Performance of Varying Boiler Pressure

▶ 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. All three are 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.



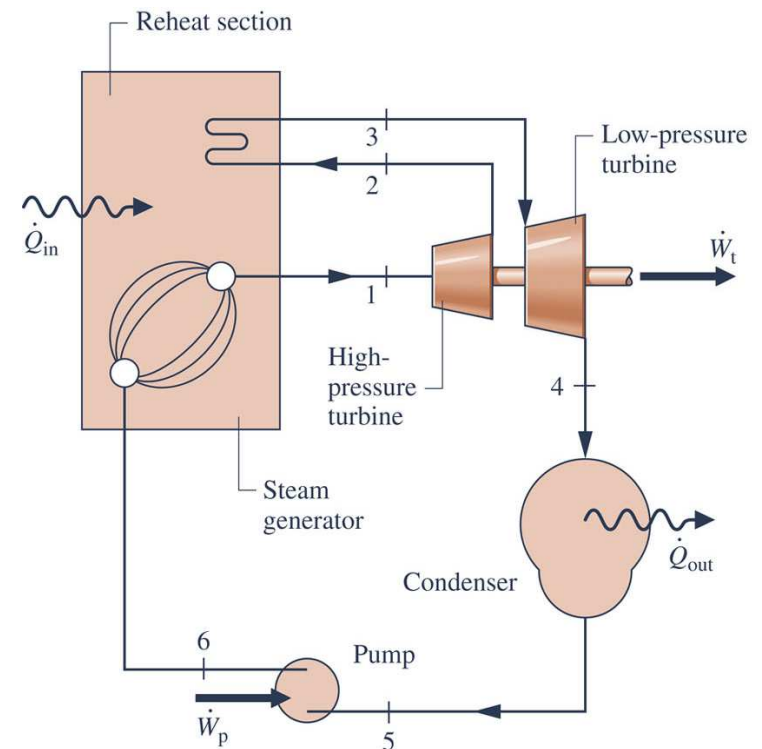
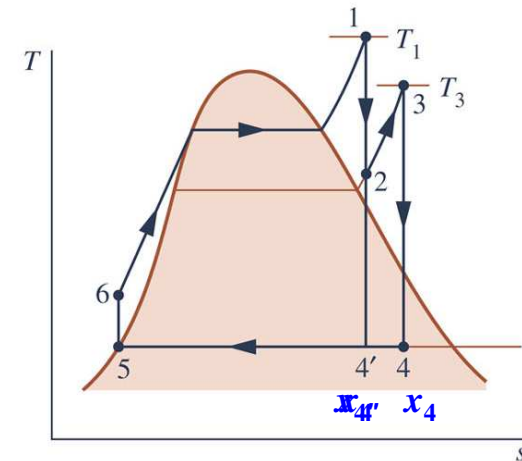
► Moreover, with superheat the quality at the turbine exit, state 2', is greater than at state 2, the turbine exit without superheat.

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

# Ideal Reheat Cycle

► 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.



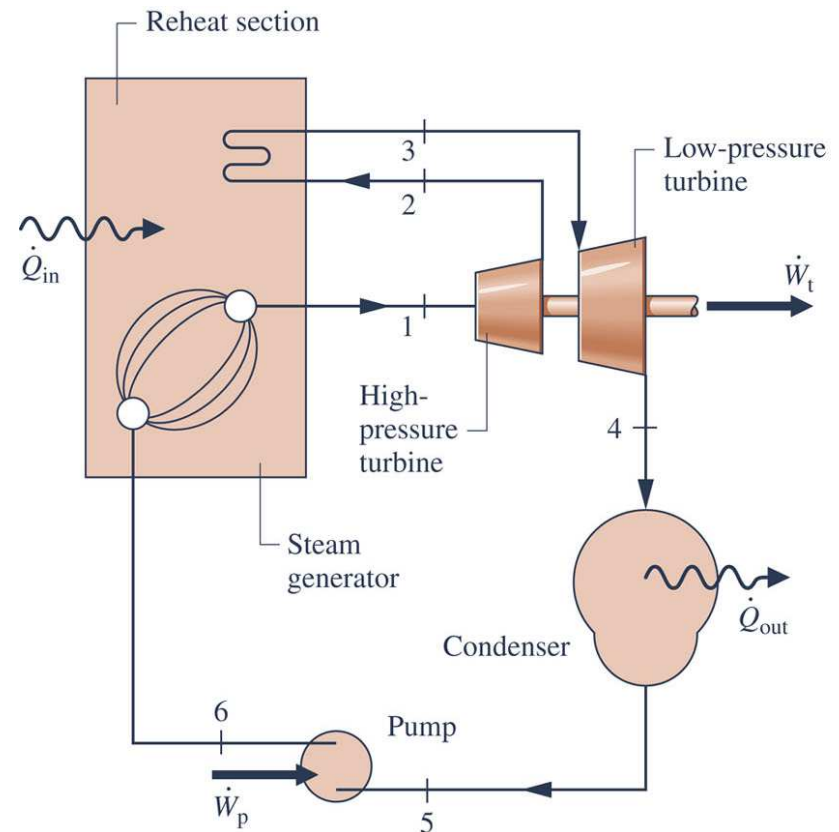
# Ideal Reheat Cycle

► 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.**

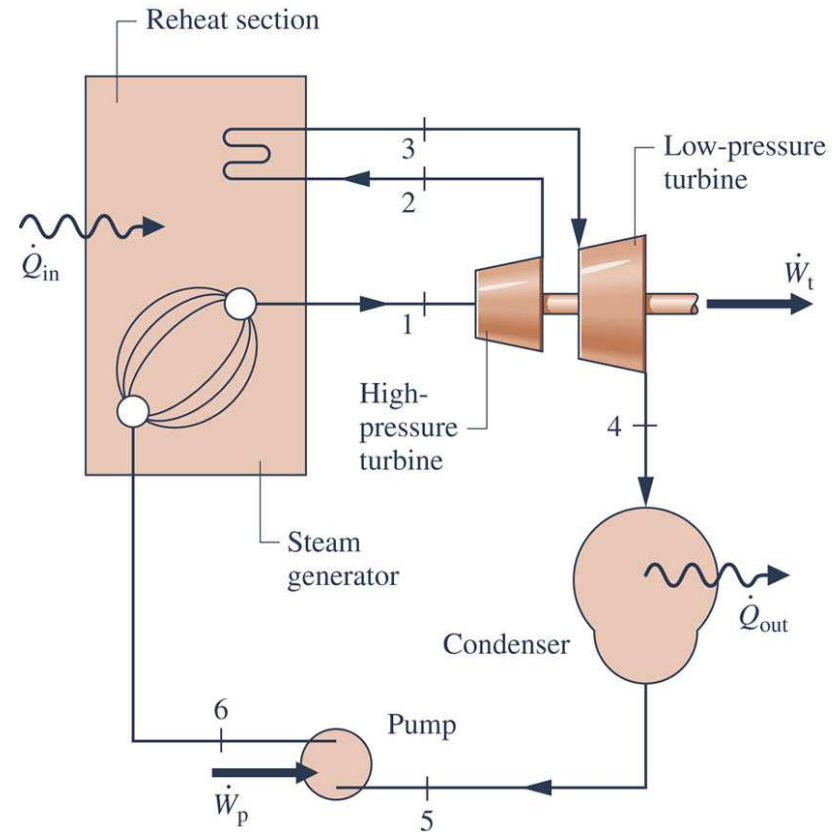


# Ideal Reheat Cycle

► 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.



