Lecture 3: Steam Power Plants

Course: MECH-422 – Power Plants

Instructor: Kashif Liaqat

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BUITEMS – DEPARTMENT OF MECHANICAL ENGINEERING

Learning Outcomes

- Explain 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.
- Describe the effects of varying key parameters on Rankine cycle performance.
- Discuss different modification of Rankine cycle for performance enhancement

Introducing Power Generation

- ►thermodynamic cycles are a fundamental aspect of several power plant types that employ renewable or nonrenewable sources.

- ►Steam power systems in which a working fluid is alternately vaporized and condensed is the focus of this Chapter.

- ►The basic building block of vapor power systems is the ***Rankine cycle***.

Introducing Steam (Vapor) Power Plants (1 of 11)

►The components of four alternative vapor power plant configurations are shown schematically in the following slide.

►They are

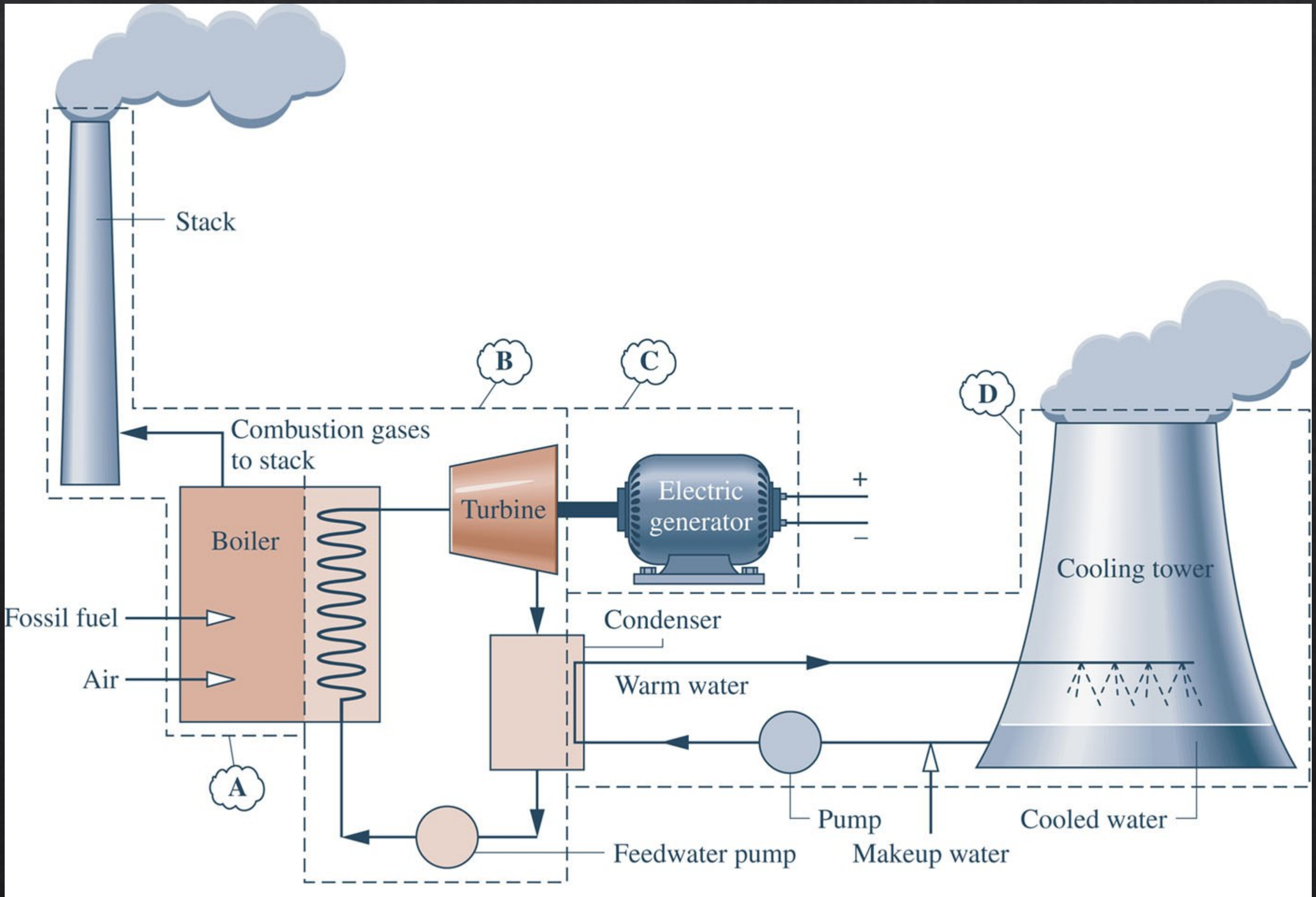
- ►Fossil-fueled vapor power plants.
- ►Pressurized-water reactor nuclear vapor power plants.
- ►Concentrating solar thermal vapor power plants.
- ►Geothermal vapor power plants.

►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 (2 of 11)

