

RME1102
Fundamentals of Mechanical Engineering

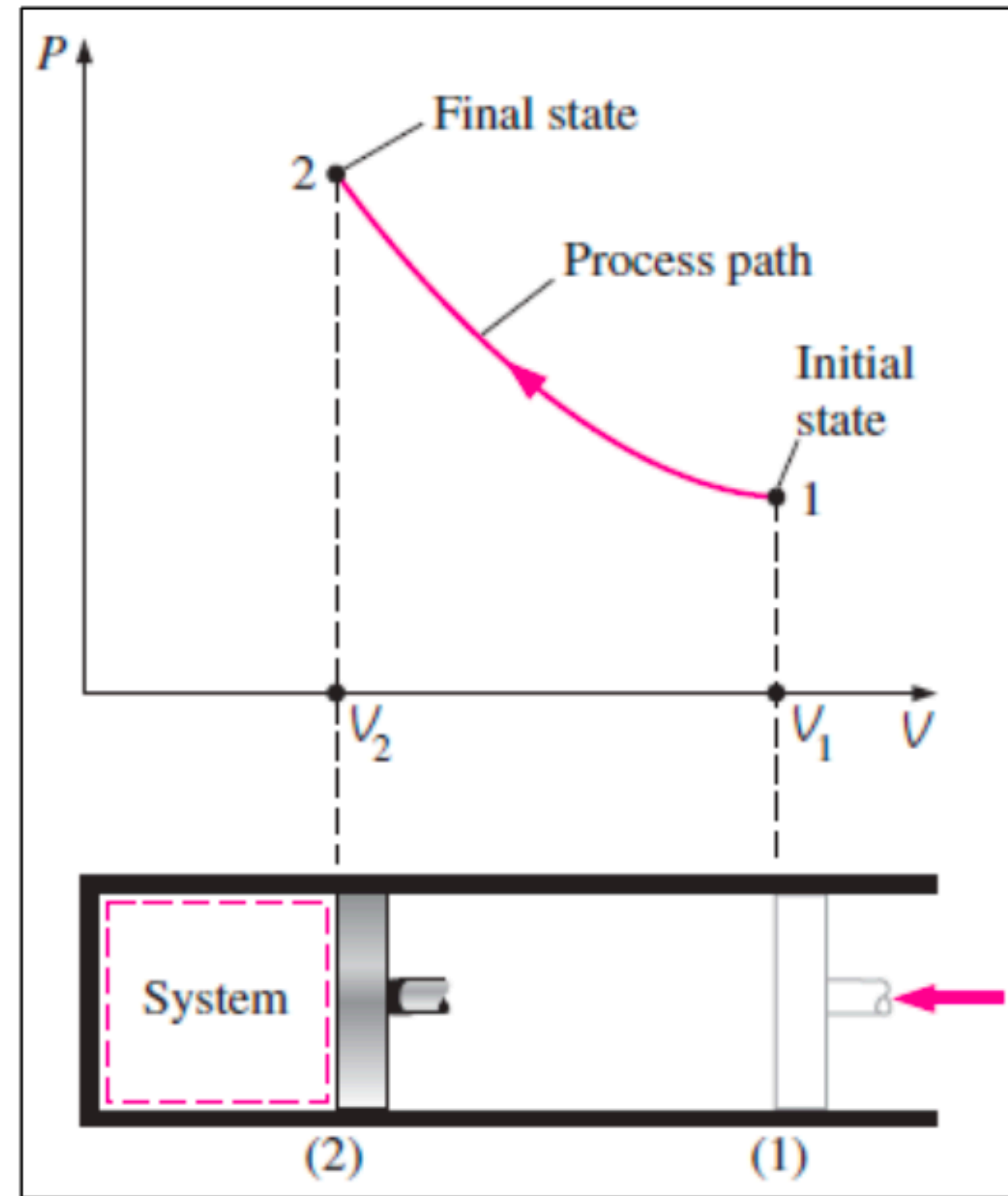
Lecture 5

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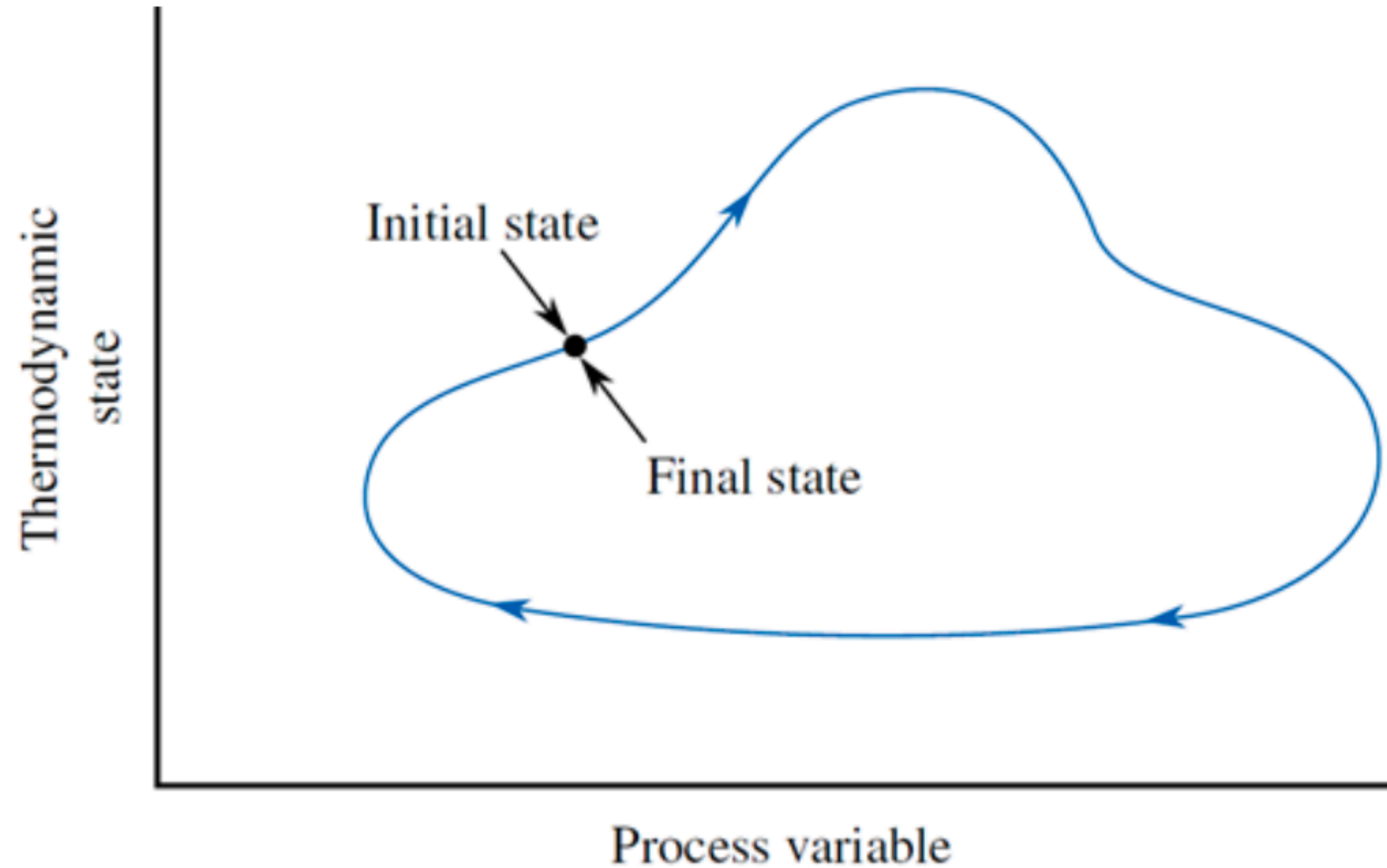
Thermodynamic process and cycle

- **Process:** When any of the properties of a system change, the state changes and the system is said to have undergone a process. A process is a transformation from one state to another.



Thermodynamic process and cycle, cont'd

- **Cycle:** A thermodynamic cycle is a sequence of processes that begins and ends at the same state.



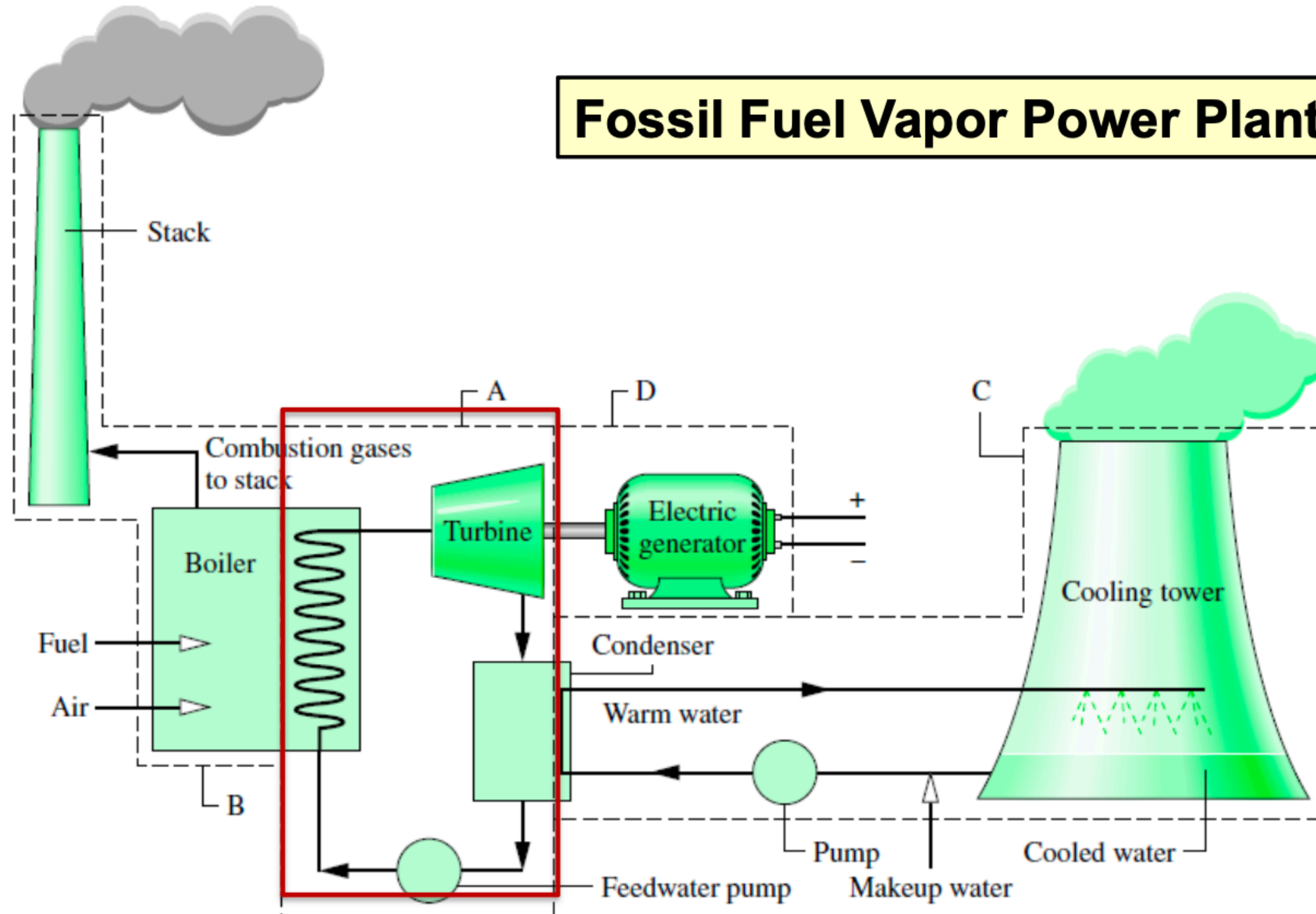
Thermodynamic cycle

- **Two most important areas** of application for thermodynamics are **power generation** and **refrigeration**.
 - They are usually accomplished by **systems that operate on thermodynamic cycle**.
- **Thermodynamic cycles can be divided into two general categories:**
 - **Power cycle**
 - **Refrigeration cycle**

Power cycle

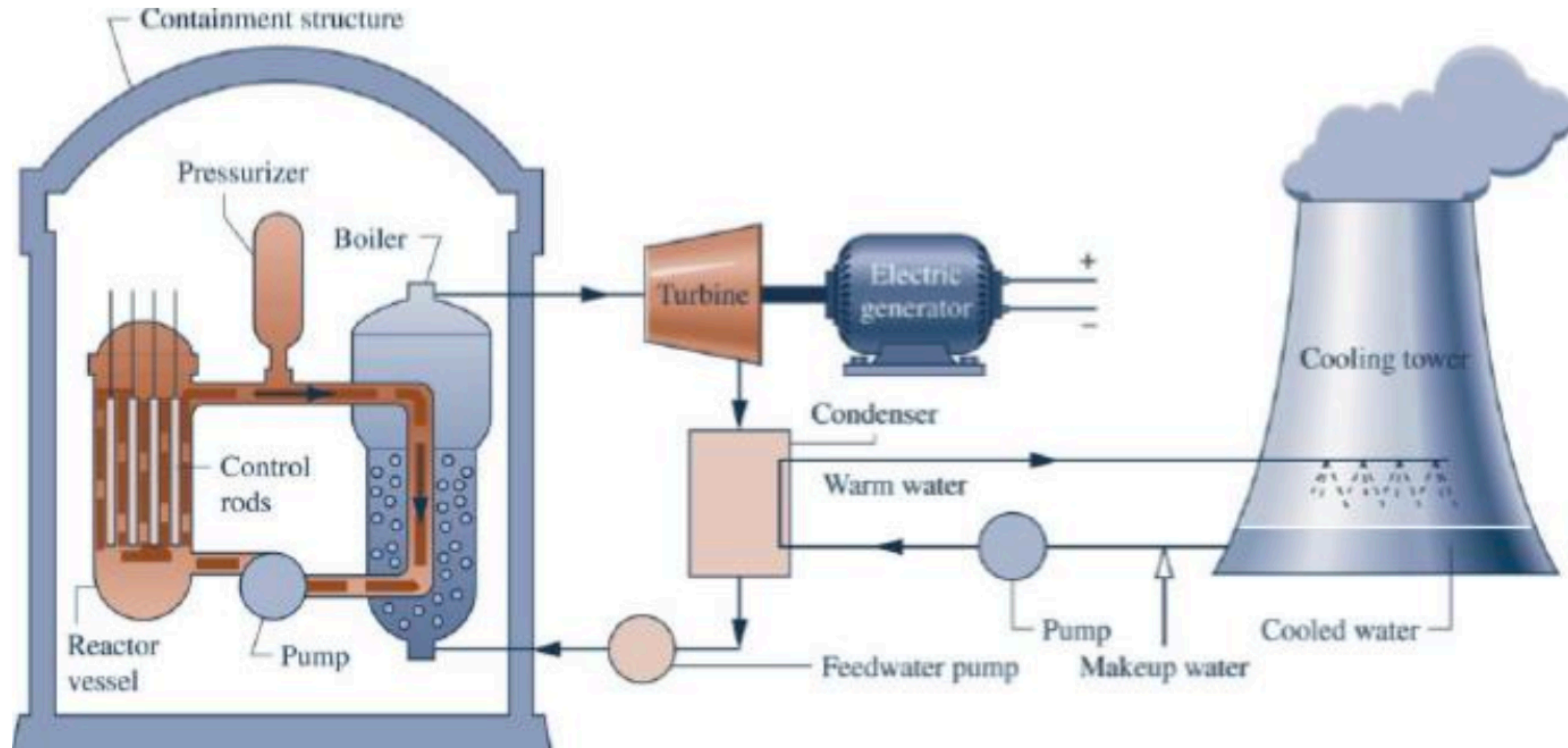
- Depending on **the phase of the working fluid**, can be divided into-
 - **Gas cycles:** In gas cycles, the working fluid remains in the gaseous phase throughout the entire cycle.
 - SI Engines, Diesel Engines (Otto cycle, Brayton cycle)
 - **Vapor cycles:** the working fluid exists in the vapor phase during one part of the cycle and in the liquid phase during another part.
 - Steam is the most common working fluid used in vapor power cycles because of its many desirable characteristics.
 - Steam power plants (coal plants, nuclear plants, natural gas plants)