$$\eta = \frac{\dot{W}_{tHP} + \dot{W}_{tLP} - \dot{W}_p}{\dot{Q}_{6-1} + \dot{Q}_{2-3}}$$

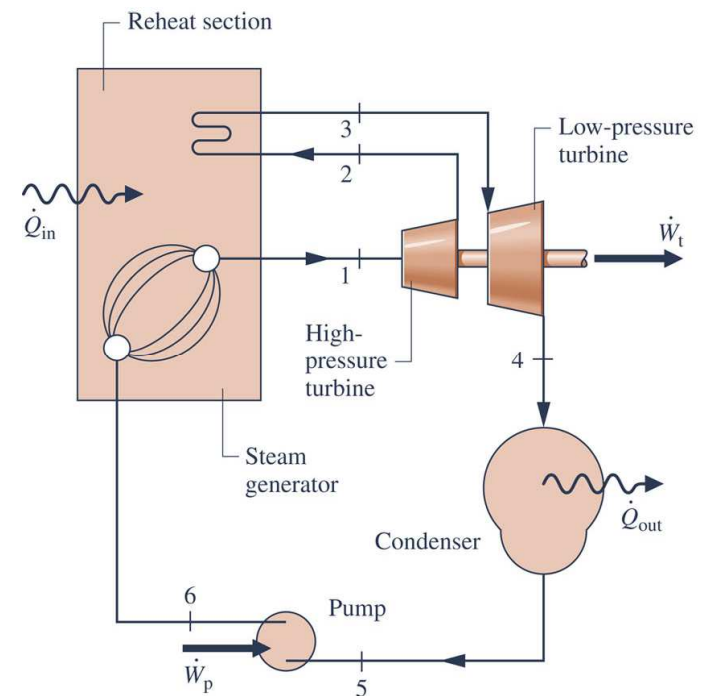
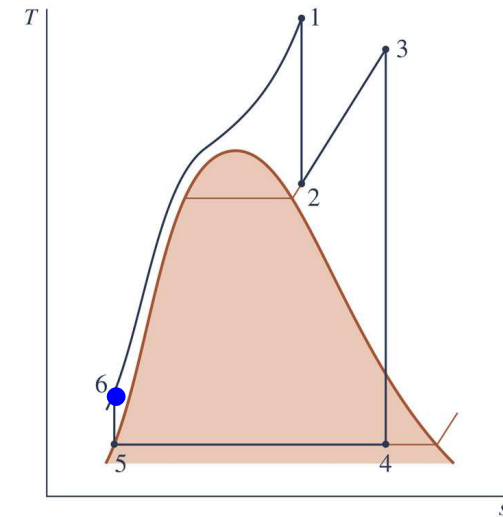


## Supercritical Ideal Reheat Cycle

- ▶ 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.

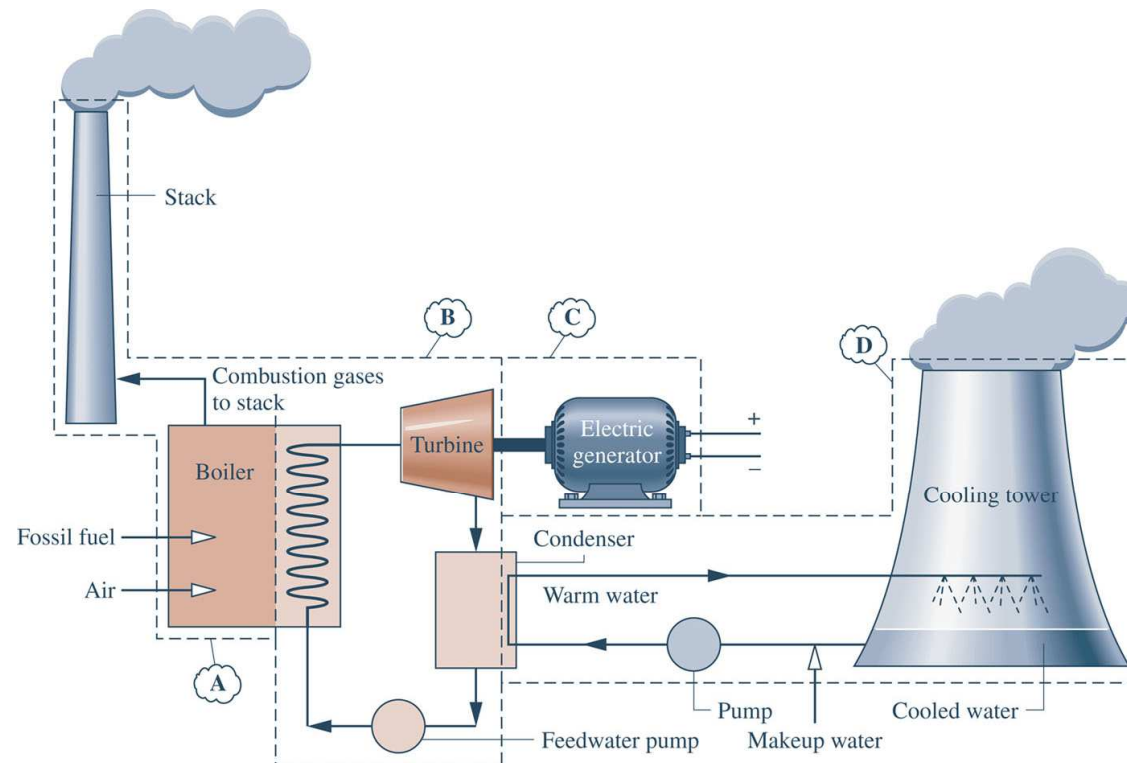
# Supercritical Ideal Reheat Cycle

- ▶ **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%**.