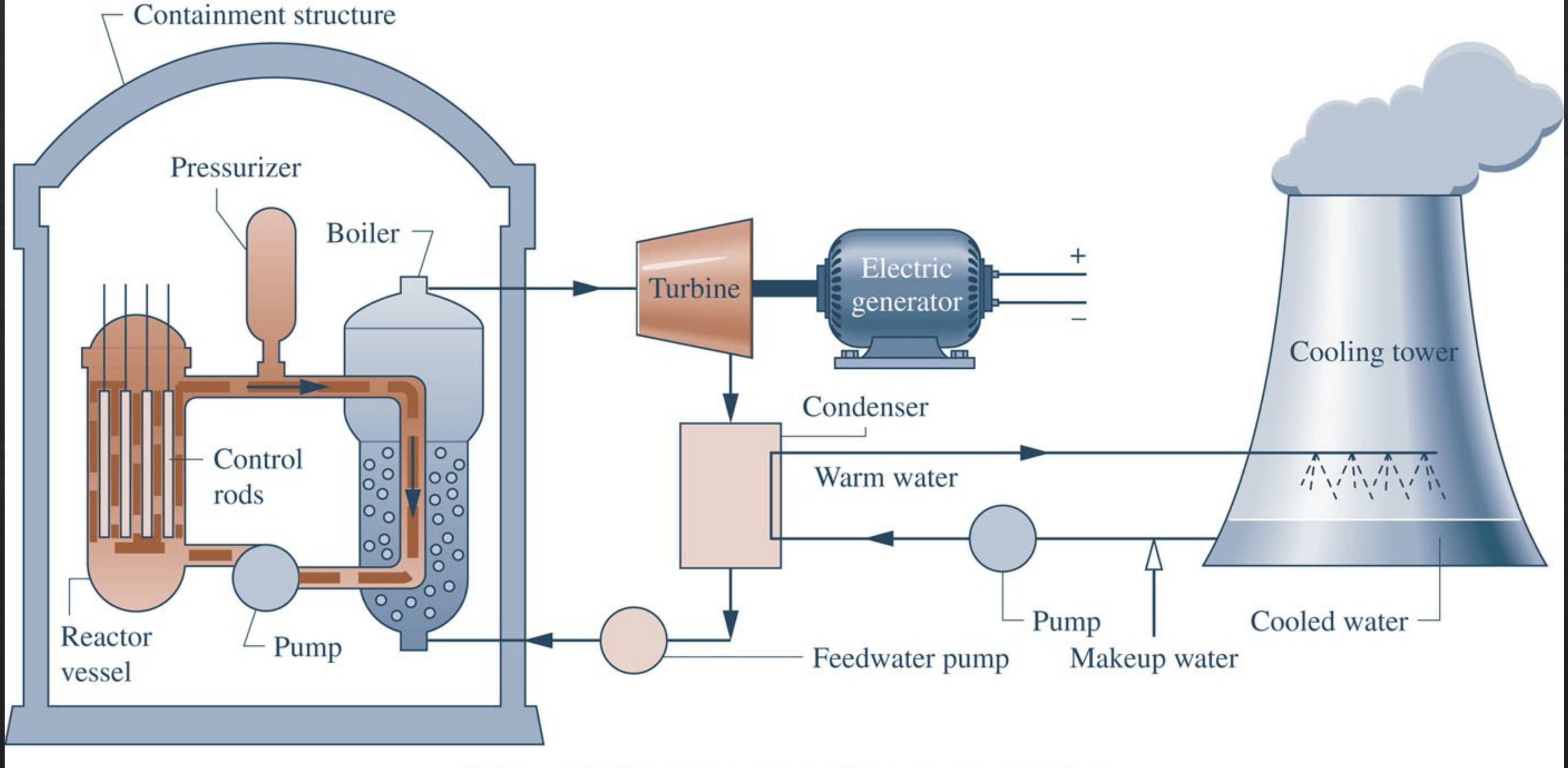
► In fossil-fueled plants, the energy required for vaporization originates in combustion of the fuel.



(a) Fossil-fueled vapor power plant.

Introducing Vapor Power Plants (3 of 11)

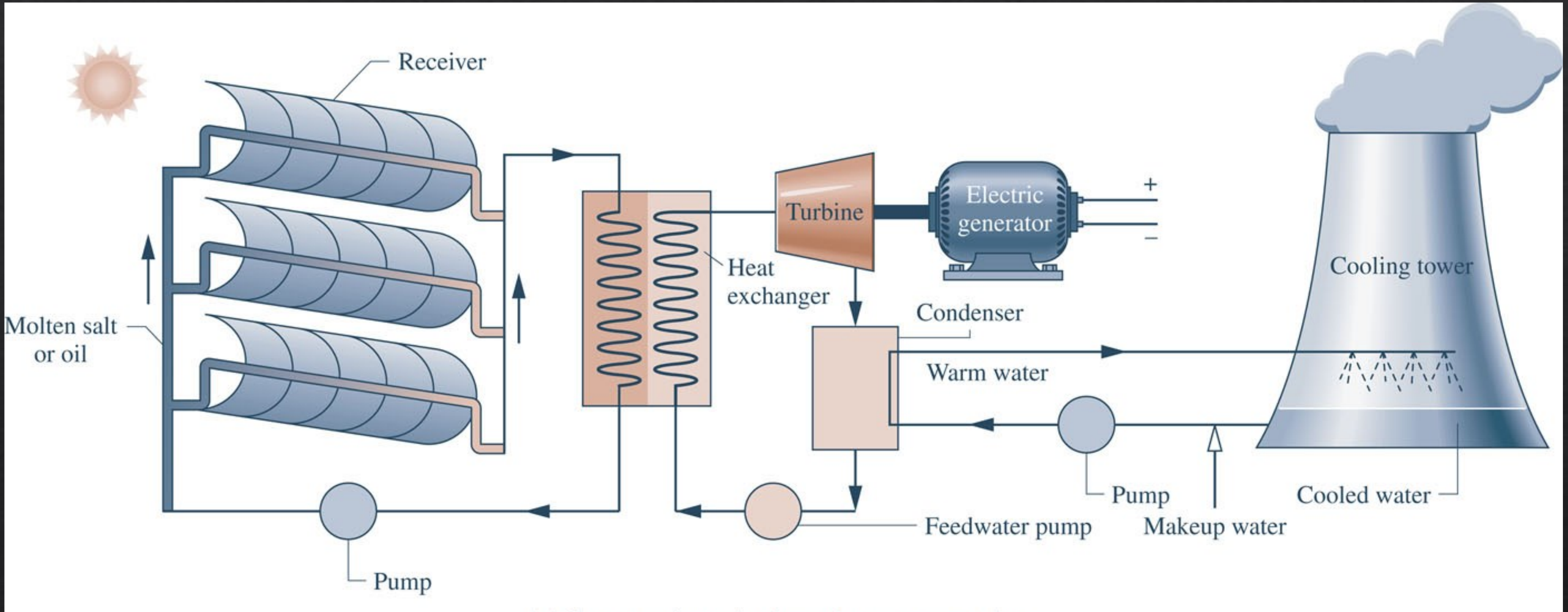
►In nuclear plants, the energy required for vaporization originates in a controlled nuclear reaction.