Vapor power plant



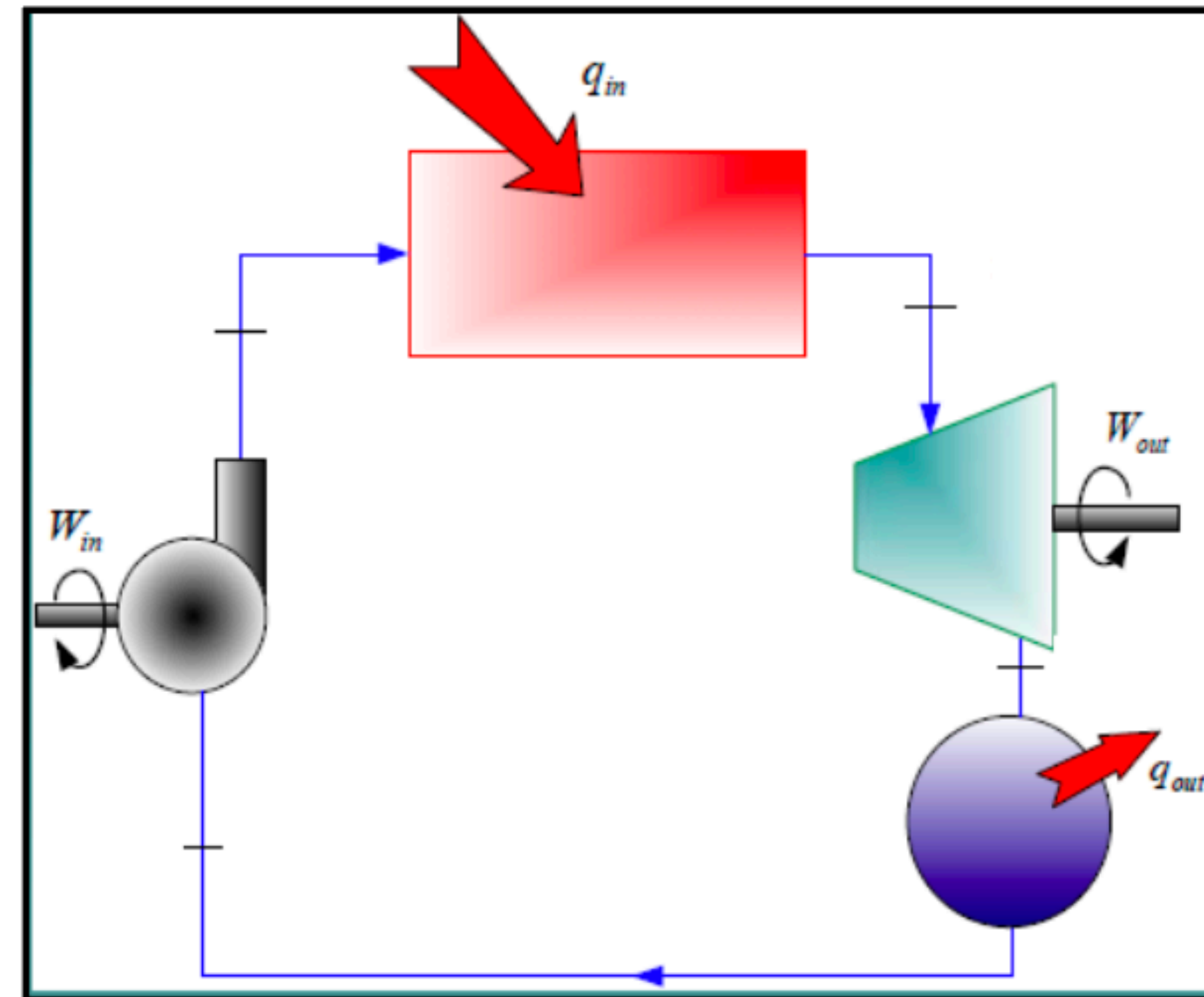
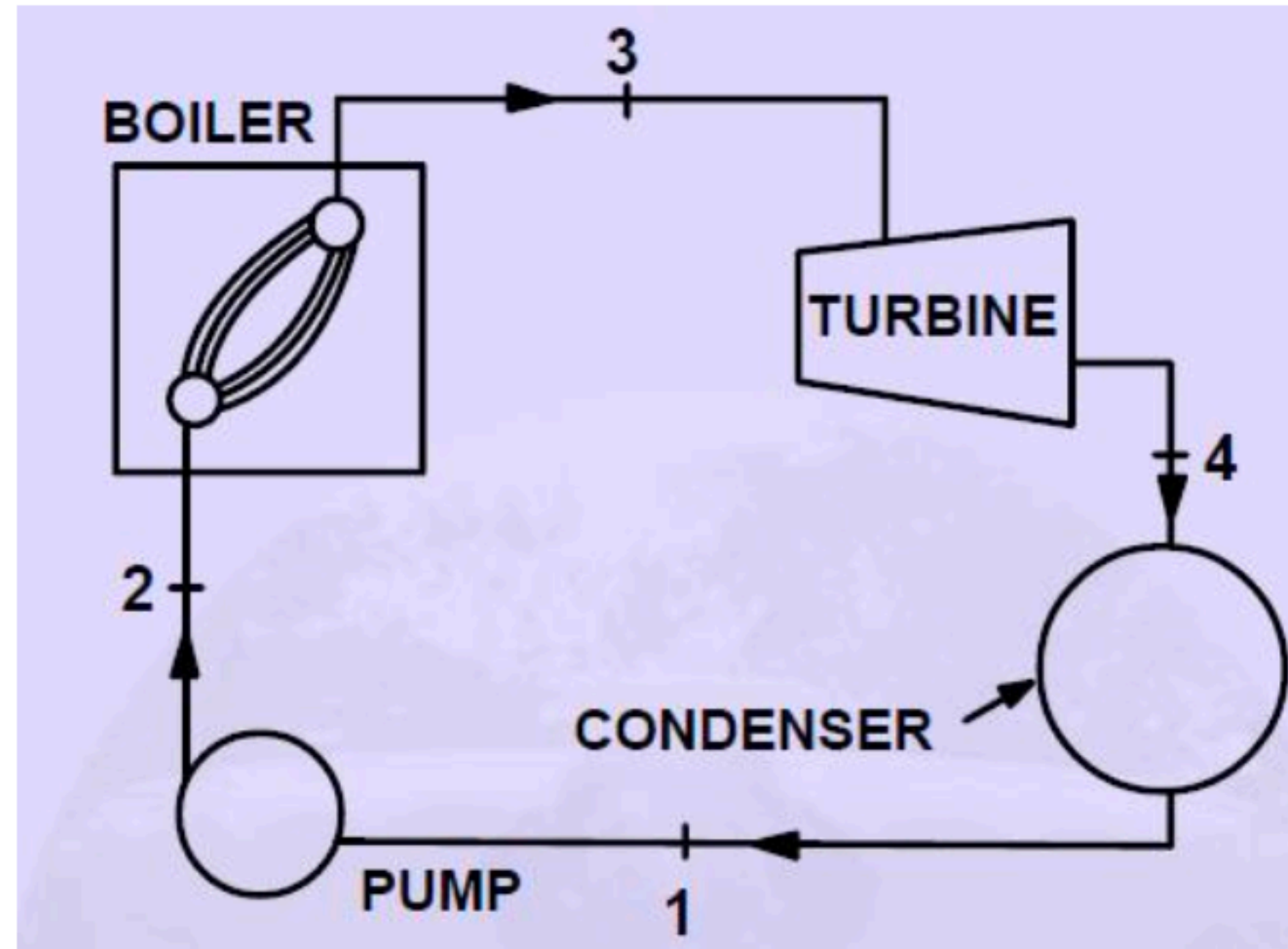
Vapor power plants, cont'd