# Principal Irreversibilities

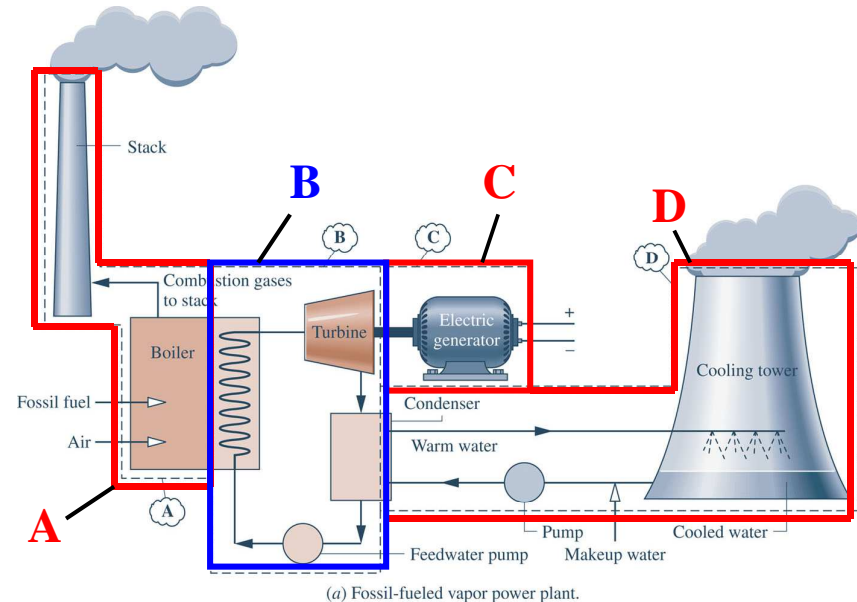
► Irreversibilities are associated with each of the four subsystems designated by **A**, **B**, **C**, and **D** on the figure.



(a) Fossil-fueled vapor power plant.

# Principal Irreversibilities

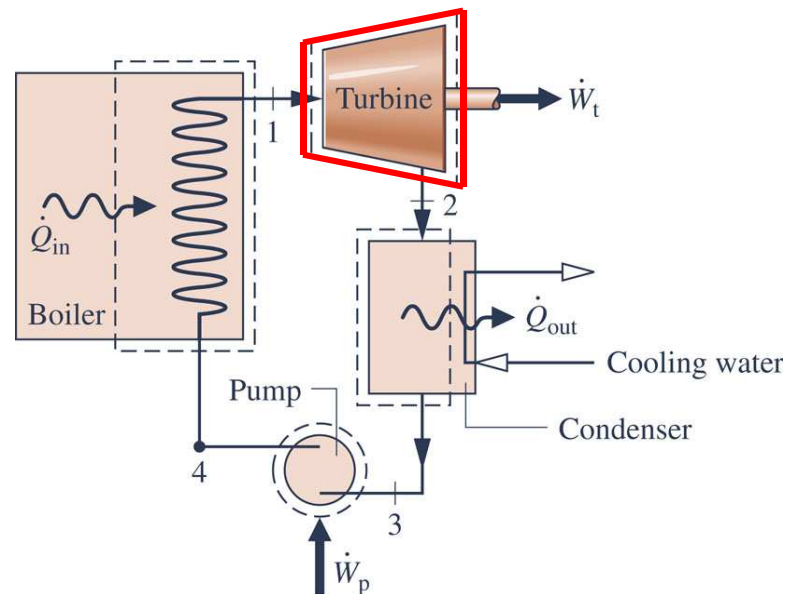
► For a fossil-fueled vapor power plant the most significant site of irreversibility *by far* is subsystem **A**. There, irreversibility is associated with combustion of the fuel and subsequent heat transfer from hot combustion gases to vaporize water flowing through the closed loop of subsystem **B**, which is the focus of discussion.



- As such irreversibilities occur in the surroundings of subsystem **B**, they are classified as *external* irreversibilities for that subsystem.
- Irreversibilities in subsystems **C** and **D** are also external irreversibilities of subsystem **B** but they are minor relative to the combustion and heat transfer irreversibilities occurring in the boiler.
- Combustion irreversibility is studied in Chapter 13.

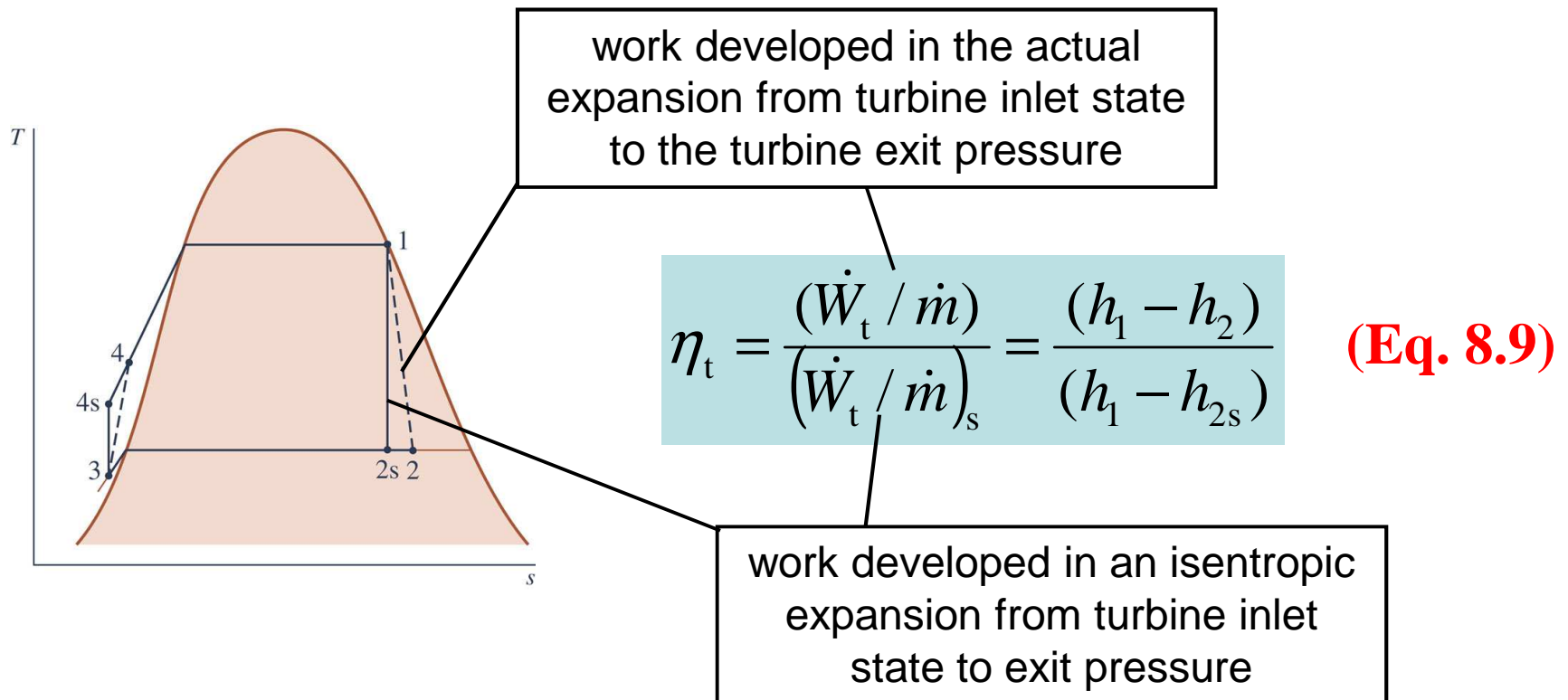
# Principal Irreversibilities

- ▶ Irreversibilities associated with subsystem **B** are called *internal*. They include the expansion of steam through the turbine and the effects of friction in flow through the pump, boiler, and condenser.
- ▶ The **most significant internal irreversibility** associated with subsystem **B** is **expansion through the turbine**.