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

Introducing Vapor Power Plants (4 of 11)

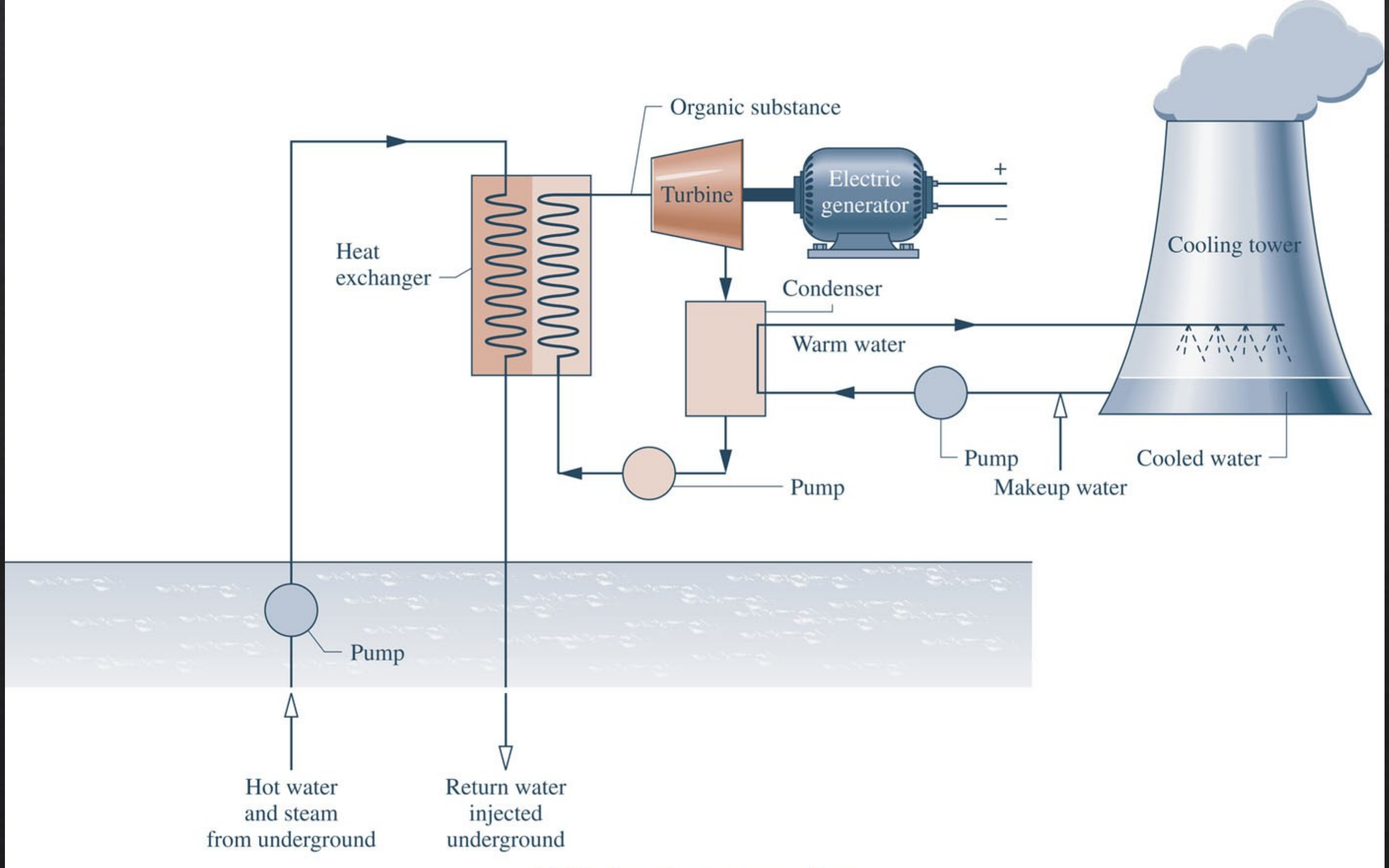
► In solar plants, the energy required for vaporization originates in collected and concentrated solar radiation.



(c) Concentrating solar thermal vapor power plant.

Introducing Vapor Power Plants (5 of 11)

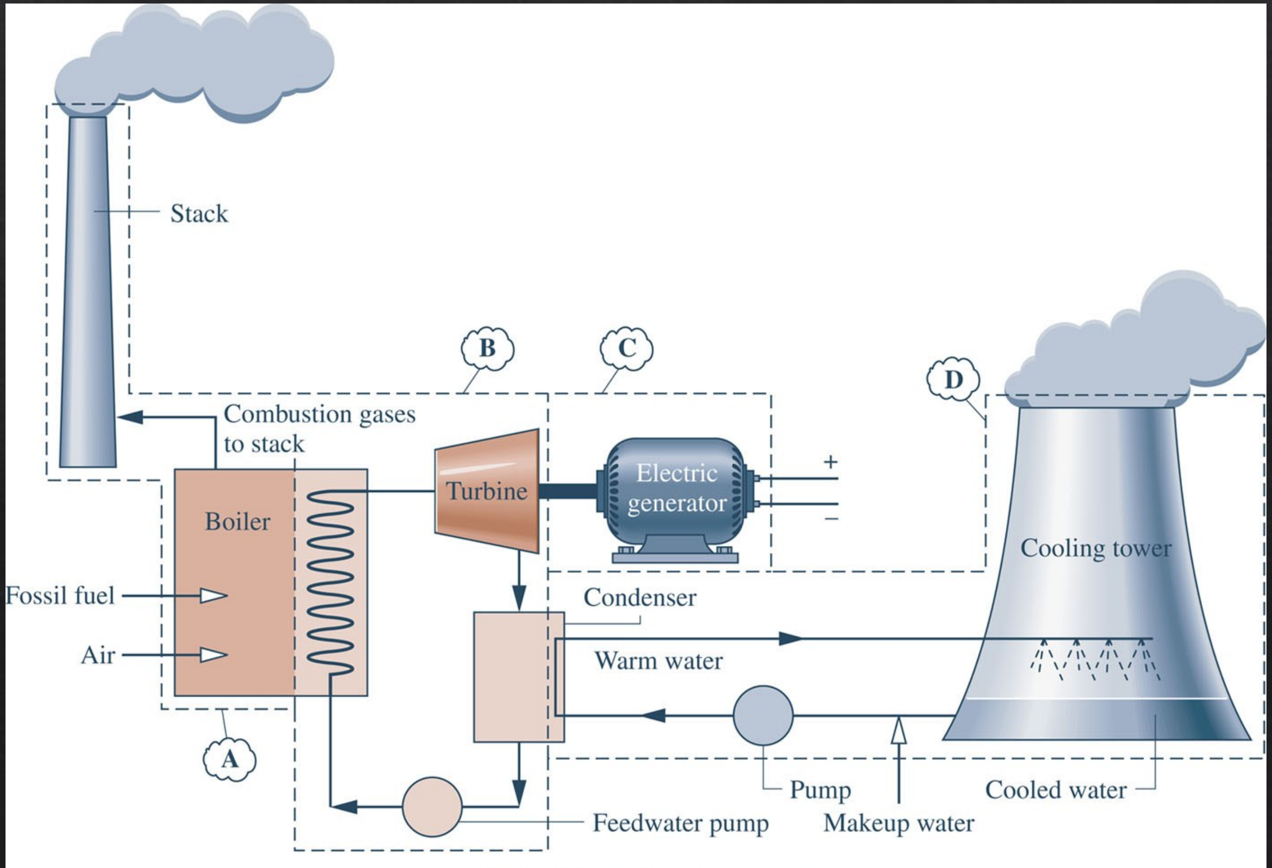
►In geothermal plants, the energy required for vaporization originates in hot water and/or steam drawn from below the earth's surface.