Nuclear Vapor Power Plant

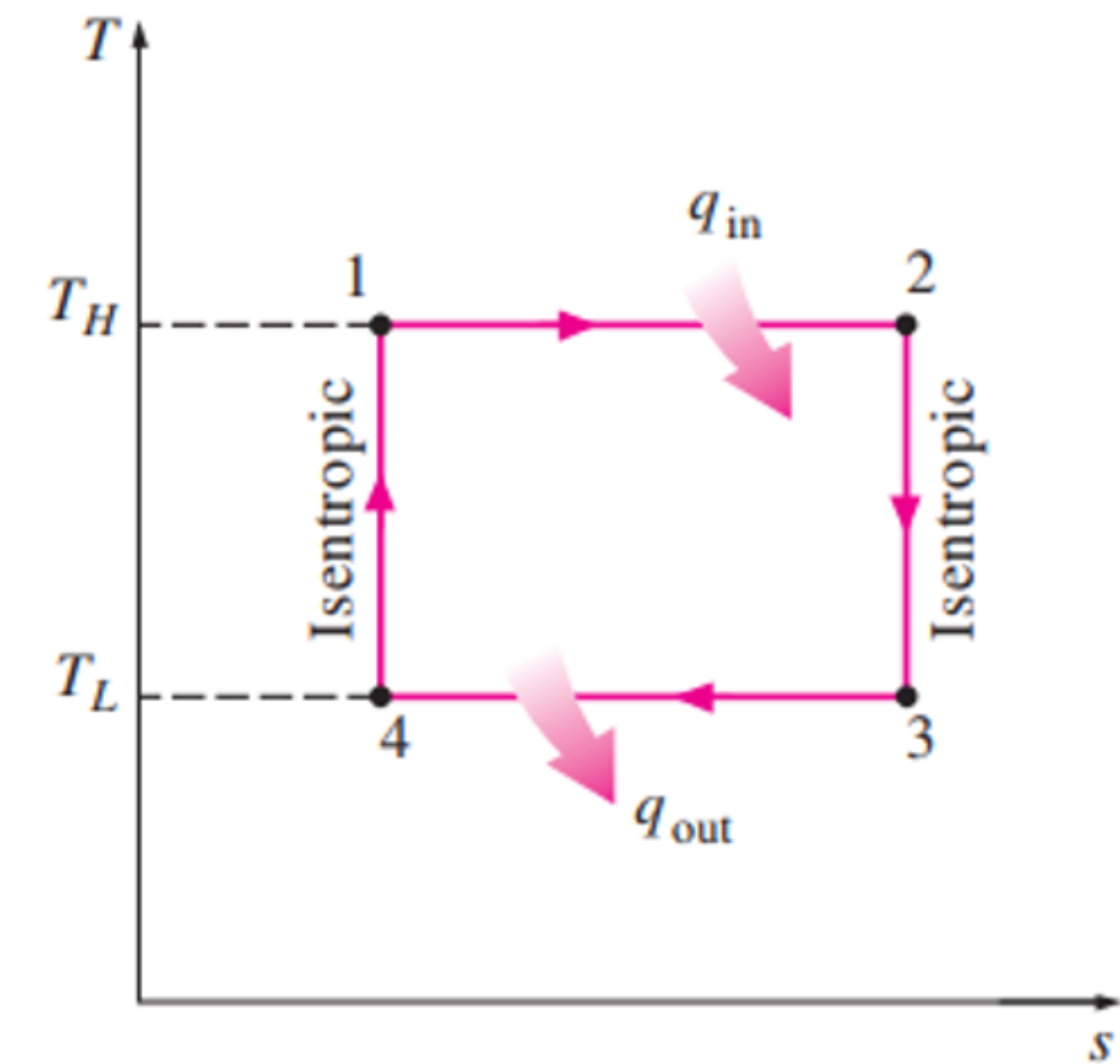
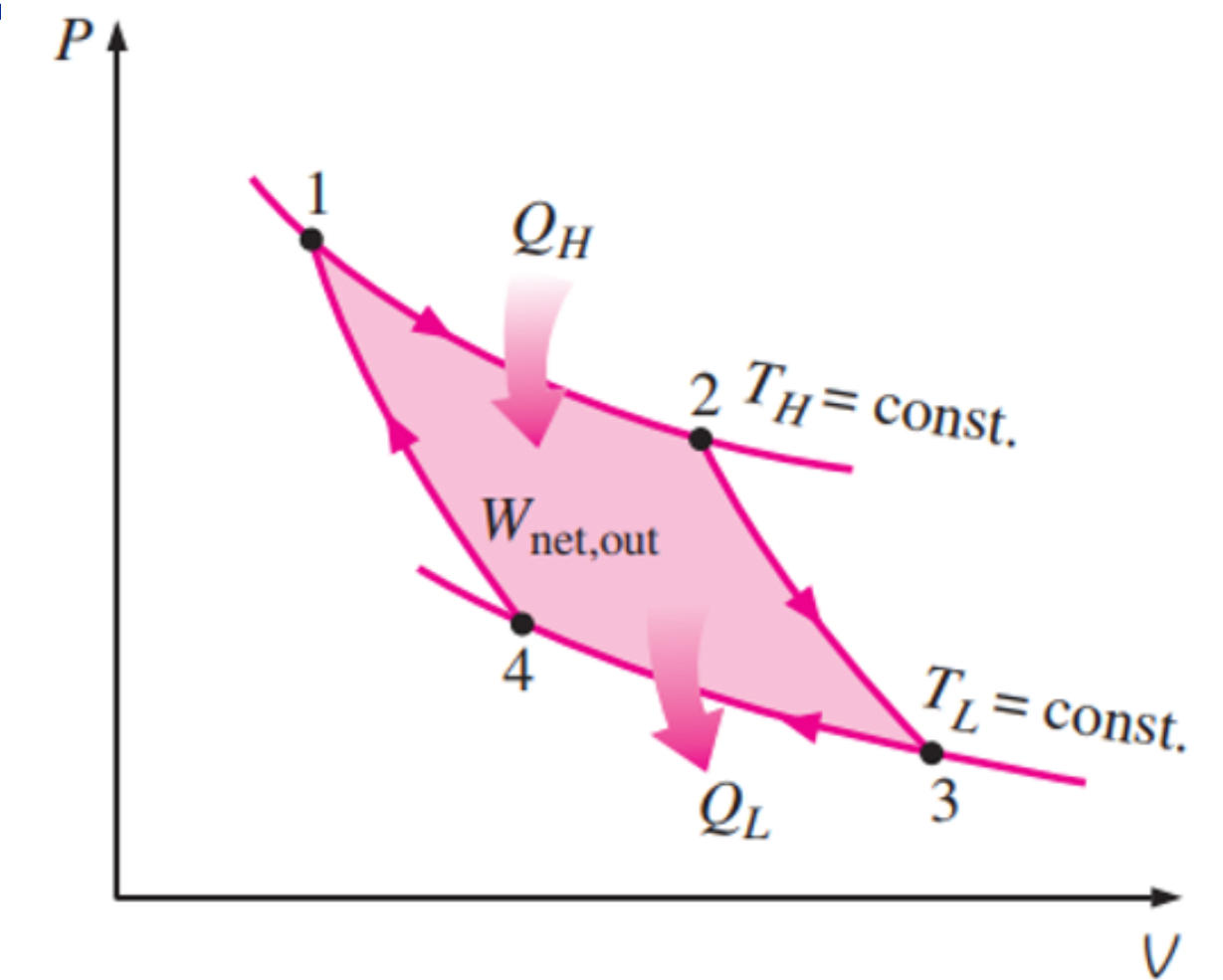
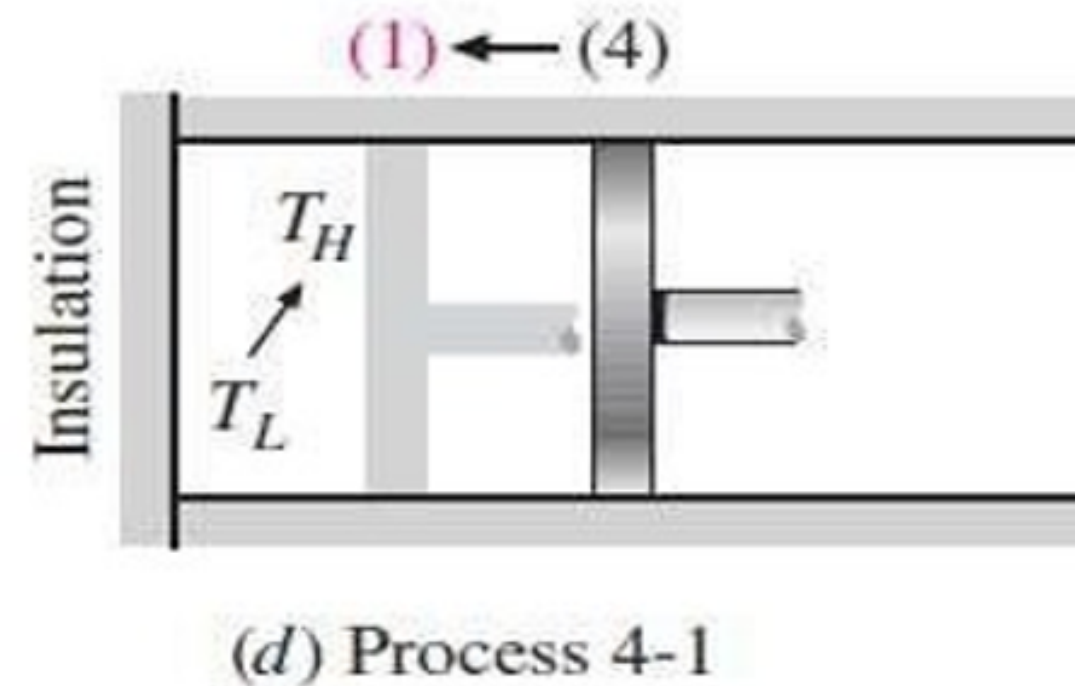
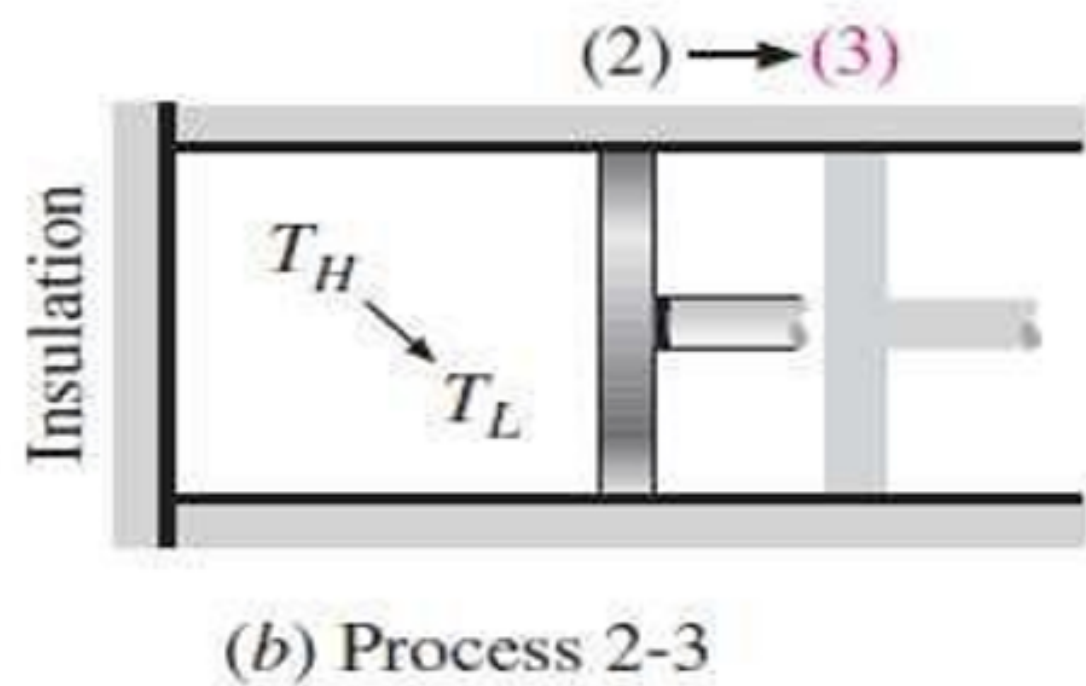
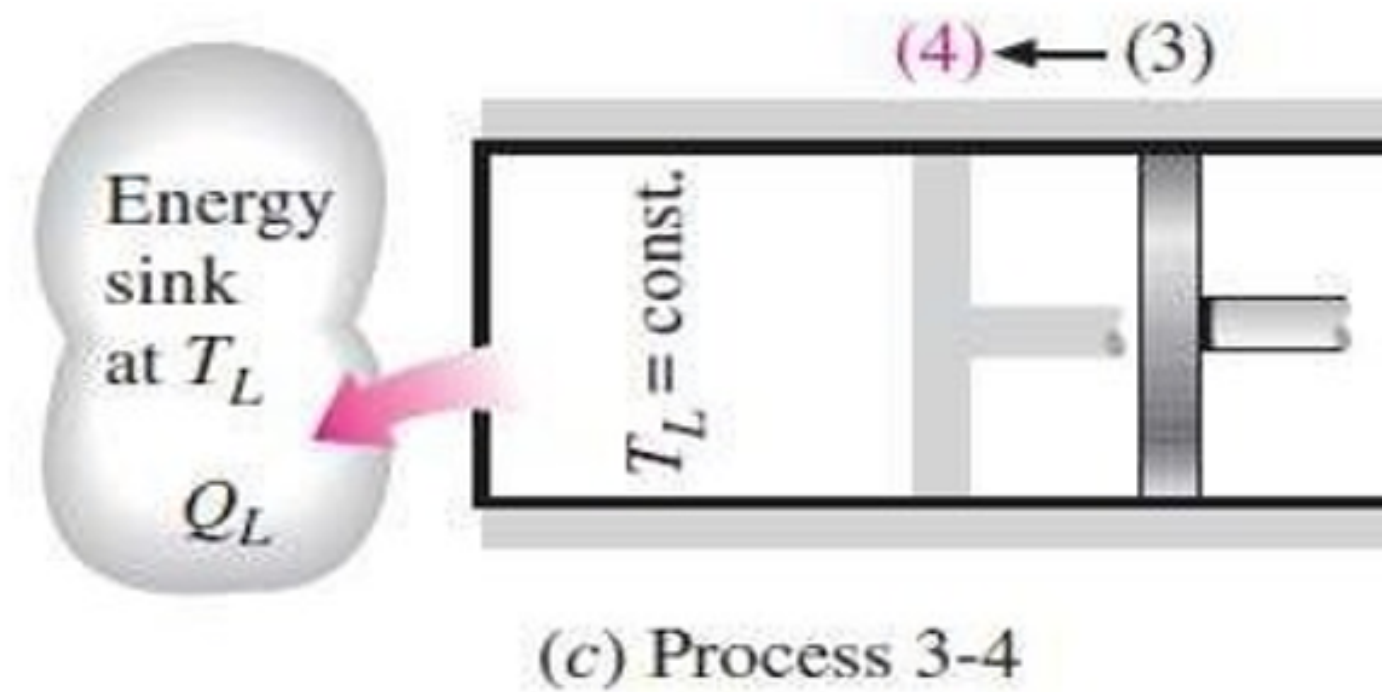
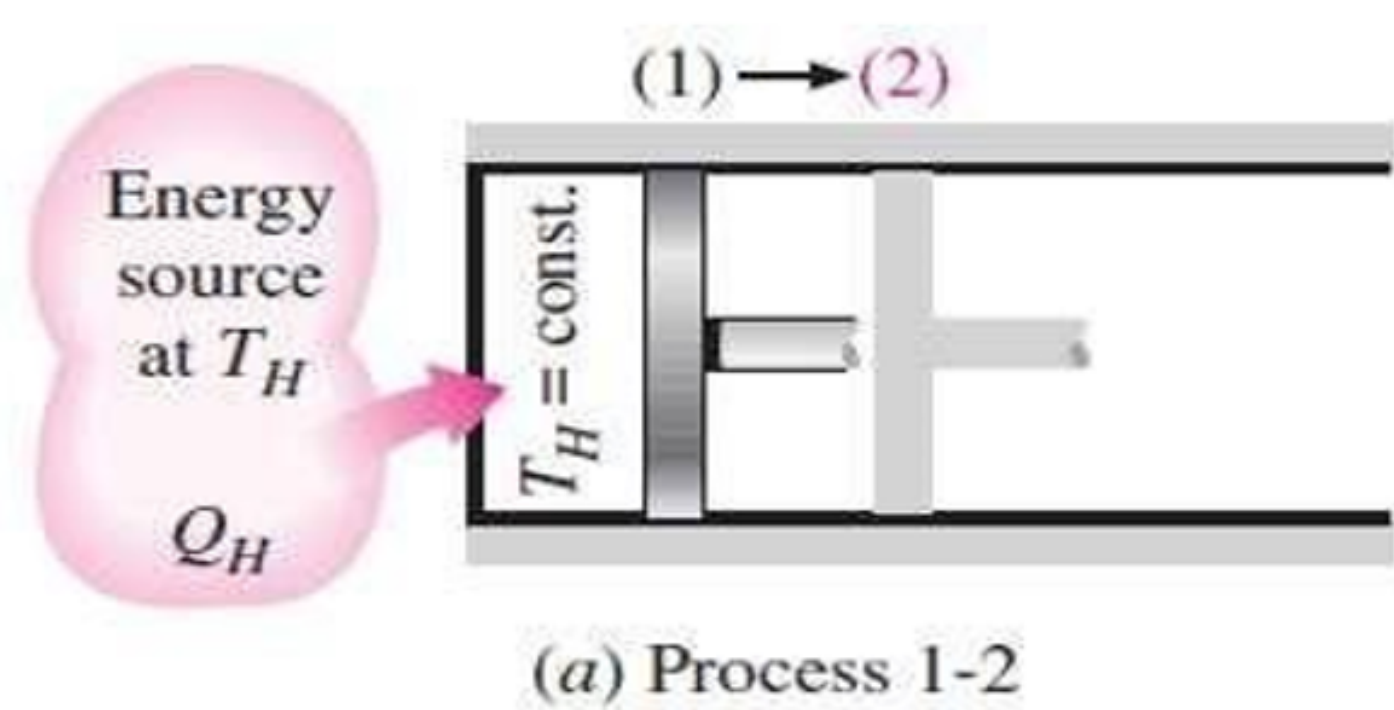


Carnot cycle

- An ideal and the most efficient possible cycle (engine).
- A totally (internally and externally) reversible cycle
- It consists of 4 reversible processes.