# Principal Irreversibilities

► **Isentropic turbine efficiency**, introduced in **Sec. 6.12.1**, accounts for the effects of irreversibilities within the turbine in terms of actual and isentropic turbine work, each per unit of mass flowing through the turbine.



# Principal Irreversibilities

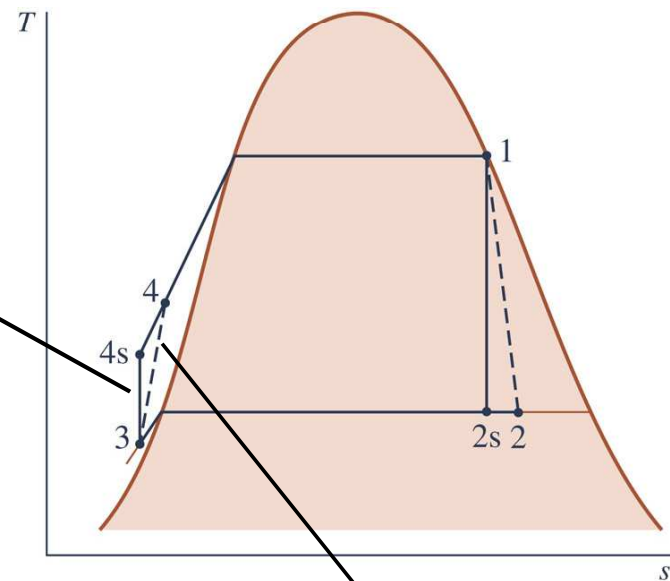
▶ While pump work input is much less than turbine work output, **irreversibilities in the pump affect net power output** of the vapor plant.

▶ **Isentropic pump efficiency**, introduced in **Sec. 6.12.3**, **accounts for the effects of irreversibilities within the pump** in terms of actual and isentropic pump work input, each per unit of mass flowing through the pump.

work input for an isentropic process from pump inlet state to exit pressure

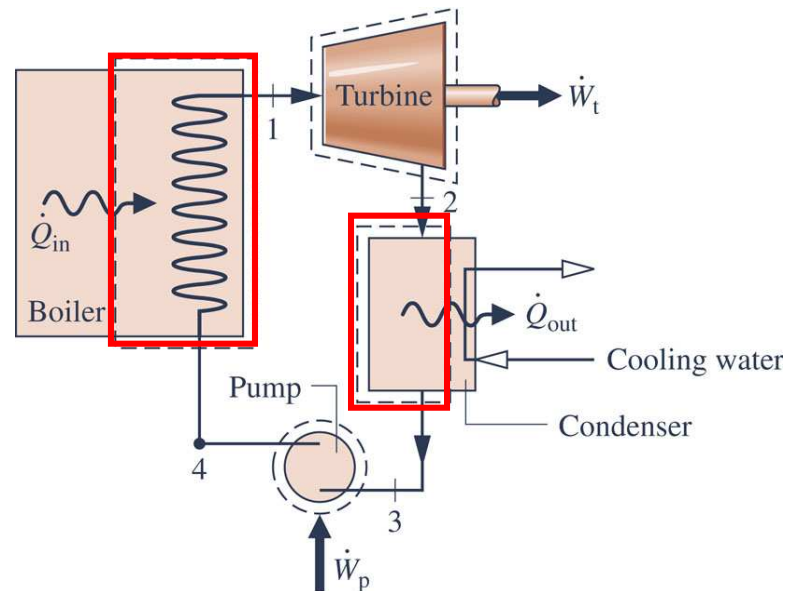
$$\eta_p = \frac{(\dot{W}_p / \dot{m})_s}{(\dot{W}_p / \dot{m})} = \frac{(h_{4s} - h_3)}{(h_4 - h_3)} \quad \text{(Eq. 8.10a)}$$

work input for the actual process from pump inlet state to the pump exit pressure



# Principal Irreversibilities

- ▶ For simplicity, **frictional effects** resulting in pressure reductions from inlet to exit for the **boiler** and **condenser are ignored** in **Chapter 8**.
- ▶ Flow through these components is assumed to occur at **constant pressure**.