(*d*) Geothermal vapor power plant.

Introducing Vapor Power Plants (6 of 11)

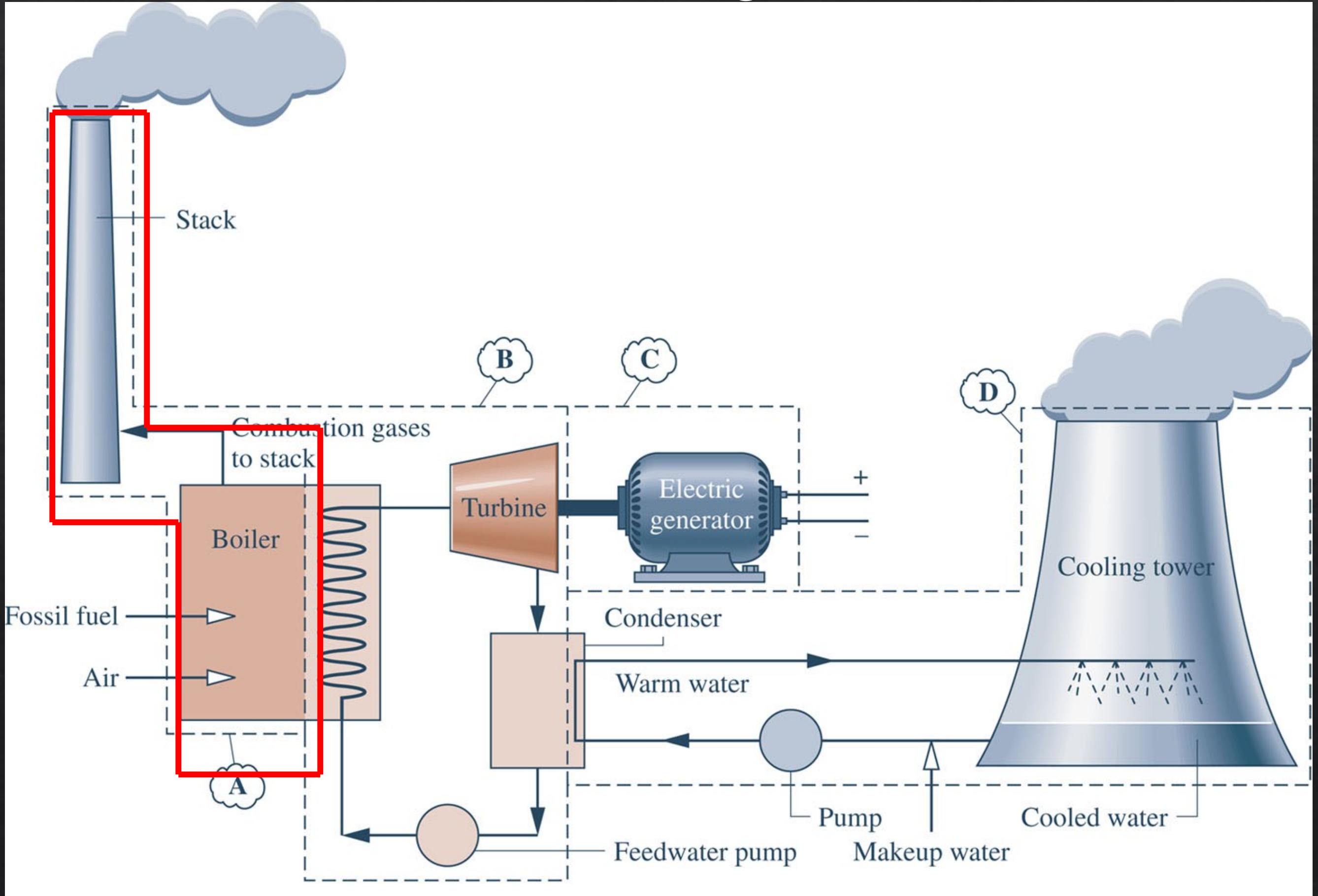
►The fossil-fueled vapor power plant of (a) will be considered as representative. The overall plant is broken into four major subsystems identified by A, B, C, and D. Water is the working fluid.



(a) Fossil-fueled vapor power plant.

Introducing Vapor Power Plants (7 of 11)