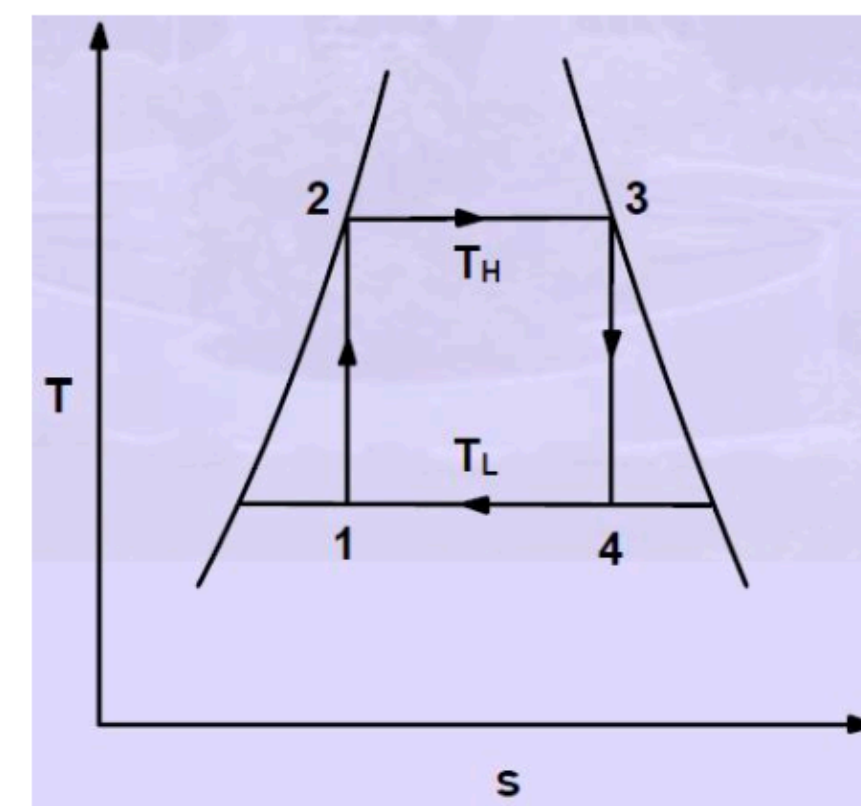
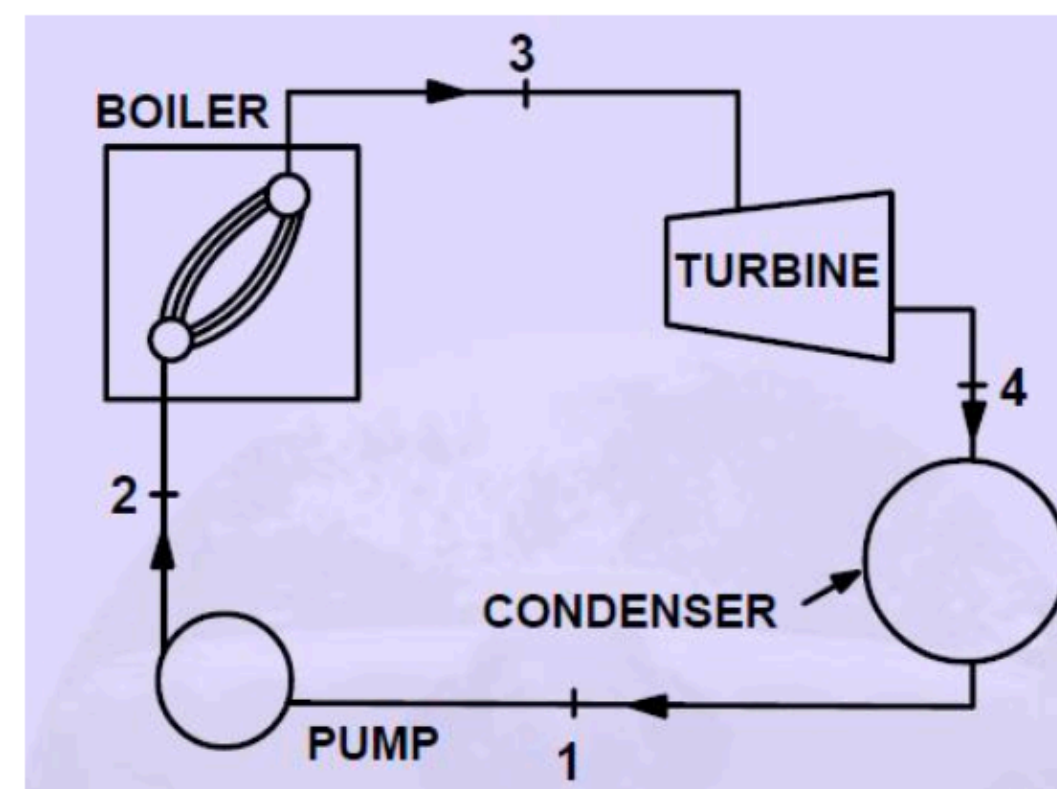
Carnot cycle, cont'd



1-2: Reversible Isothermal Expansion, 2-3: Reversible Adiabatic Expansion
 3-4: Reversible Isothermal Compression, 4-1: Reversible Adiabatic Compression

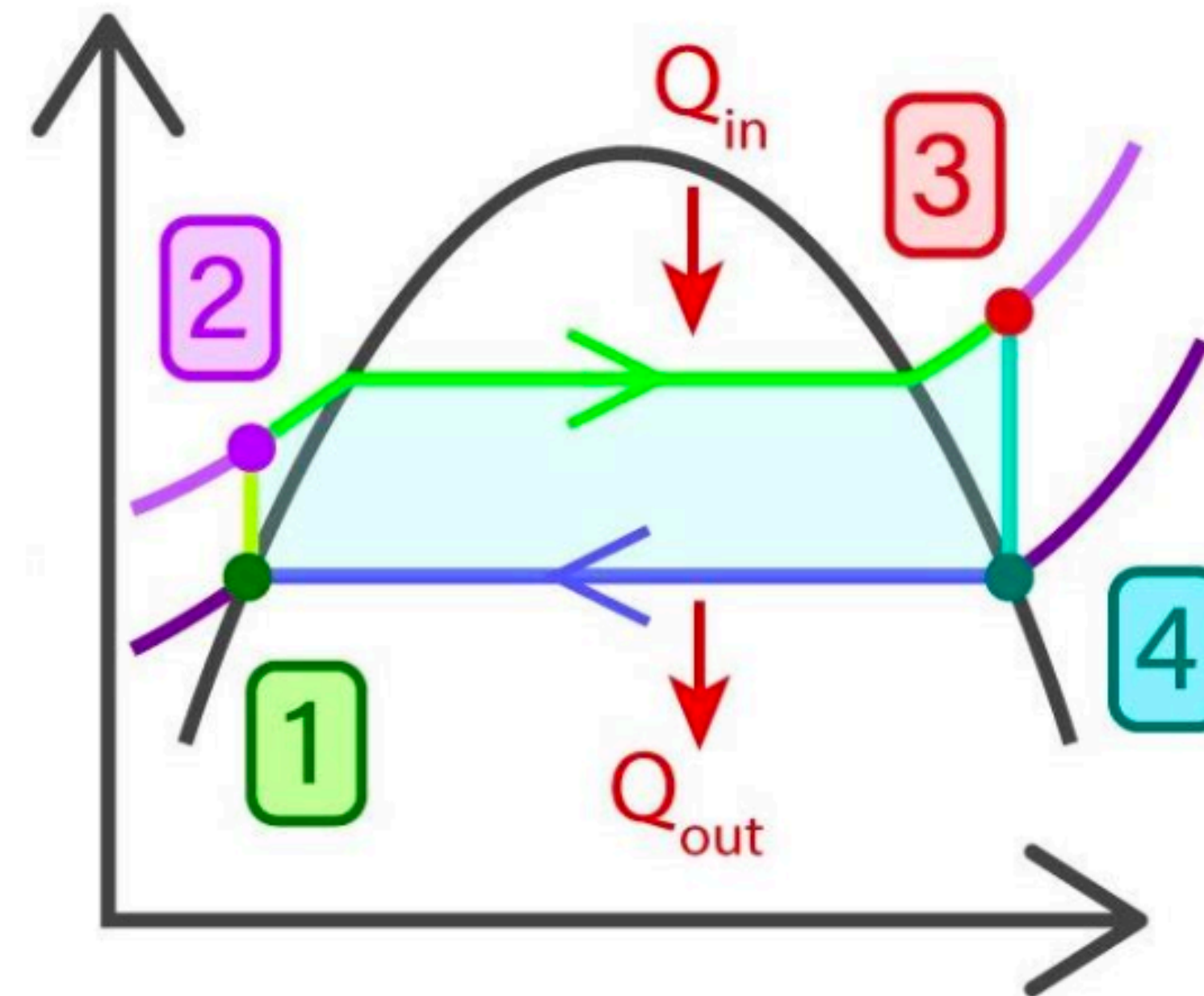
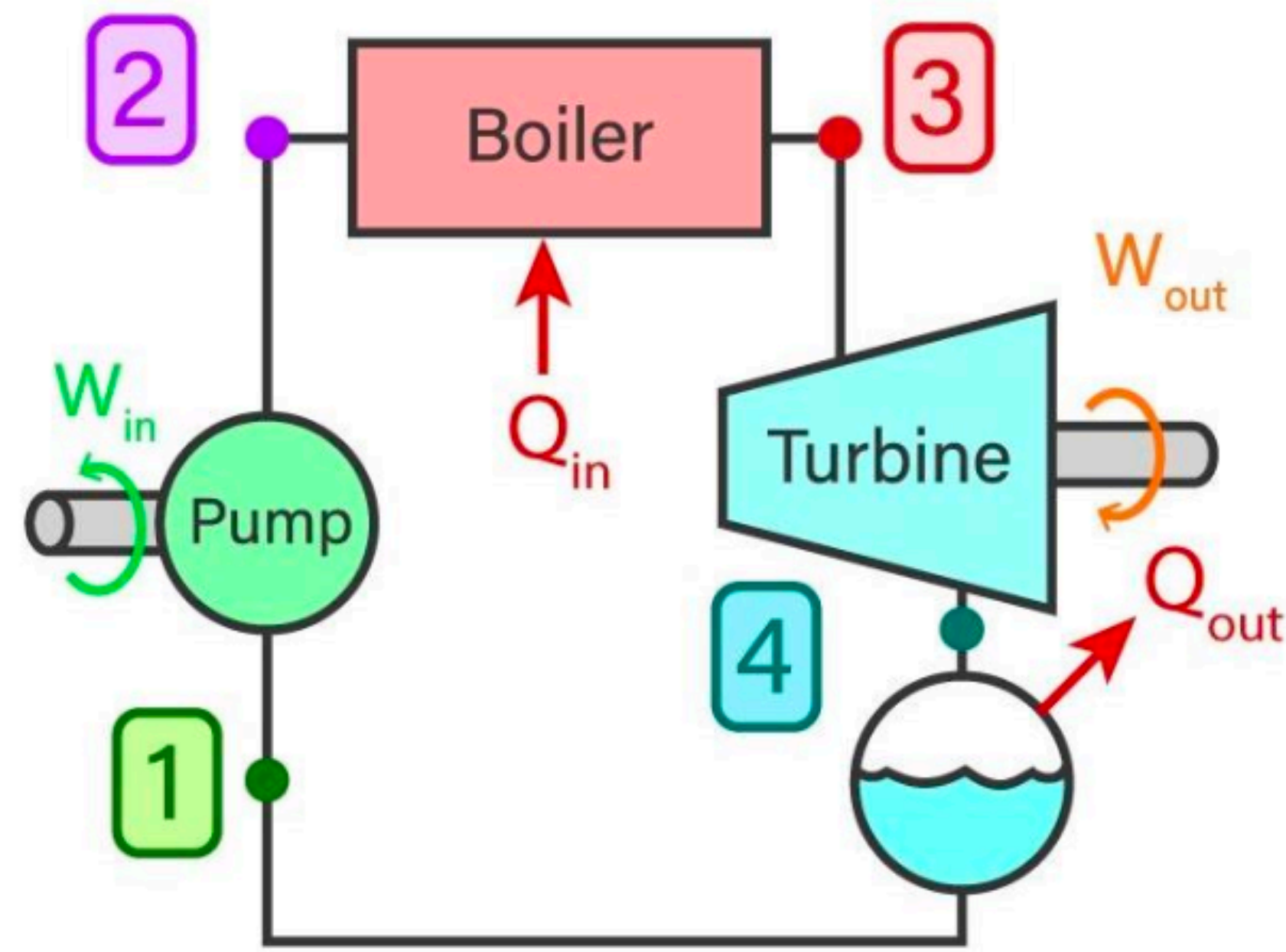
Impracticalities of Carnot Cycle

1. Practically, it is very difficult to add or reject heat to or from the working fluid at constant temperature. But **it is comparatively easy to add or reject heat to or from the working fluid at constant pressure.**
2. The quality of the steam decreases during the **isentropic expansion process (3-4) and is in the two-phase region.** At the end This is not acceptable for turbines.
 - The impingement of liquid droplets on turbine blades causes **Erosion.**
3. The **isentropic compression process** involves the compression of a liquid- vapor mixture to a saturated liquid.
 - **It is not practical that a compressor or pump will handle two phases.**