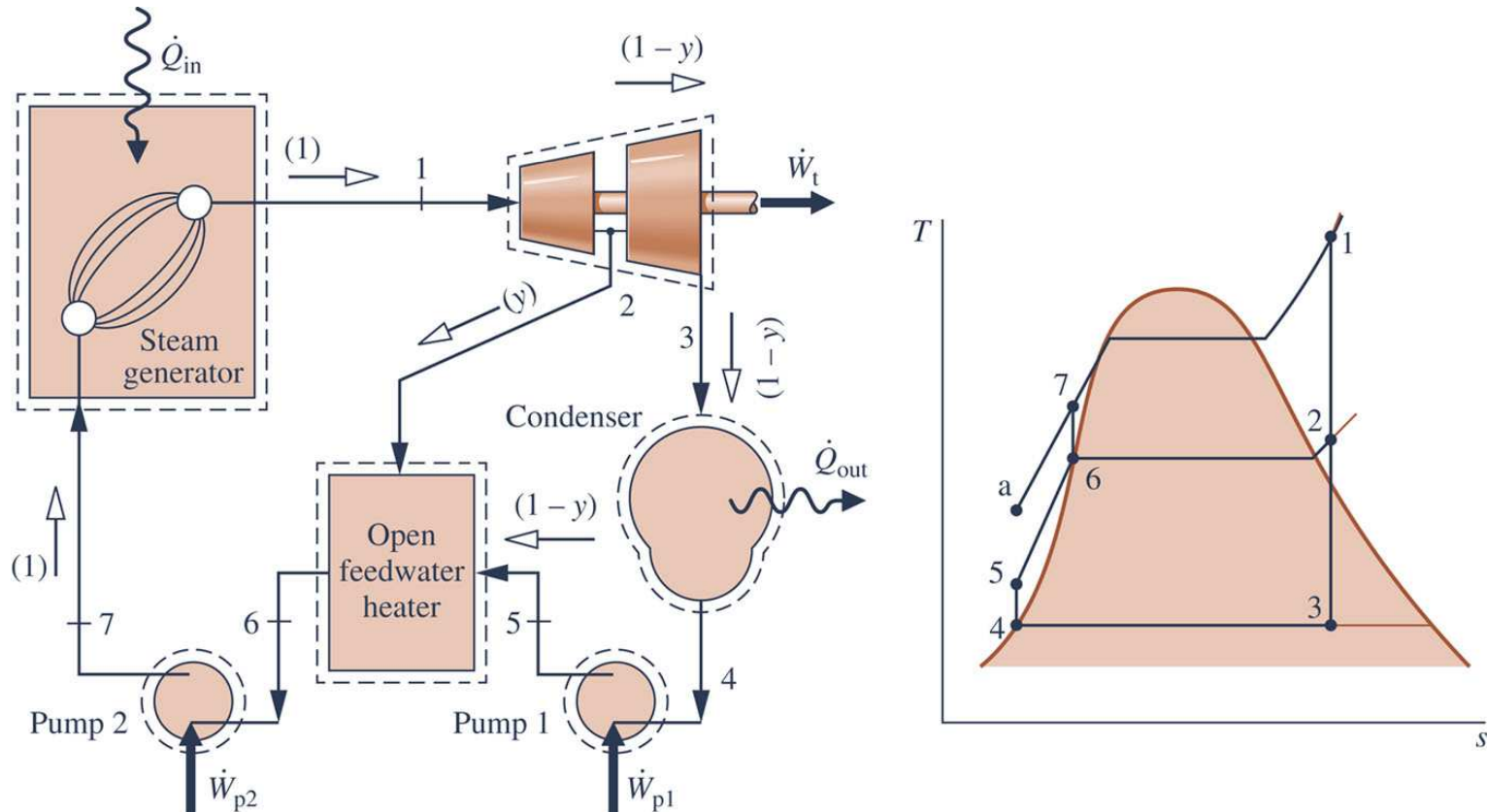


# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

- ▶ Another **method for increasing thermal efficiency** of vapor power plants is by application of **regenerative feedwater heaters**.
- ▶ Regenerative feedwater heating **increases the average temperature of heat addition**, thereby increasing the thermal efficiency.
- ▶ In vapor power plants **both *open* and *closed* feedwater heaters are typically used**. Each feedwater heater type is considered in **Sec. 8.4**.

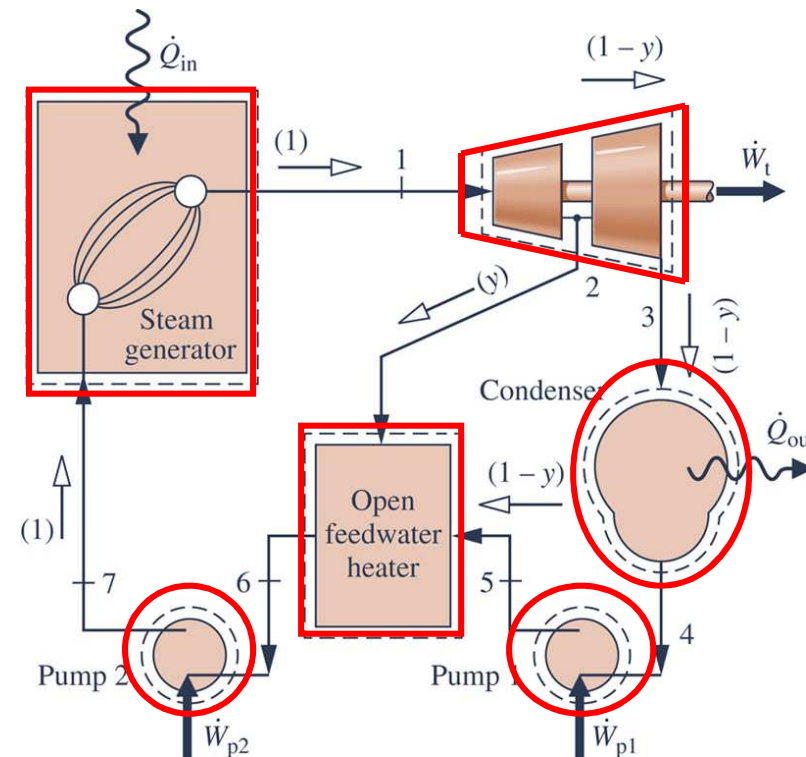
# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

► A vapor power cycle using a **single open feedwater heater** (a mixing chamber) is shown in the figure.



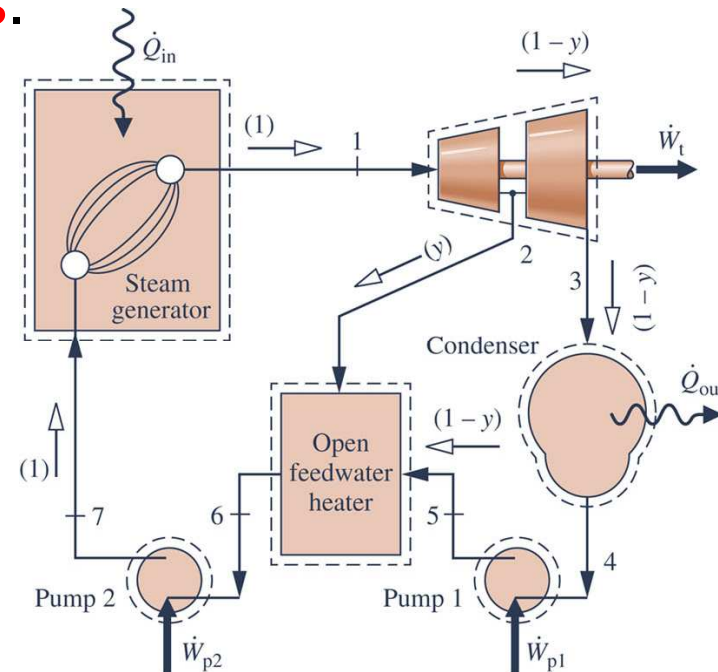
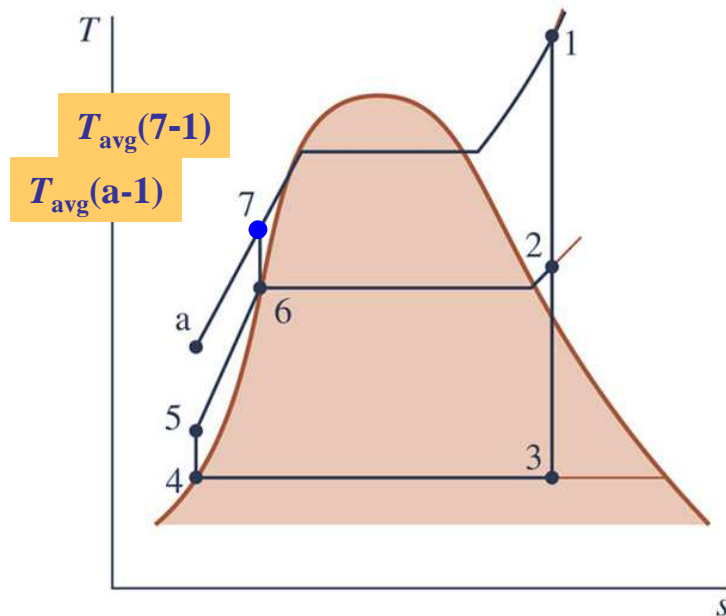
# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