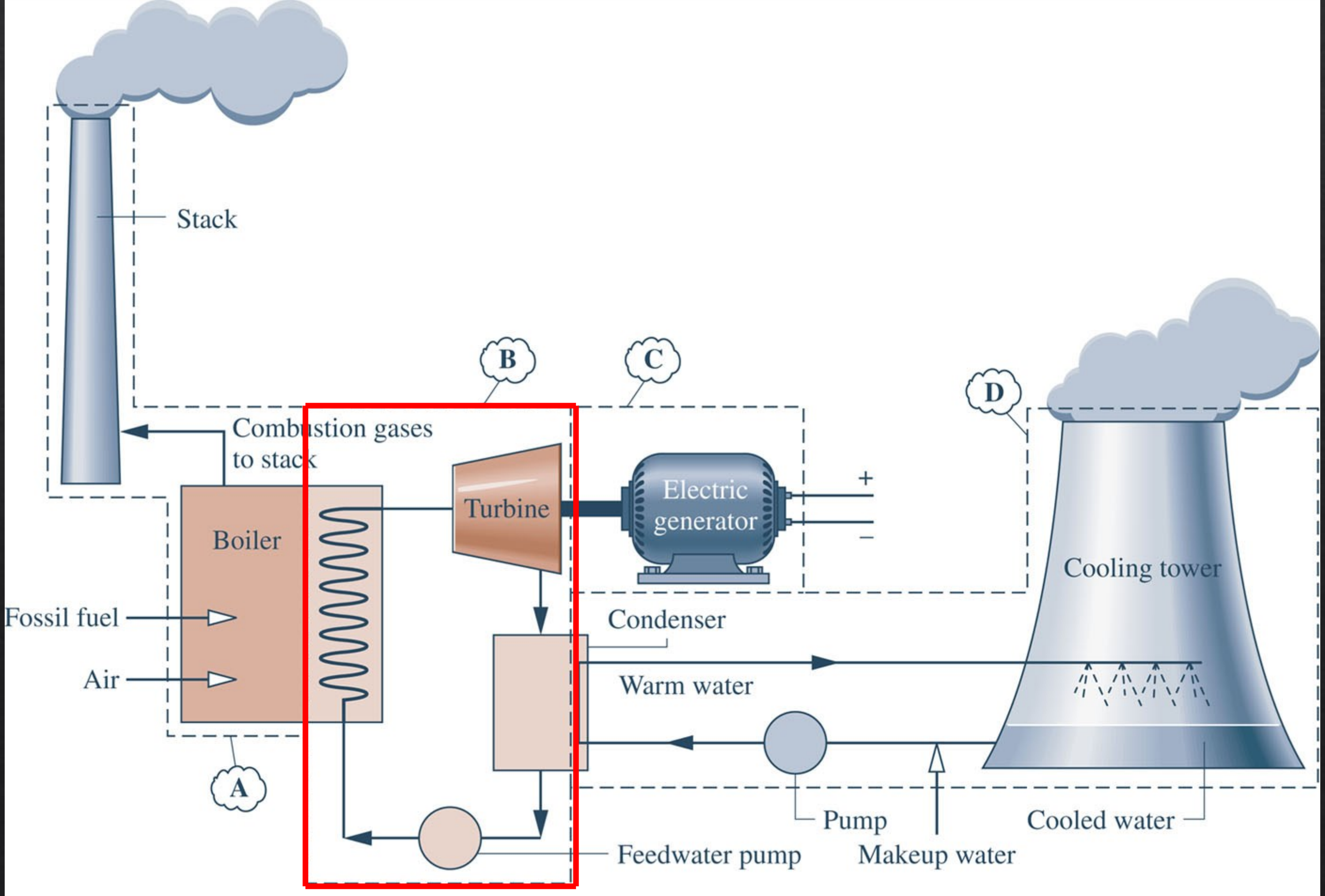
►Subsystem A provides the heat transfer of energy needed to vaporize water circulating in subsystem B. In fossil-fueled plants this heat transfer has its origin in the combustion of the fuel.



(a) Fossil-fueled vapor power plant.

Introducing Vapor Power Plants (8 of 11)

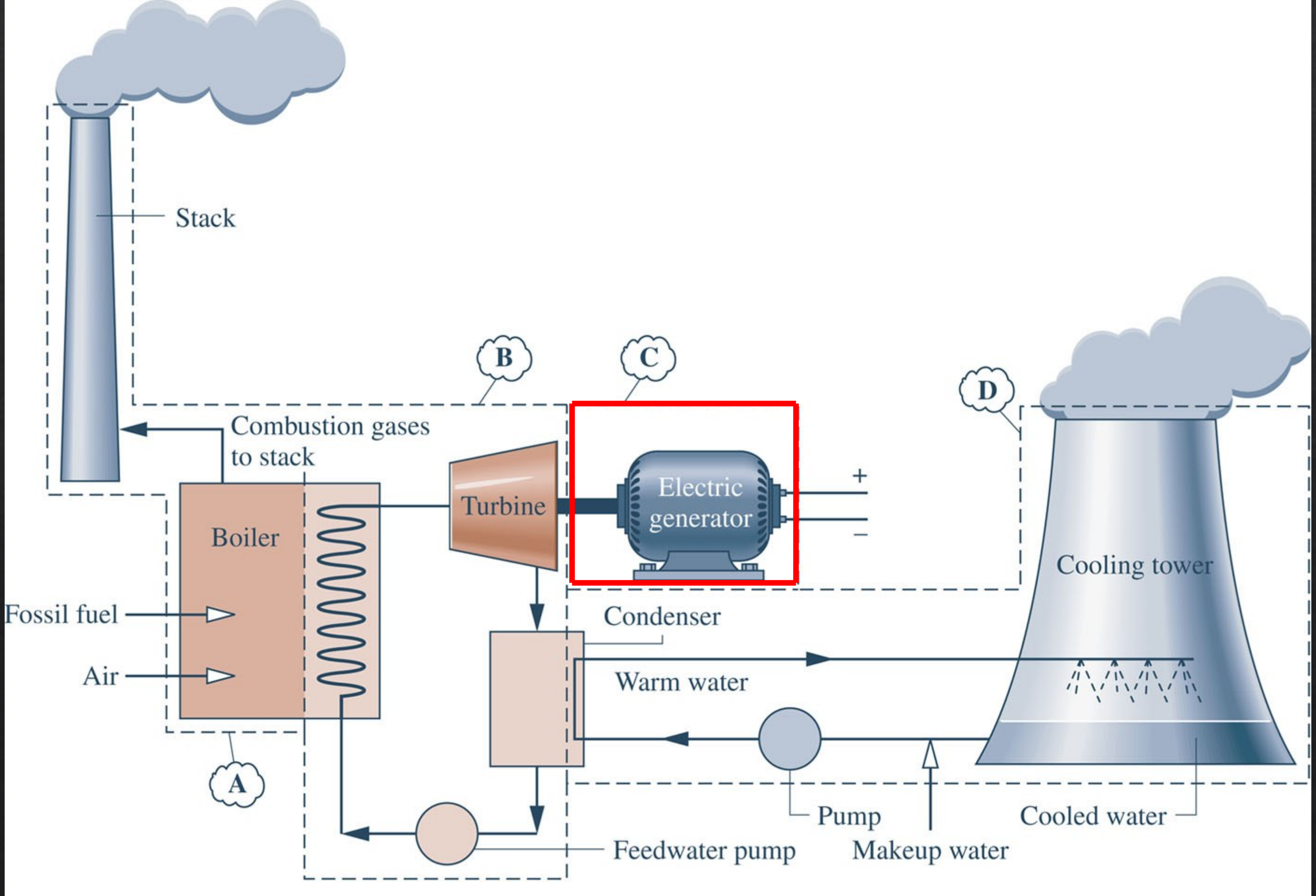
►In subsystem B, the water vapor expands through the turbine, developing power. The water then condenses and returns to the boiler.



(*a*) Fossil-fueled vapor power plant.