Ideal Rankine cycle

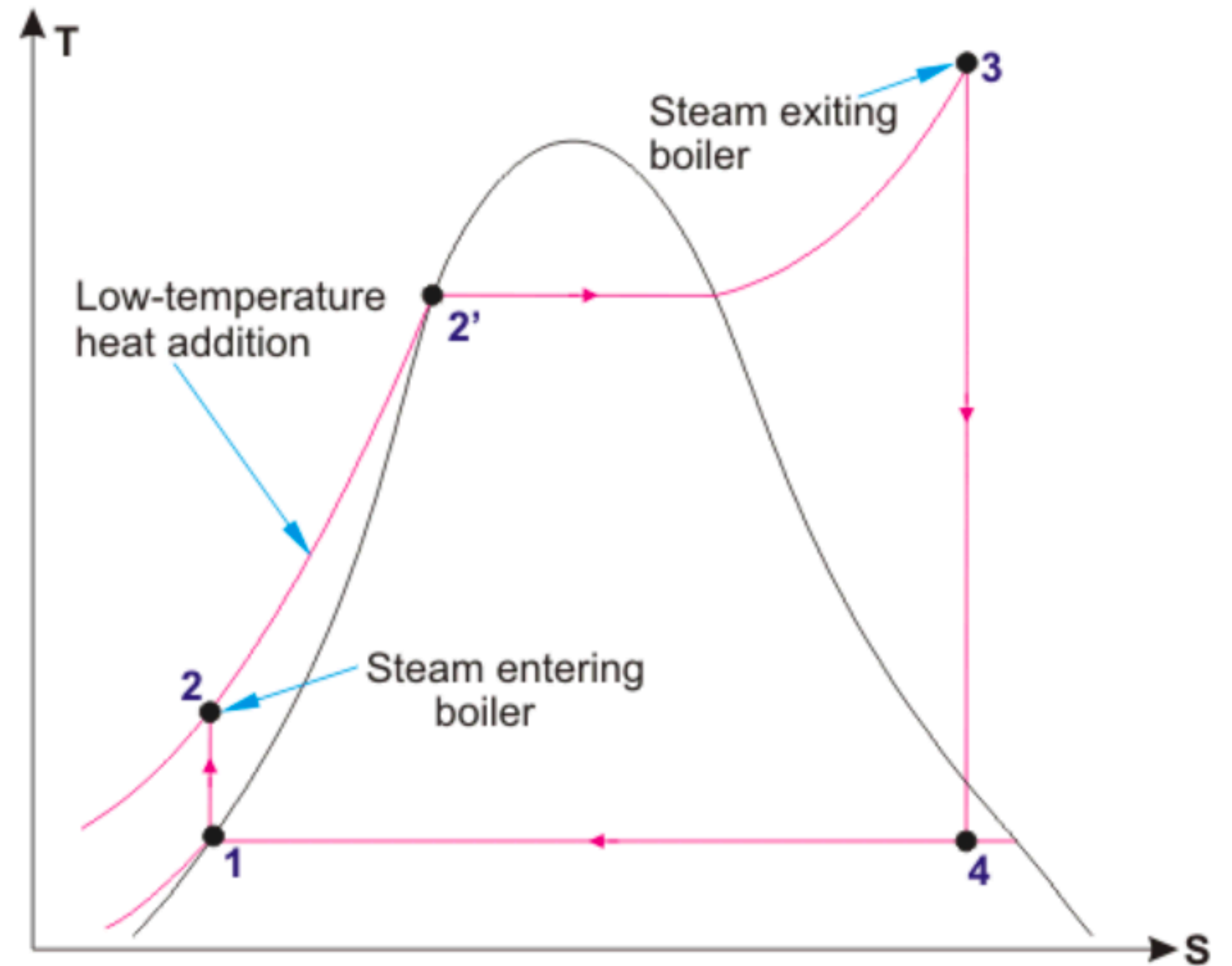
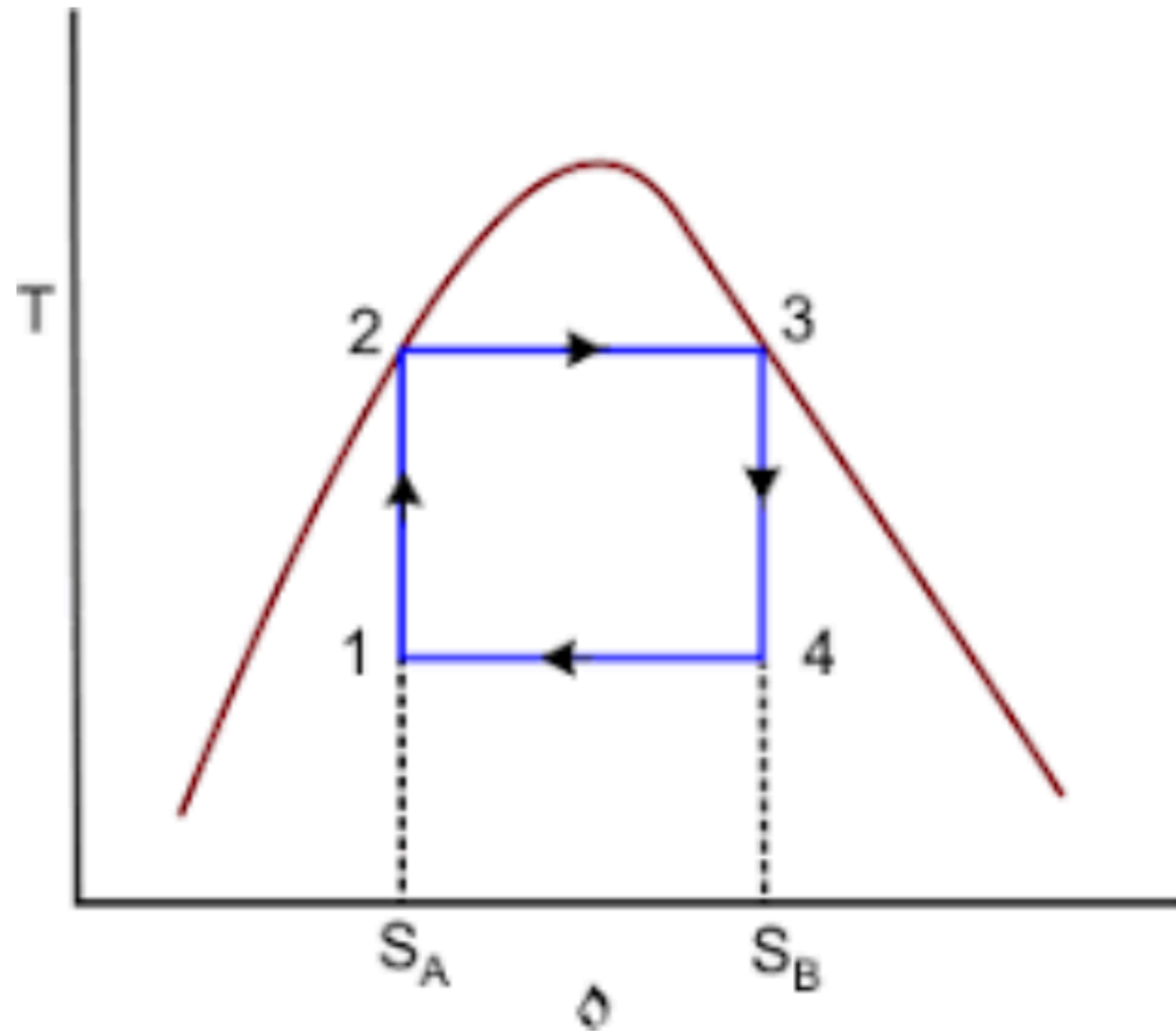
The Rankine cycle is the ideal cycle to represent the vapor power plants.



1 to 2: isentropic compression in pump
2 to 3: Constant pressure heat addition
in a boiler

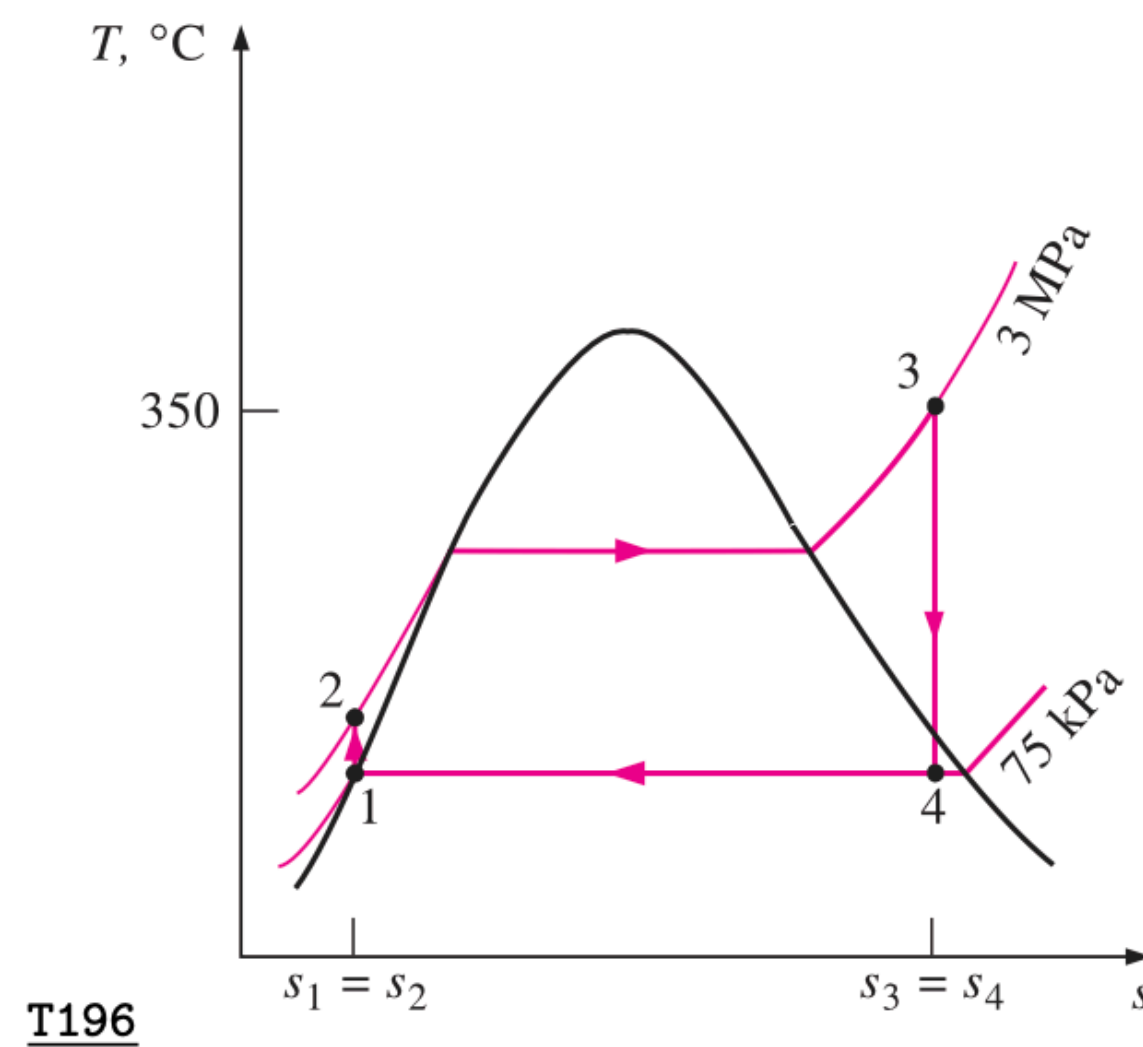
3 to 4: isentropic expansion in a turbine
4 to 1: Constant pressure heat rejection
in a condenser

Carnot and ideal Rankine cycle



Example 1

- [Cengel 10.1]: Ideal Rankine Cycle: Steam enters the turbine at 3 MPa and 350°C, and condenser is at 75 kPa.



T196

⇒ Steady state ⇒ $dE_{cv}/dt = 0$

⇒ $Z_2 = Z_1$ & $V_2 = V_1$, $\dot{m}_i = \dot{m}_e = \dot{m}$

$$\Rightarrow 0 = q - w + (h_i - h_e)$$

- Turbine: $q = 0$, $w = w_T = h_3 - h_4$
- Pump: $q = 0$, $w = w_P = h_1 - h_2$
- Boiler: $w = 0$, $q = q_B = h_3 - h_2$
- Condenser: $w = 0$, $q = q_C$

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

$$BWR = \frac{W_{pump}}{W_{turbine}} = \frac{h_2 - h_1}{h_3 - h_4}$$

- h_2 is in compressed state & difficult to estimate. Hence, $w_P = -\int_1^2 v dP$.

⇒ $w_{net} = w_T + w_P = (713.0 - 3.03) \text{ kJ/kg} = 710.0 \text{ kJ/kg}$. ▶ $w_T \gg w_P$.

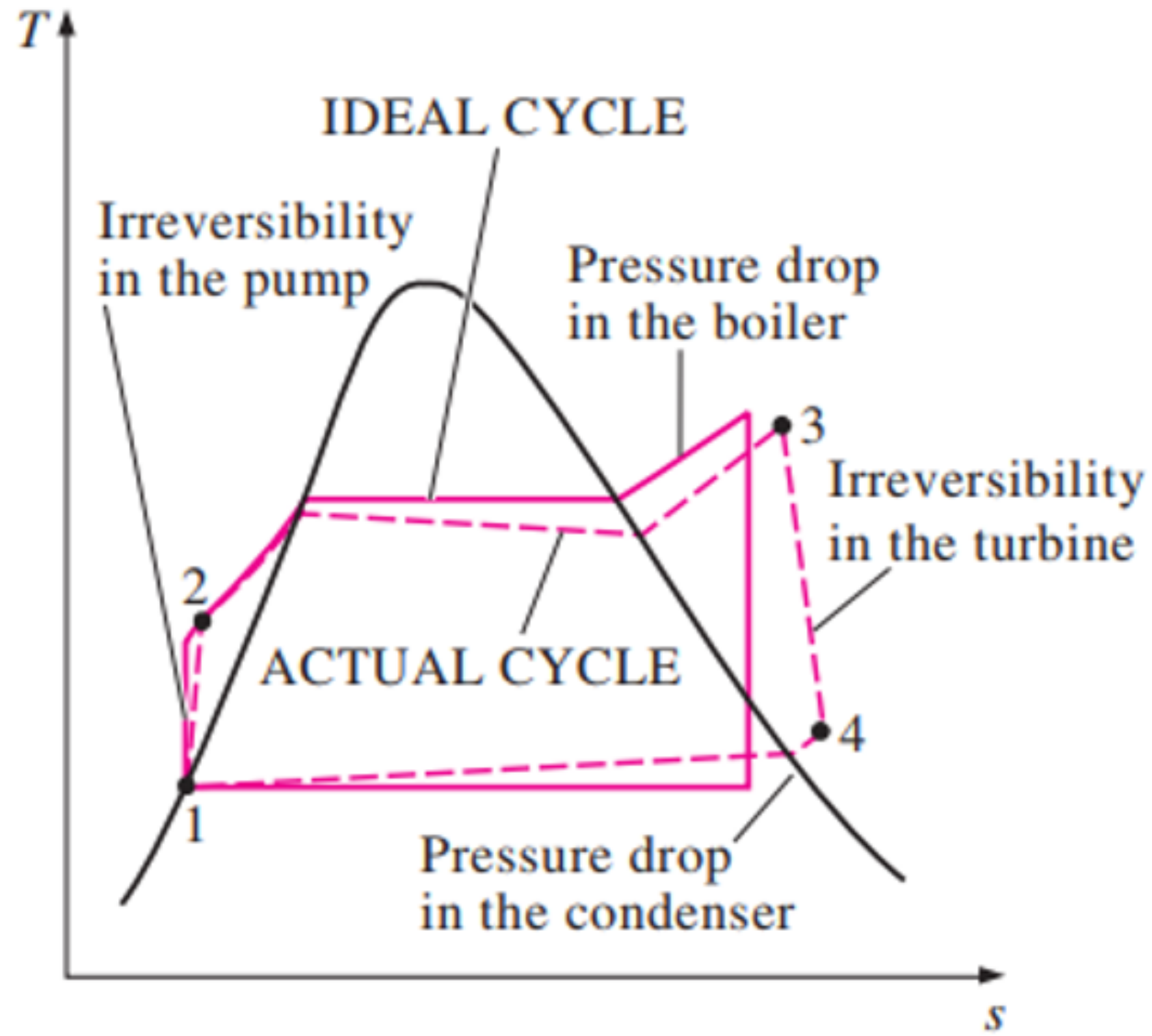
⇒ $q_{in} = q_B = h_3 - h_2 = 2728.6 \text{ kJ/kg}$