- ▶ In this cycle, water passes **isentropically through** each of **two turbine stages**, 1-2 and 2-3, and each of **two pumps**, 4-5 and 6-7.
- ▶ Flow through the **steam generator**, 7-1, and **condenser**, 3-4, occur at **constant pressure**.
- ▶ **Mixing** occurs **within the feedwater heater**, thereby introducing a **source of irreversibility** into an otherwise ideal cycle.
- ▶ The **feedwater heater** is assumed to **operate adiabatically**.



# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

- ▶ Referring to the  $T$ - $s$  diagram, heat transfer to the cycle takes place from state 7 to state 1, rather than from state a to state 1 as would be the case if there were no open feedwater heater.
- ▶ Accordingly, when an open feedwater heater is included, the average temperature of heat addition to the cycle increases; thus, thermal efficiency increases.

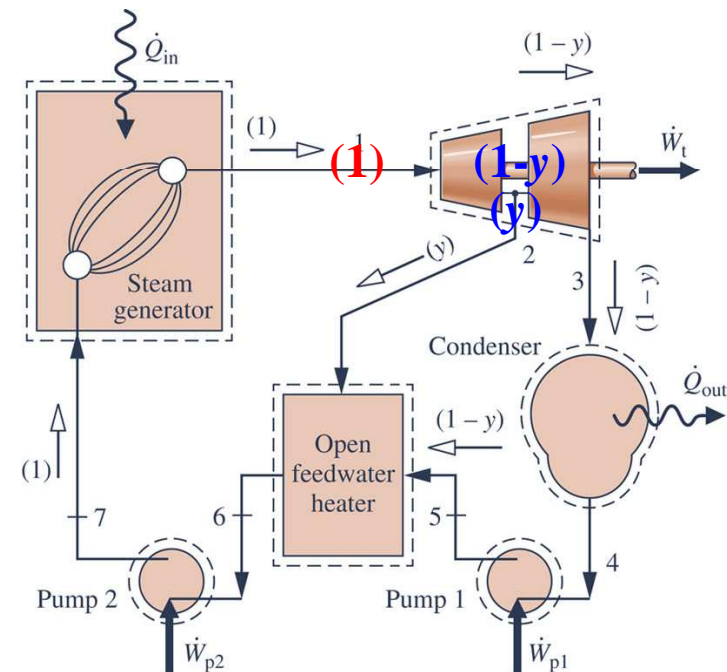


# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

▶ Referring to the **schematic**, let us follow a **unit of mass** as it **moves through the cycle**. The unit of mass is denoted in parentheses by **(1)**.

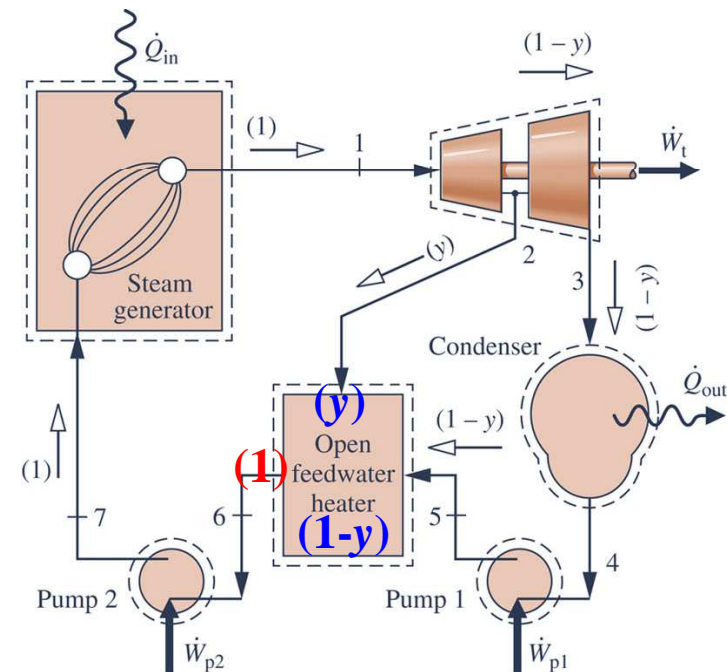
▶ The unit of mass **(1)** enters the **turbine** at state **1** and expands to state **2** where a **fraction (y)** is diverted into the open feedwater heater.

▶ The **remaining fraction (1-y)** expands through the **second turbine stage** to state **3**, is **condensed** to state **4**, and then **pumped** to state **5** where it enters the **open feedwater heater**.



# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

- ▶ The fractions  $(y)$  and  $(1-y)$  entering the feedwater heater at states 2 and 5, respectively, **mix** within that component, giving a single stream at state 6 and recovering the unit of mass **(1)**.
- ▶ The unit of mass **(1)** at state 6 is **pumped** to state 7 where it enters the **steam generator** and **returns to state 1** after heating.



# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

► Applying steady-state mass and energy rate balances to a control volume enclosing the feedwater heater, the fraction of the total flow  $y$  is

$$y = \frac{h_6 - h_5}{h_2 - h_5} \quad (\text{Eq. 8.12})$$

► With fraction  $y$  known, mass and energy rate balances applied to control volumes around the other components yield the following expressions, each on the basis of a unit of mass entering the first turbine stage.