Introducing Vapor Power Plants (9 of 11)

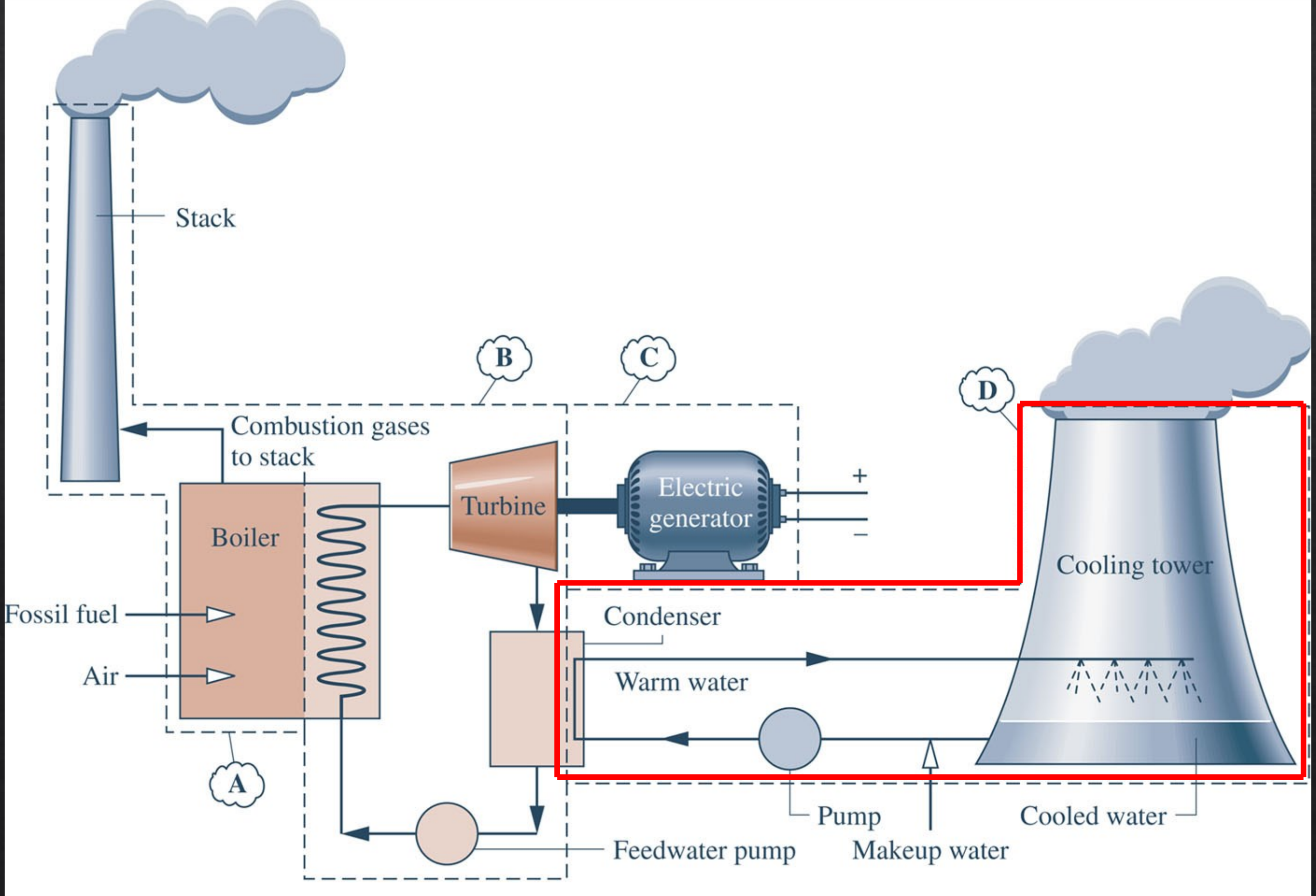
► In subsystem C, power developed by the turbine drives an electric generator.



(a) Fossil-fueled vapor power plant.

Introducing Vapor Power Plants (10 of 11)

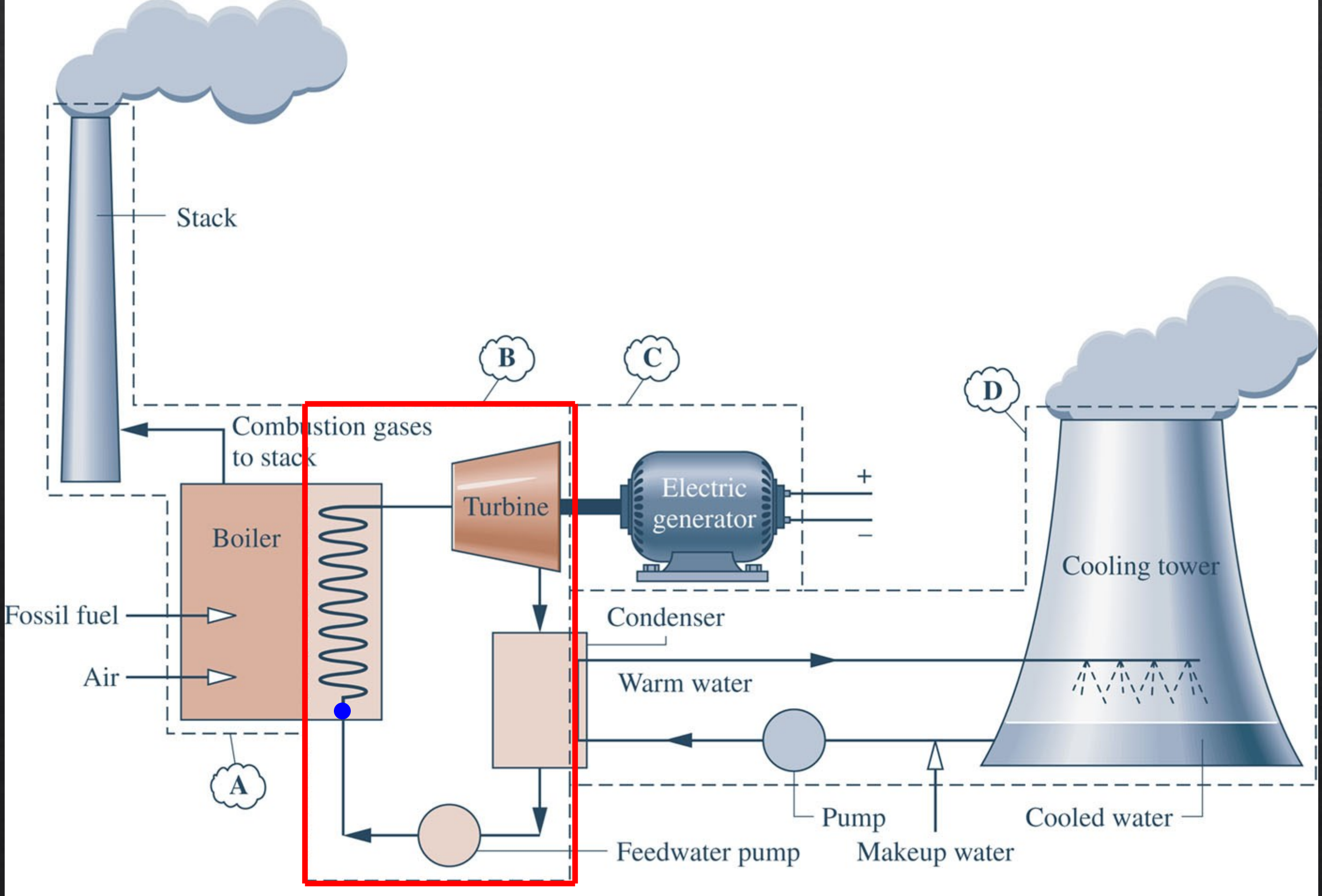
► Subsystem D removes energy by heat transfer arising from steam condensing in subsystem B.