⇒ Thermal efficiency, $\eta_{th} = \frac{w_{net}}{q_{in}} = 0.260 = 26.0\%$ ◀

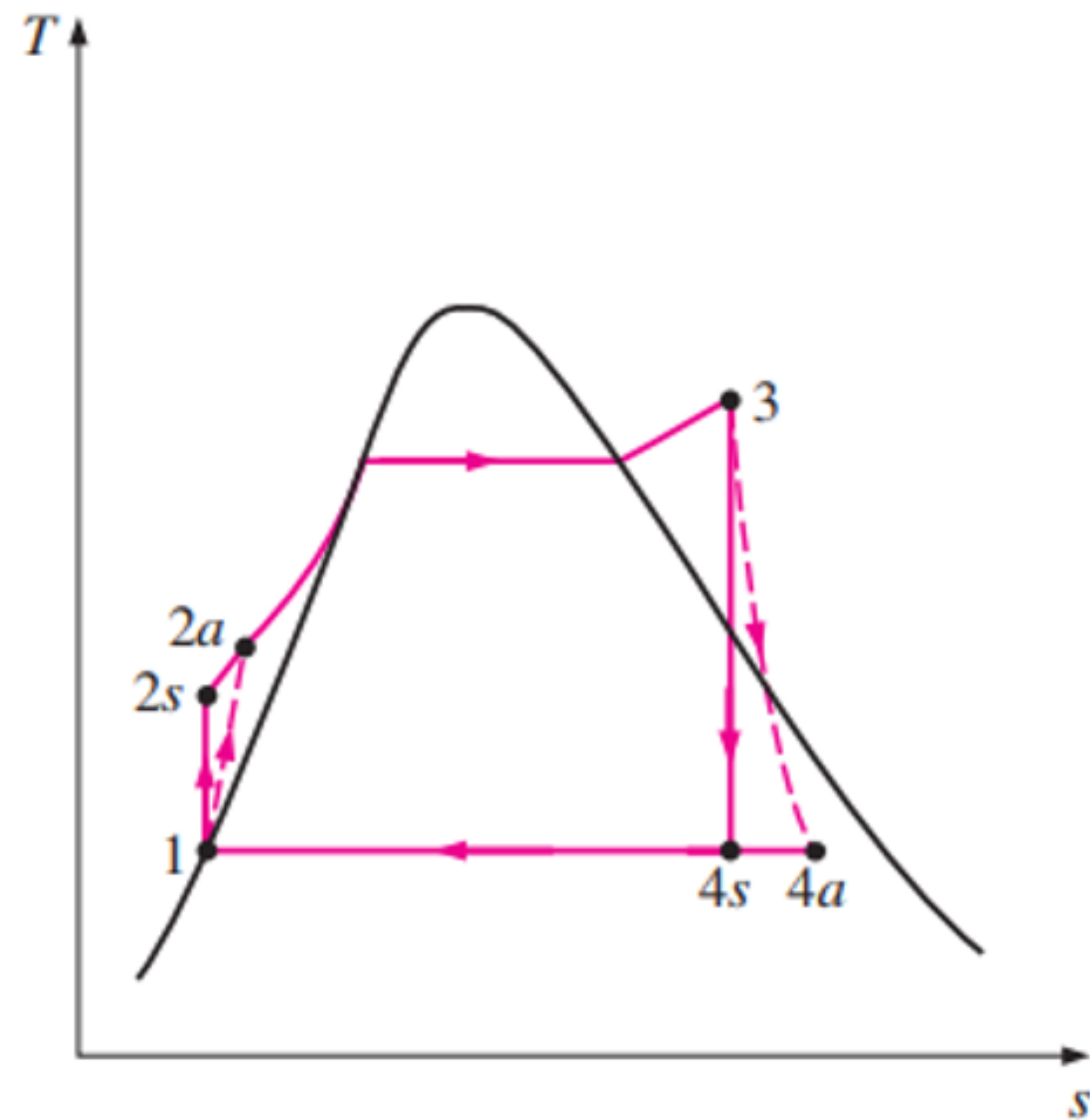
⇒ Back work ratio, $bwr = \left| \frac{w_P}{w_T} \right| = 0.0043$ ◀



Actual cycle



(a)



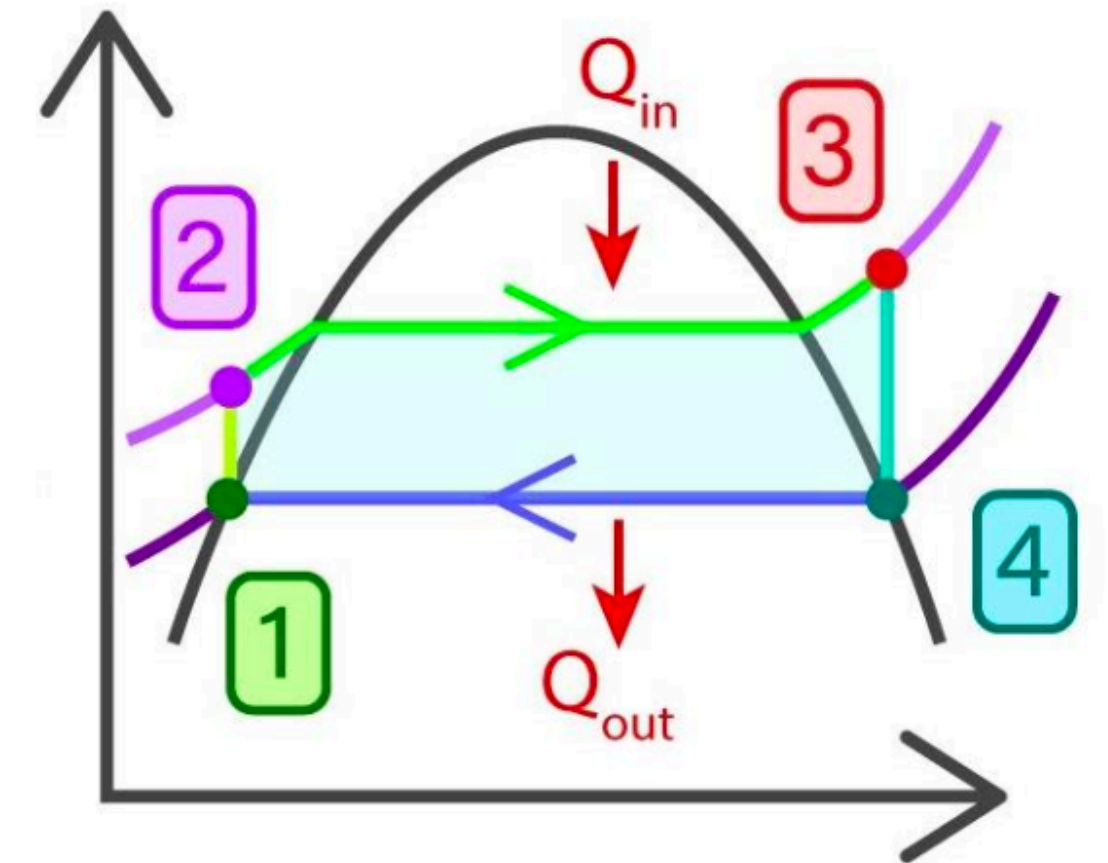
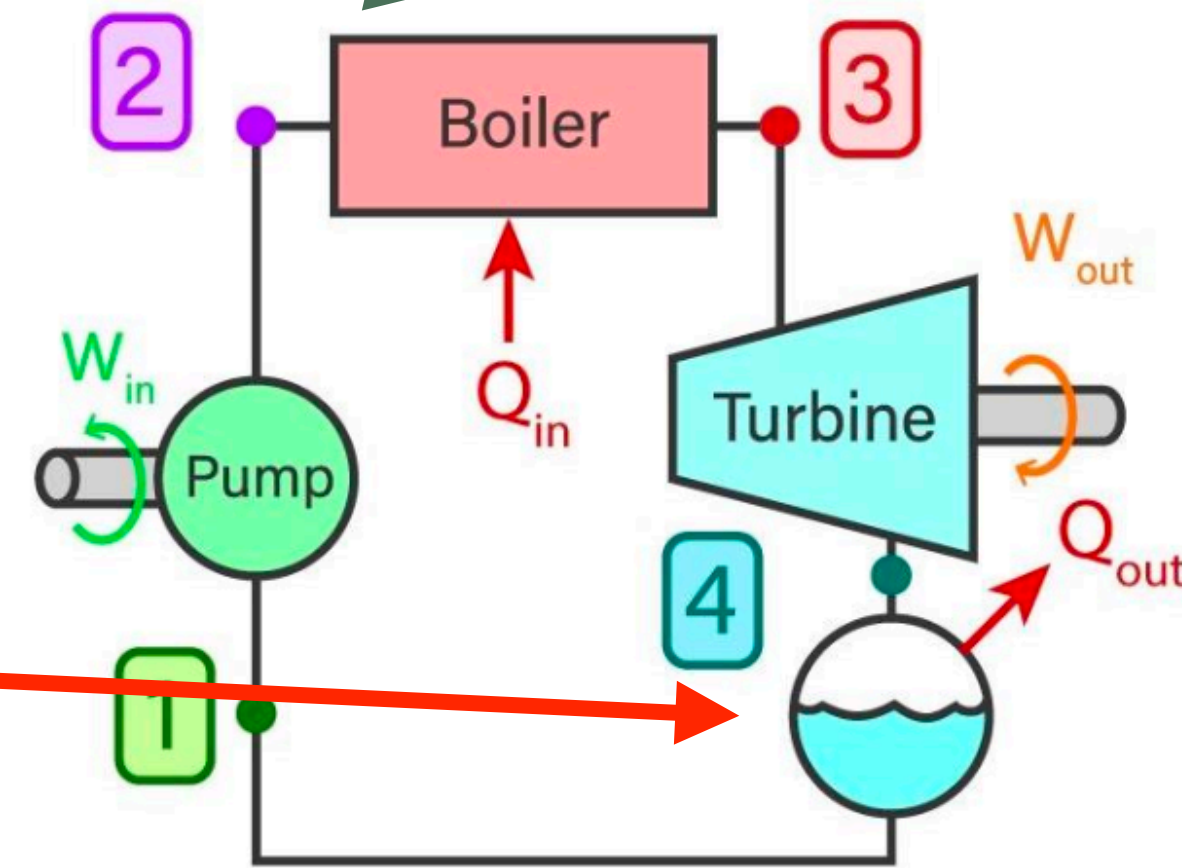
(b)

Methods for increasing efficiencies

1. **Increase temperature** of at which heat is **transferred** to the **working fluid in the boiler**.

or

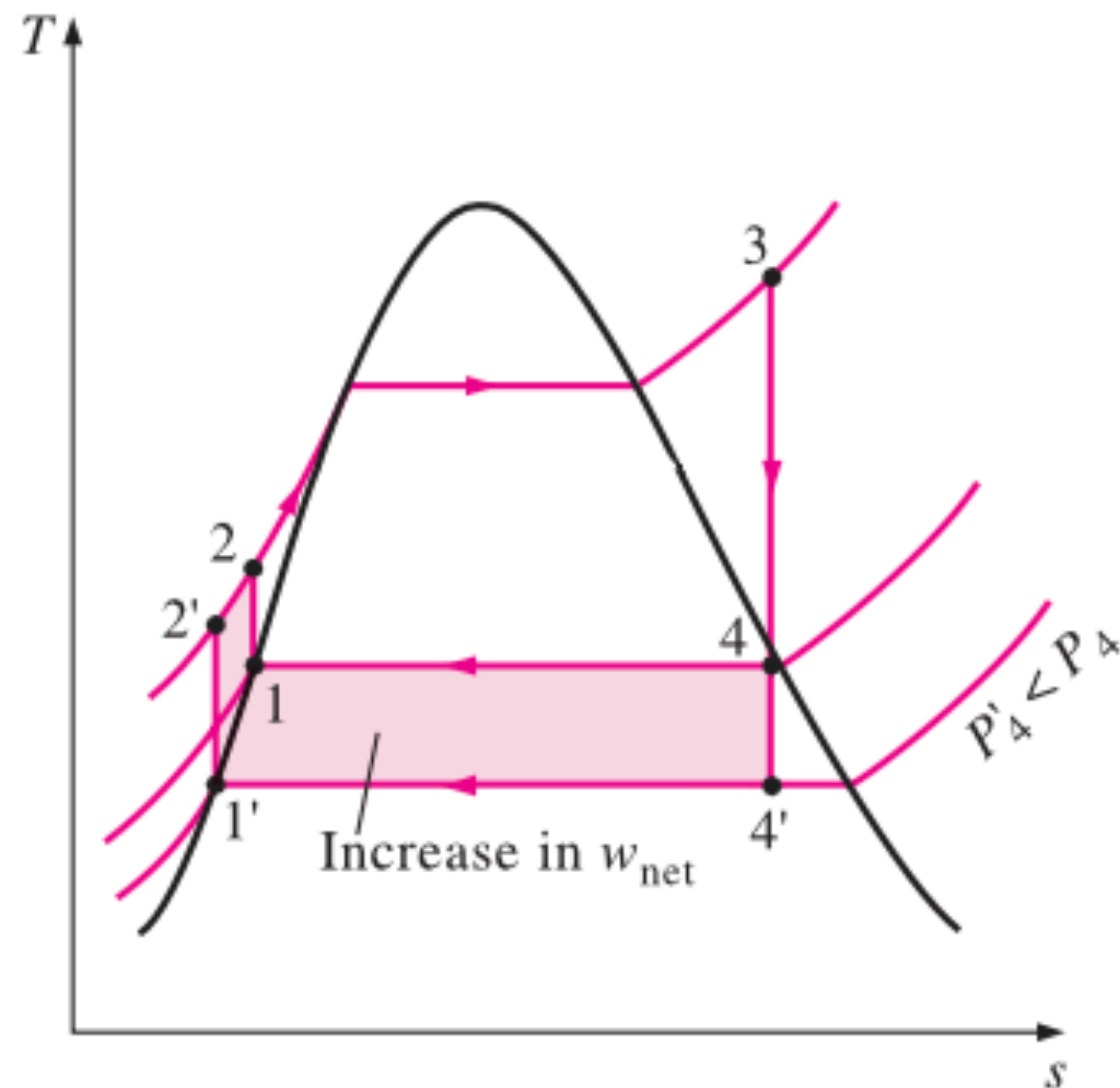
2. **Decrease temperature** of at which heat is **rejected** from the **working fluid in the condenser**.