# Regenerative Vapor Power Cycle Using an Open Feedwater Heater

- ▶ For the **turbine stages**

$$\frac{\dot{W}_t}{\dot{m}_1} = (h_1 - h_2) + (1 - y)(h_2 - h_3)$$

**(Eq. 8.13)**

- ▶ For the **pumps**

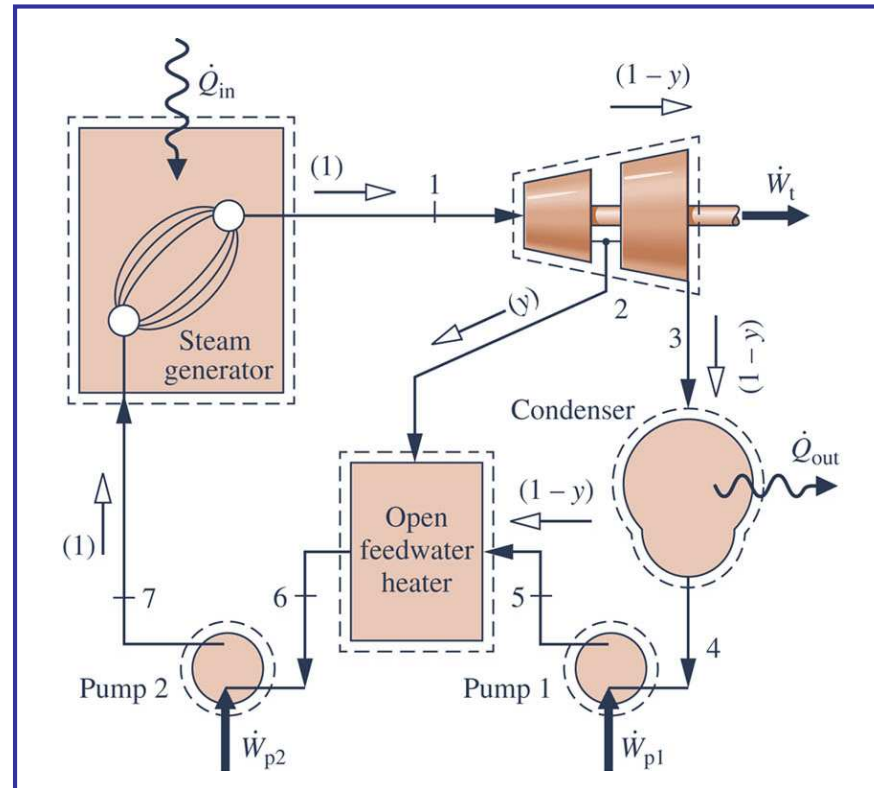
$$\frac{\dot{W}_p}{\dot{m}_1} = (h_7 - h_6) + (1 - y)(h_5 - h_4)$$

**(Eq. 8.14)**

- ▶ For the **steam generator**

$$\frac{\dot{Q}_{in}}{\dot{m}_1} = h_1 - h_7$$

**(Eq. 8.15)**



- ▶ For the **condenser**

$$\frac{\dot{Q}_{out}}{\dot{m}_1} = (1 - y)(h_3 - h_4)$$

**(Eq. 8.16)**

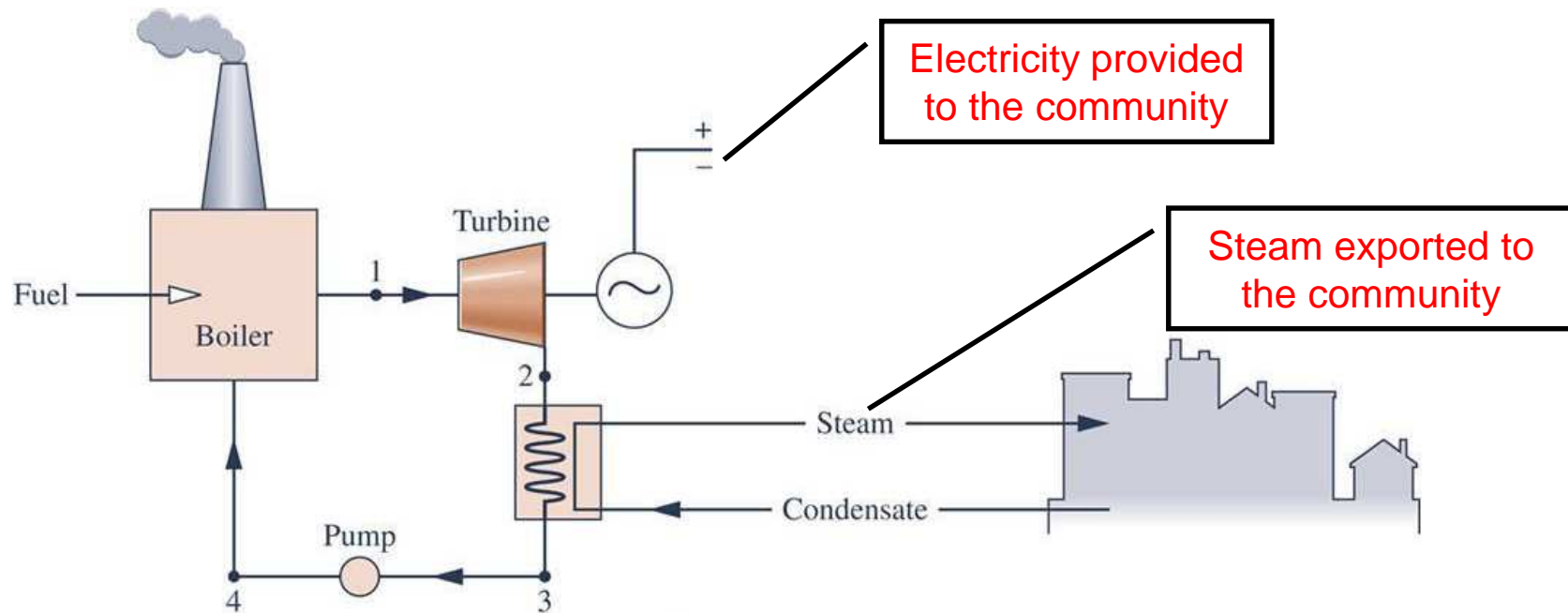


# Cogeneration Systems

- ▶ Are **integrated systems** that simultaneously yield two valuable products, **electricity** and **steam** (or hot water) from a single fuel input.
- ▶ Typically provide **cost savings** relative to producing power and steam (or hot water) in **separate systems**.
- ▶ Are widely deployed in **industrial plants, refineries, food processing plants**, and other facilities requiring process steam, hot water, and electricity.
- ▶ Can be based on **vapor power plants, gas turbine power plants, internal combustion engines, and fuel cells**.