(a) Fossil-fueled vapor power plant.

Introducing Vapor Power Plants (11 of 11)

► 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.

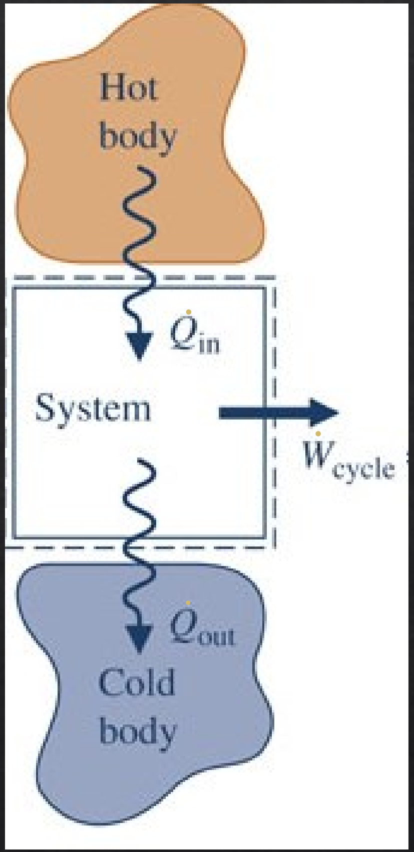
Power Cycle Review (1 of 2)

► 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:

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

► The thermal efficiency of a power cycle is

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



Power Cycle Review (2 of 2)

► 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.

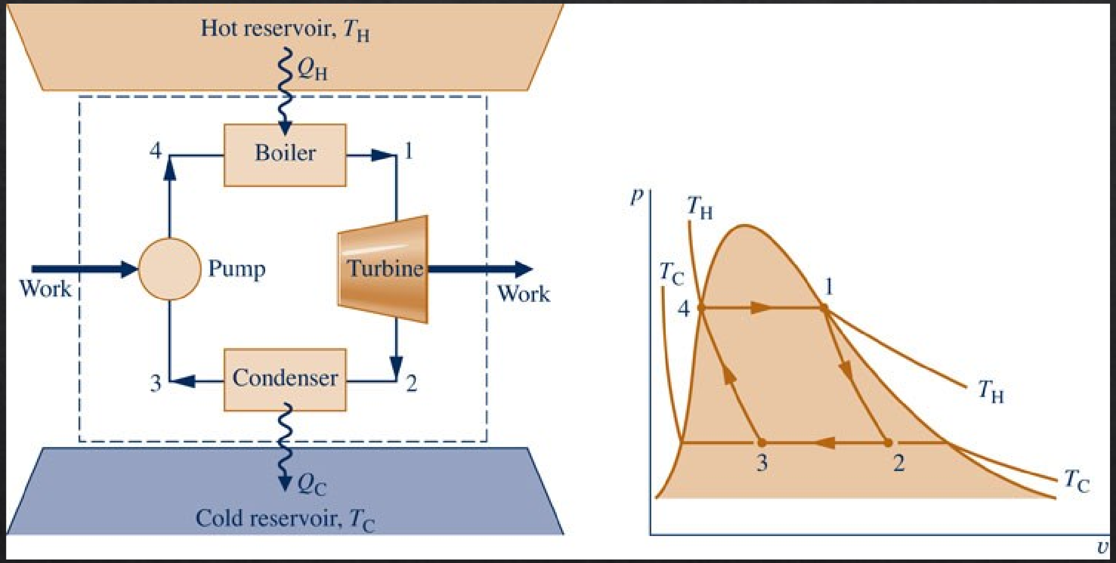
Carnot Cycle

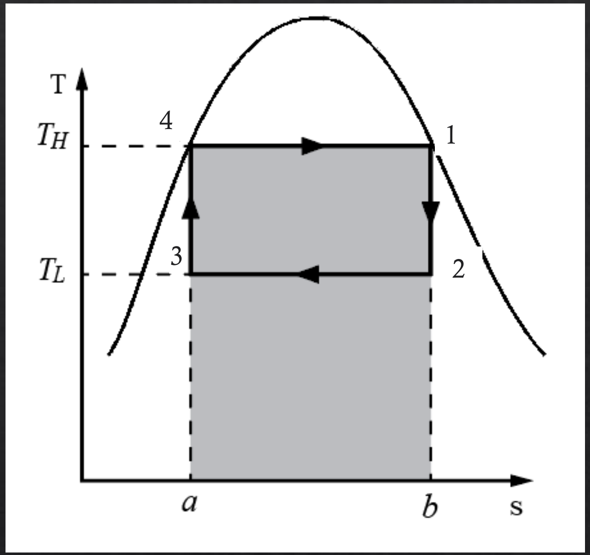
- The Carnot cycle provides a specific example of a reversible cycle that operates between two thermal reservoirs.

- In a Carnot cycle, the system executing the cycle undergoes a series of four internally reversible processes: two adiabatic processes alternated with two isothermal processes.