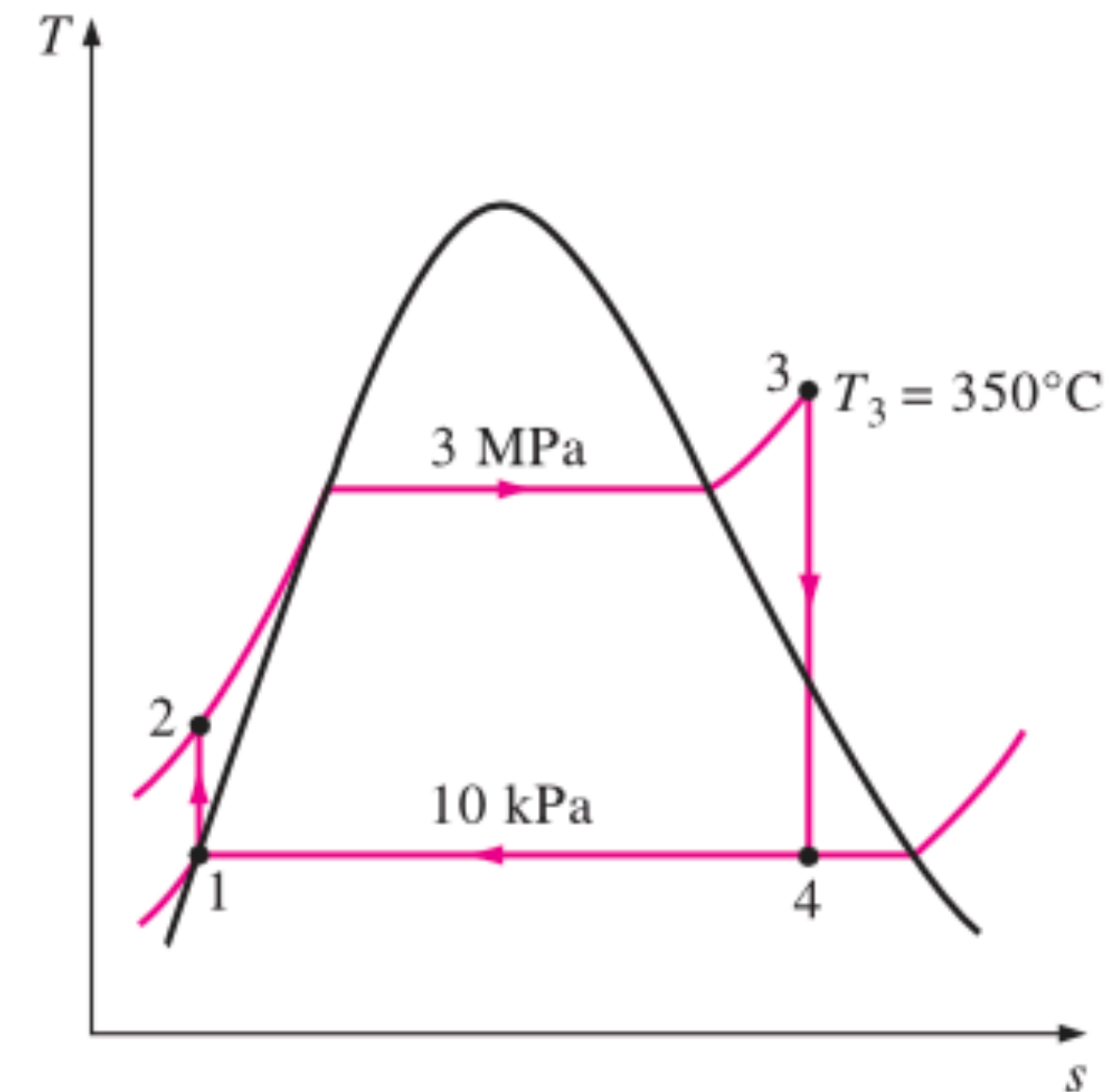
1 to 2: isentropic compression in pump
2 to 3: Constant pressure heat addition
in a boiler

3 to 4: isentropic expansion in a turbine
4 to 1: Constant pressure heat rejection
in a condenser

Effect of lowering condenser pressure



T199

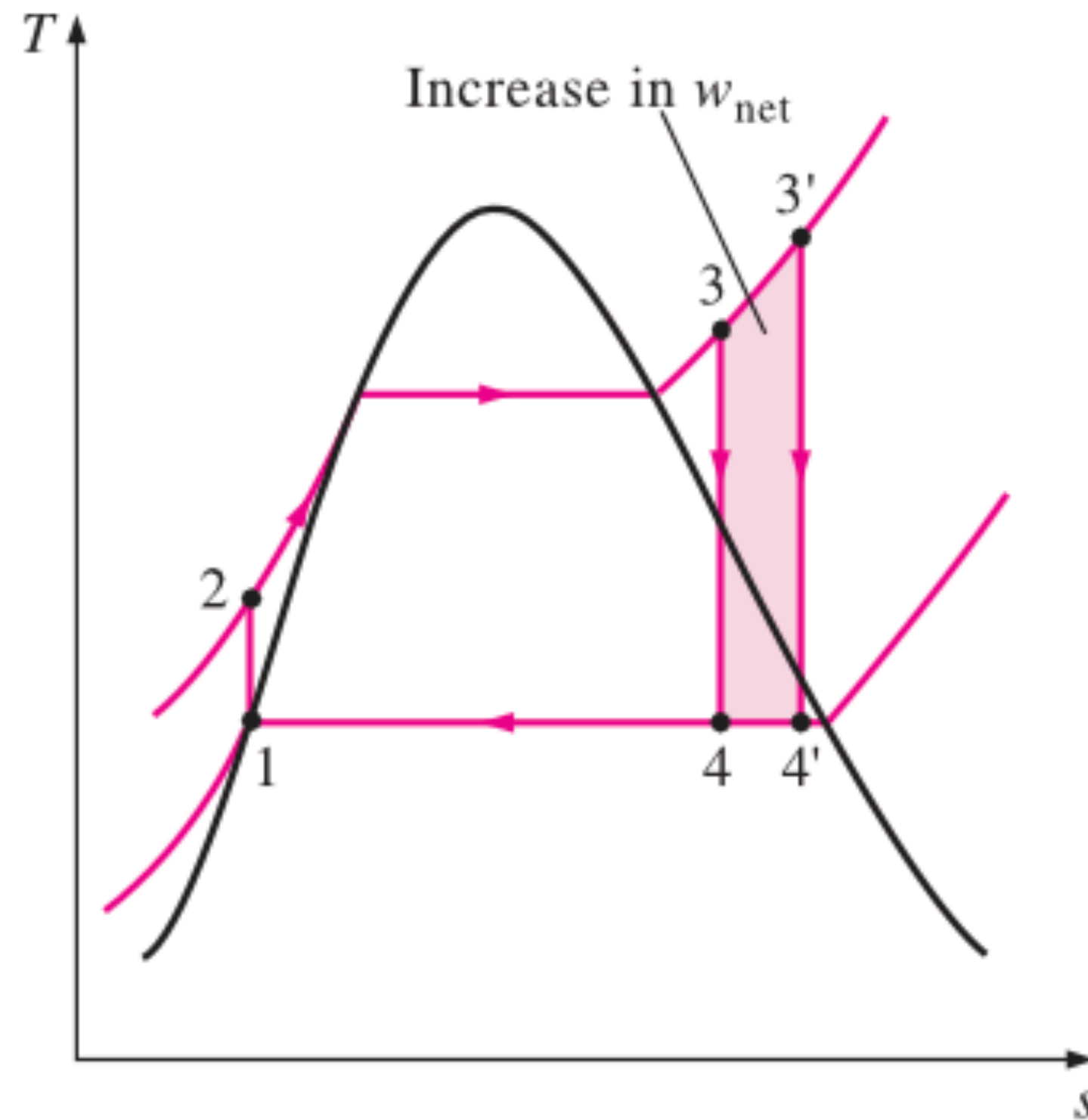


T218

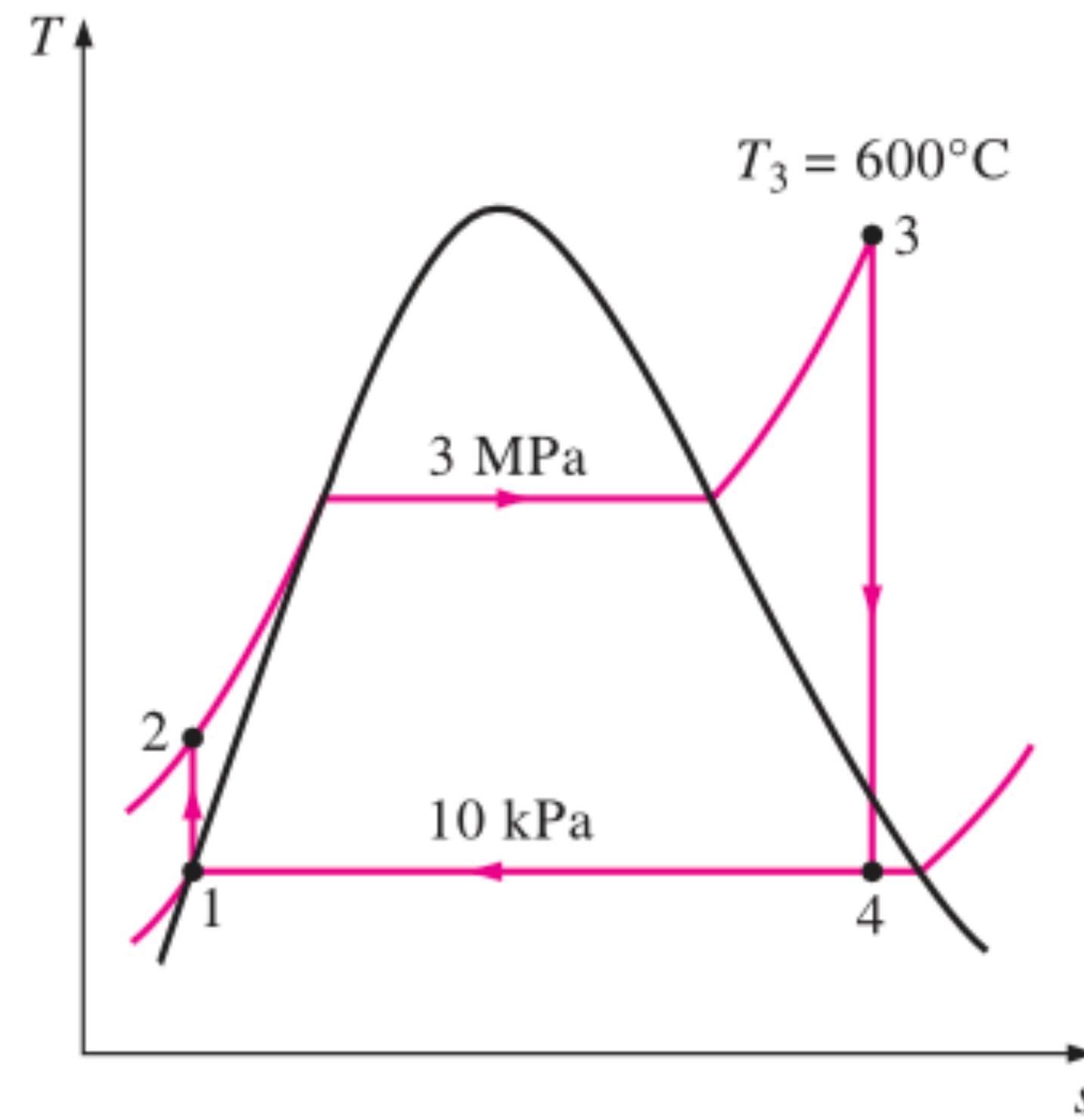
- $P_{cond} = P_{sat}(T_{cond}) : T_{cond} - T_{atm} \simeq 10 - 15^\circ\text{C}$.
- $P_{cond} \downarrow \implies w_{net} \uparrow, \eta_{th} \uparrow \ \& \ x_4 \downarrow$. Higher moisture decreases turbine efficiency and erodes its blades. In general, $x_4 \geq 0.9$ is maintained. Lower P_{cond} promotes leakage.