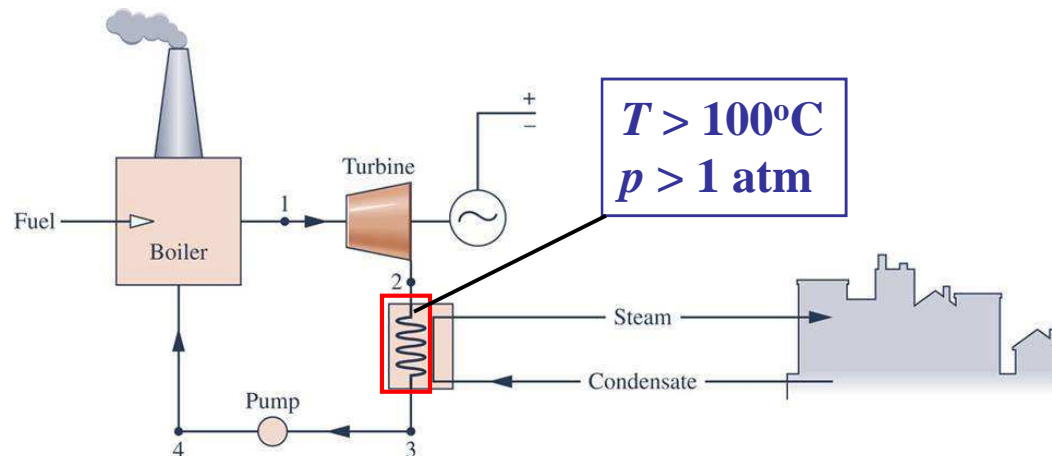
# Cogeneration Systems

- ▶ An application of **cogeneration** based on vapor power plants is **district heating** – providing steam or hot water for space heating together with electricity for domestic, commercial, and industrial use.



# Cogeneration Systems

- ▶ Exporting useful steam to the community limits the electricity that also can be provided from a given fuel input, however.
- ▶ For instance, to produce saturated vapor at **100°C (1 atm)** for export to the community water circulating through the power plant will condense at a higher temperature and thus at a higher pressure.
- ▶ In such an operating mode thermal efficiency is less than when condensation occurs at a pressure below 1 atm, as in a plant fully dedicated to power production.

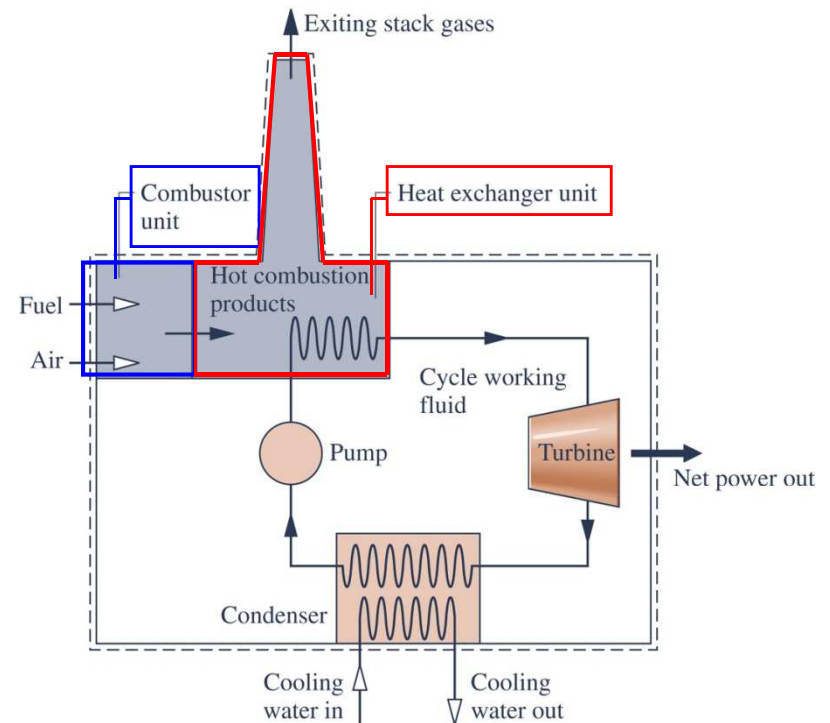


# Exergy Accounting of a Vapor Power Plant

► **Exergy analysis**, introduced in **Chapter 7**, provides insights about vapor power cycle performance beyond what is achievable using conservation of mass and conservation of energy principles.

► The **value added by an exergy analysis** is demonstrated by application to the vapor power plant shown in the figure.

► For simplicity, the **boiler is assumed to have two units**: a **combustor** where fuel and air burn to produce hot combustion gases, followed by a **heat exchanger** where water circulating through the closed loop of the Rankine cycle is vaporized by the hot gases.



# Exergy Accounting of a Vapor Power Plant

- ▶ An **exergy accounting** of the vapor plant is provided in the table.
- ▶ Table values are determined in **Examples 8.7 through 8.9** or assumed for purposes of illustration (stack gas loss, exergy destruction in combustor).

**Table 8.4**

**Vapor Power Plant Exergy Accounting<sup>a</sup>**

Outputs	
Net power out <sup>b</sup>	30%
Losses	
Condenser cooling water <sup>c</sup>	1%
Stack gases (assumed)	1%
Exergy destruction	
Boiler	
Combustion unit (assumed)	30%
Heat exchanger unit <sup>d</sup>	30%
Turbine <sup>e</sup>	5%
Pump <sup>f</sup>	—
Condenser <sup>g</sup>	3%
Total	100%

<sup>a</sup>All values are expressed as a percentage of the exergy carried into the plant with the fuel. Values are rounded to the nearest full percent. Exergy losses associated with stray heat transfer from plant components are ignored.

<sup>b</sup>Example 8.8.  
<sup>c</sup>Example 8.9.  
<sup>d</sup>Example 8.7.  
<sup>e</sup>Example 8.8.  
<sup>f</sup>Example 8.8.  
<sup>g</sup>Example 8.9.

# Exergy Accounting of a Vapor Power Plant

▶ The table provides several **insights about vapor power cycle performance**.

▶ The net power developed is just 30% of the exergy entering with the fuel. The **exergetic efficiency** of the plant is thus **30%**.

▶ Exergy **destructions** are far **more significant than exergy losses**.

▶ The **largest portion** of the **exergy entering with the fuel is destroyed**.

▶ The **boiler** is the site of **greatest exergy destruction**.

▶ Exergy **loss via condenser cooling water and stack gases** are each **minor**.

**Table 8.4**

**Vapor Power Plant Exergy Accounting<sup>a</sup>**

Outputs	
Net power out <sup>b</sup>	30%
Losses	
Condenser cooling water <sup>c</sup>	1%
Stack gases (assumed)	1%
Exergy destruction	
Boiler	
Combustion unit (assumed)	30%
Heat exchanger unit <sup>d</sup>	30%
Turbine <sup>e</sup>	5%
Pump <sup>f</sup>	—
Condenser <sup>g</sup>	3%
Total	100%

<sup>a</sup>All values are expressed as a percentage of the exergy carried into the plant with the fuel. Values are rounded to the nearest full percent. Exergy losses associated with stray heat transfer from plant components are ignored.

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<sup>c</sup>Example 8.9.

<sup>d</sup>Example 8.7.

<sup>e</sup>Example 8.8.

<sup>f</sup>Example 8.8.

<sup>g</sup>Example 8.9.