The Carnot cycle

The ***p-v and T-S* diagram** and **schematic** of water executing a Carnot cycle through four interconnected components are shown below:





1-2 Isentropic Expansion
2-3 Isothermal Heat Rejection
3-4 Isentropic Compression
4-1 Isothermal Heat Addition

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

$$\eta_{Carnot} = \frac{w_{Net}}{q_{In}}$$

The first law of thermodynamics

For a CV with multiple inlets and outlets,

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i \left(h_i + \frac{1}{2} V_i^2 + g\, z_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{1}{2} V_e^2 + g\, z_e \right)$$

For a CV with single inlet and outlet

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}_i \left(h_i + \frac{1}{2} V_i^2 + g\, z_i \right) - \dot{m}_e \left(h_e + \frac{1}{2} V_e^2 + g\, z_e \right)$$

For a steady state CV

$$\frac{\dot{Q}_{CV}}{\dot{m}} - \frac{\dot{W}_{CV}}{\dot{m}} + \left(h_i - h_e\right) + \frac{1}{2}\left(V_i^2 - V_e^2\right) + g\left(z_i - z_e\right) = 0$$

The thermodynamic analysis of any cycle or any component of a cycle involves the conservation of mass and energy laws and the second law of thermodynamics as well as the thermodynamic data needed for these laws.

where E_{CV} is the total energy of the control volume (J); $\dot{W}_{CV}$ is the power involved (produced or consumed) in the control volume (W); $\dot{Q}_{CV}$ is the heat transfer to or from the control volume (W); $\dot{m}$ is the mass flow rate of the working fluid (kg/s); h, $\vec{V}$, and Z are enthalpy (J/kg), velocity (m/s), and elevation (m) of the inlet and outlet flows in the CV, respectively.

The first law of thermodynamics

For an adiabatic (no heat transfer) steady-state expansion and compression processes with no change in potential and kinetic energies between the inlet and outlet flows, Equation 2.6 is reduced to

$$\frac{\dot{W}_{\text{Turb}}}{\dot{m}} = (h_i - h_e) \quad \text{or} \quad w_{\text{Turb}} = (h_i - h_e) \tag{2.7}$$

$$\frac{\dot{W}_{\text{Pump}}}{\dot{m}} = (h_e - h_i) \quad \text{or} \quad w_{\text{Pump}} = (h_e - h_i) \tag{2.8}$$

Similarly, the heat transfers during the heat addition and rejection processes are (with the same assumptions, i.e., steady state and no change in potential and kinetic energies)

$$\frac{\dot{Q}_{\text{SG}}}{\dot{m}} = (h_e - h_i) \quad \text{or} \quad q_{\text{SG}} = (h_e - h_i) \tag{2.9}$$

$$\frac{\dot{Q}_{\text{Cond}}}{\dot{m}} = (h_i - h_e) \quad \text{or} \quad q_{\text{Cond}} = (h_i - h_e) \tag{2.10}$$

where $\dot{W}$ and $\dot{Q}$ are the rate of energy transfer (kW), q and w are the specific energy transfers (kJ/kg), and $\dot{m}$ is the mass flow rate (kg/s).

The first law of thermodynamics

$$\eta_{Th} = \frac{w_{Net}}{q_{SG}} = \frac{w_{Turb} - w_{Pump}}{q_{SG}} \tag{2.11}$$

Another parameter that is being used to describe the performance of power generation cycles is the back work ratio (BWR),

$$\text{Back work ratio} = \text{BWR} = \frac{w_{Pump}}{w_{Turb}} \tag{2.12}$$

The BWR indicates what percentage of the work (power) produced in the turbine is consumed in the pump. The lower BWR is desirable because it means less work (power) is consumed in the pump and more work (power) is available as the net output. Alternatively, some texts used the work ratio (WR) for this purpose defined as

$$\text{Work ratio} = \text{WR} = \frac{w_{Net}}{w_{Turb}} \tag{2.13}$$

Working Fluid Properties

- Appendix of Textbook
- Other resources
  - SteamProperty App
  - Coolprop (Supports multiple programming languages such as MATLAB, Python)
  - EES (Engineering Equation Solver)
  - Interactive Thermodynamics
  - https://irc.wisc.edu/properties/

Working Fluid Properties

TABLE A.1 (SI)

Saturation Temperature (Water)

		Specific Volume (m^3/kg)		Internal Energy (kJ/kg)			Enthalpy (kJ/kg)			Entropy (kJ/kg.K)		
Temp. °C	Sat. Press. kPa	Sat. Liquid v_f	Sat. Vapor v_g	Sat. Liquid u_f	Evap. u_{fg}	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g
0.01	0.6113	0.001000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
5	0.8721	0.001000	147.12	20.97	2361.3	2382.3	20.98	2489.6	2510.6	0.0761	8.9496	9.0257
10	1.2276	0.001000	106.38	42.00	2347.2	2389.2	42.01	2477.7	2519.8	0.1510	8.7498	8.9008
15	1.7051	0.001001	77.93	62.99	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	8.5569	8.7814
20	2.339	0.001002	57.79	83.95	2319.0	2402.9	83.96	2454.1	2538.1	0.2966	8.3706	8.6672

Linear Interpolation

What is the saturation pressure of water at 33°C?

$$\frac{y - y_0}{y_1 - y_0} = \frac{x - x_0}{x_1 - x_0}.$$

Saturated Water Temperature Table

Saturation Temperature (°C)	Saturation Pressure (MPa)	Specific Volume (m³/kg)	
		Saturated Liquid	Saturated Vapor
0.01	0.00061165	0.0010002	205.99
5	0.00087258	0.0010001	147.01
10	0.0012282	0.0010003	106.30
15	0.0017058	0.0010009	77.875
20	0.0023393	0.0010018	57.757
25	0.0031699	0.0010030	43.337
30	**0.004247**	0.0010044	32.878
35	**0.005629**	0.0010060	25.205
40	0.0073849	0.0010079	19.515
45	0.0095950	0.0010099	15.252
50	0.012352	0.0010121	12.027
55	0.015762	0.0010146	9.5643
60	0.019946	0.0010171	7.6672
65	0.025042	0.0010199	6.1935
70	0.031201	0.0010228	5.0395
75	0.038595	0.0010258	4.1289
80	0.047414	0.0010291	3.4052
85	0.057867	0.0010324	2.8258
90	0.070182	0.0010360	2.3591
95	0.084608	0.0010396	1.9806
100	0.10142	0.0010435	1.6718

Linear Interpolation

What is the saturation pressure of water at 33°C?

$$\frac{y - y_0}{y_1 - y_0} = \frac{x - x_0}{x_1 - x_0}.$$

T (°C)	P (MPa)
30	0.004247
33	P_{sat}
35	0.005629

Substituting the values into the interpolation equation, we get:

P_{sat} = 0.005076 MPa

Saturated Water Temperature Table

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Example 2.3

In a Carnot cycle with the working fluid of water, the operating pressure of the steam generator and the condenser are 10,000 kPa and 10 kPa, respectively. If the turbine inlet flow is saturated vapor and the pump outlet flow is saturated liquid, determine the specific heat transfers in the steam generator and the condenser (in kJ/kg), the specific work involved in the turbine and the pump (in kJ/kg), and the thermal efficiency and back work ratio of the cycle.

End of Lecture!