Effect of super heating steam to higher temperature



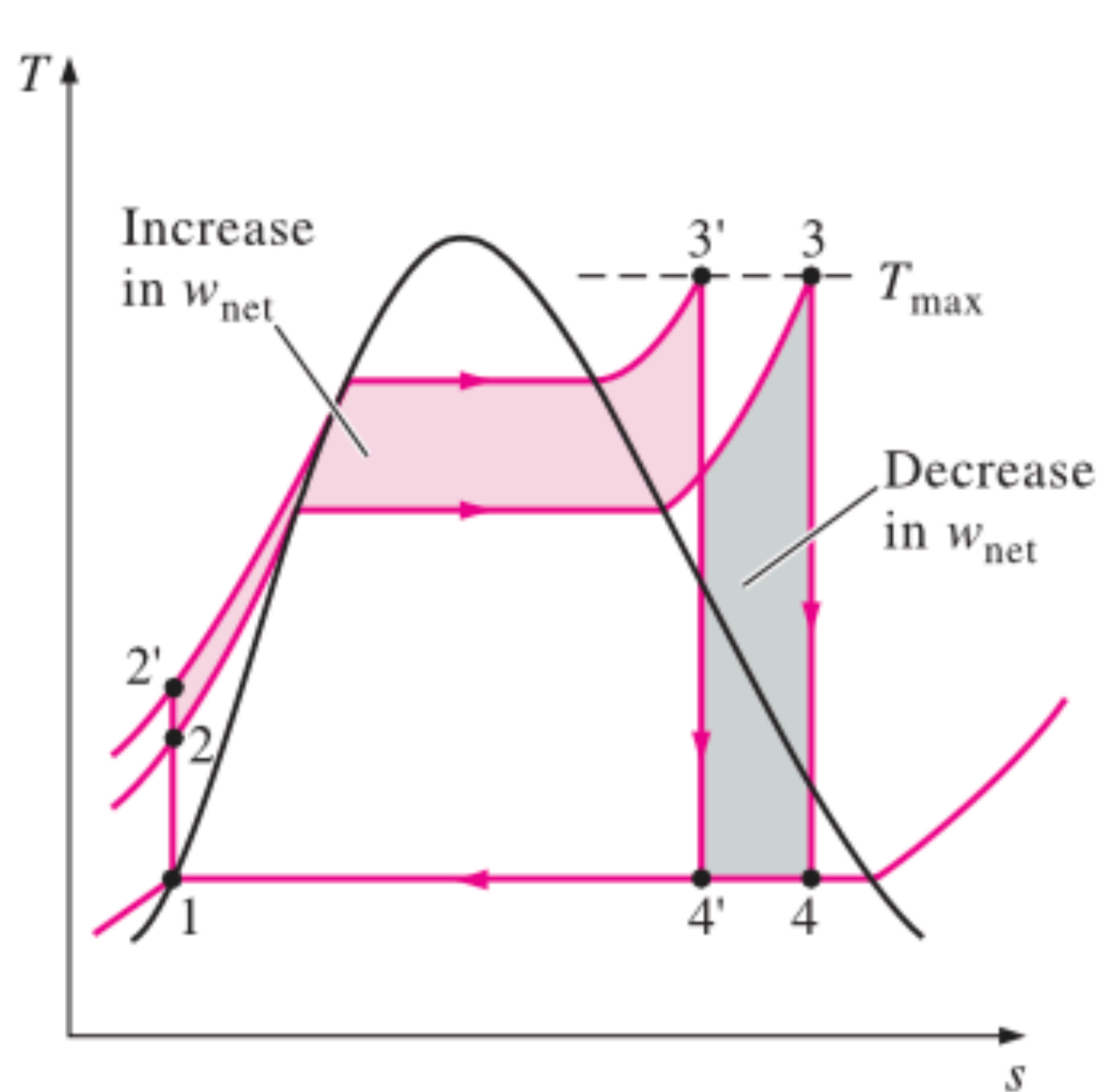
T200



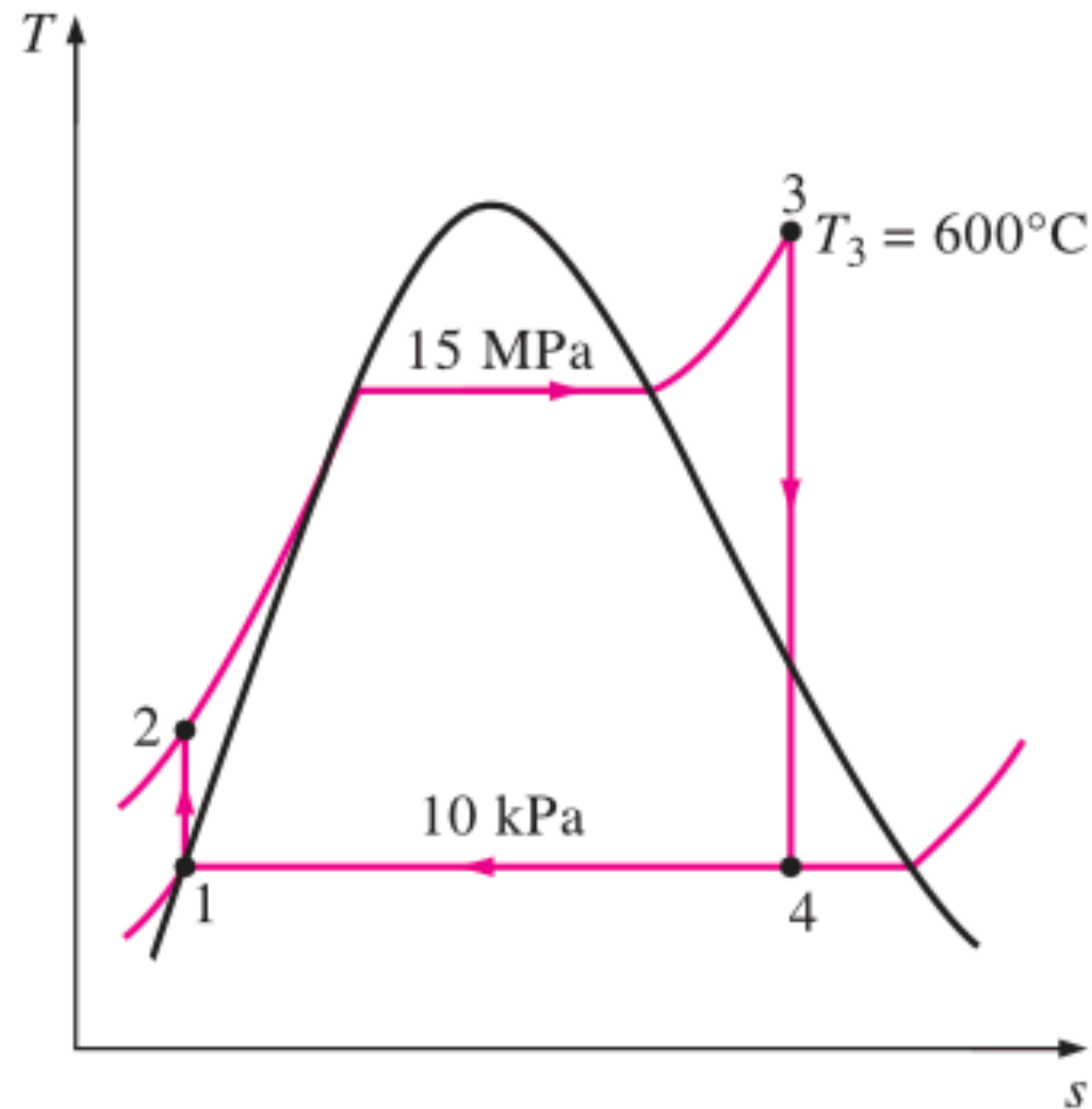
T219

- $T_{max} \uparrow \implies w_{net} \uparrow, \eta_{th} \uparrow \text{ \& } x_4 \uparrow.$
- Higher average temperature of heat addition increases η_{th} . T_{max} is limited by metallurgical considerations. In general, $T_{max} = 620^\circ\text{C}$.

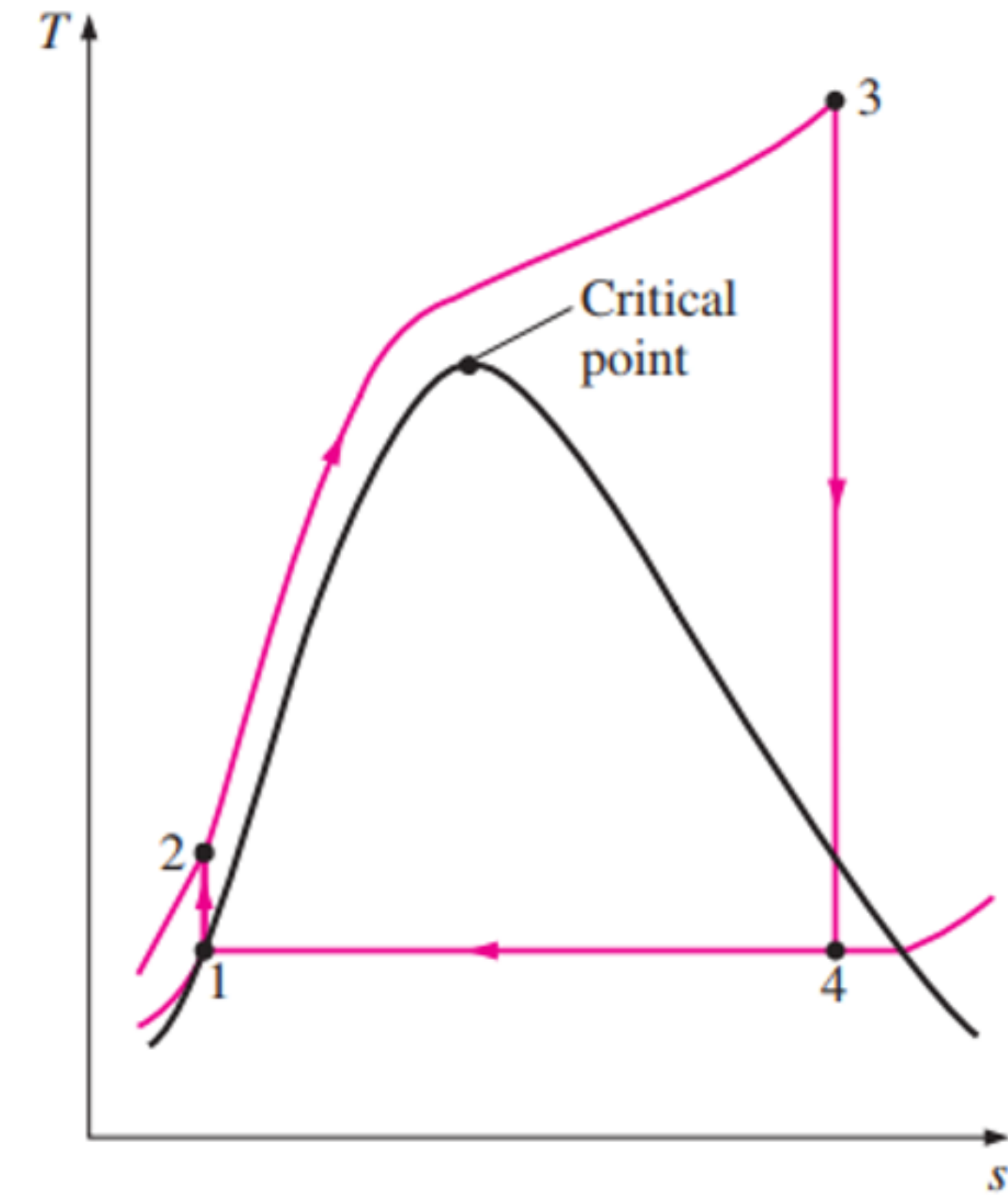
Effect of increasing boiler pressure



T201



T220



Super critical Rankine cycle

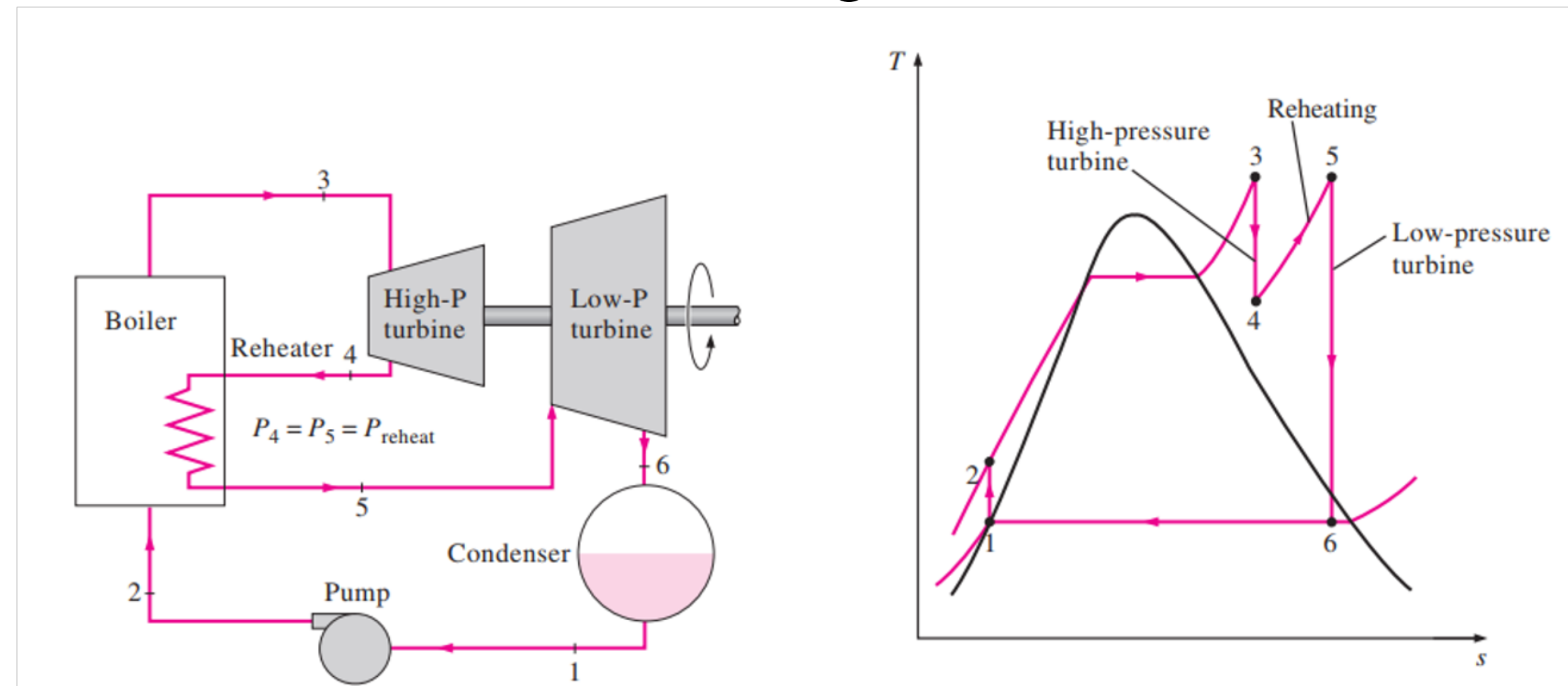
($P > 22 \text{ MPa}$)

- For fixed T_{max} : $P_B \uparrow \implies \eta_{th} \uparrow$ & $x_4 \downarrow$. Higher η_{th} is achieved because of higher average temperature of heat addition.

Reheat Rankine cycle

- How can we avoid the problem of excessive moisture at the final stage of turbine with high boiler pressure???

1. Superheat the steam to very high temperature before it enters the turbine.
2. Expand the steam in the turbine in two stages, and reheat it in between.



Total heat input,

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


Total turbine work output,

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

Why water in stead of air?


The Rankine cycle relies on boiling and condensation:

- **Water** can:
 - Absorb a *huge amount of energy* during boiling (latent heat)
 - Release that energy efficiently during condensation
- **Air** remains a gas → **no phase change**, so:
 - Much less energy per unit mass
 - Much larger equipment required

 Latent heat of vaporization of water ≈ 2257 kJ/kg

This single fact dominates the choice.

- In Rankine cycle:
 - Water is compressed as a **liquid**
 - Pump work $\approx 1\text{--}3\%$ of turbine output
- If air were used:
 - Air must be compressed as a **gas**
 - Compressor work can consume **30–50%** of turbine work

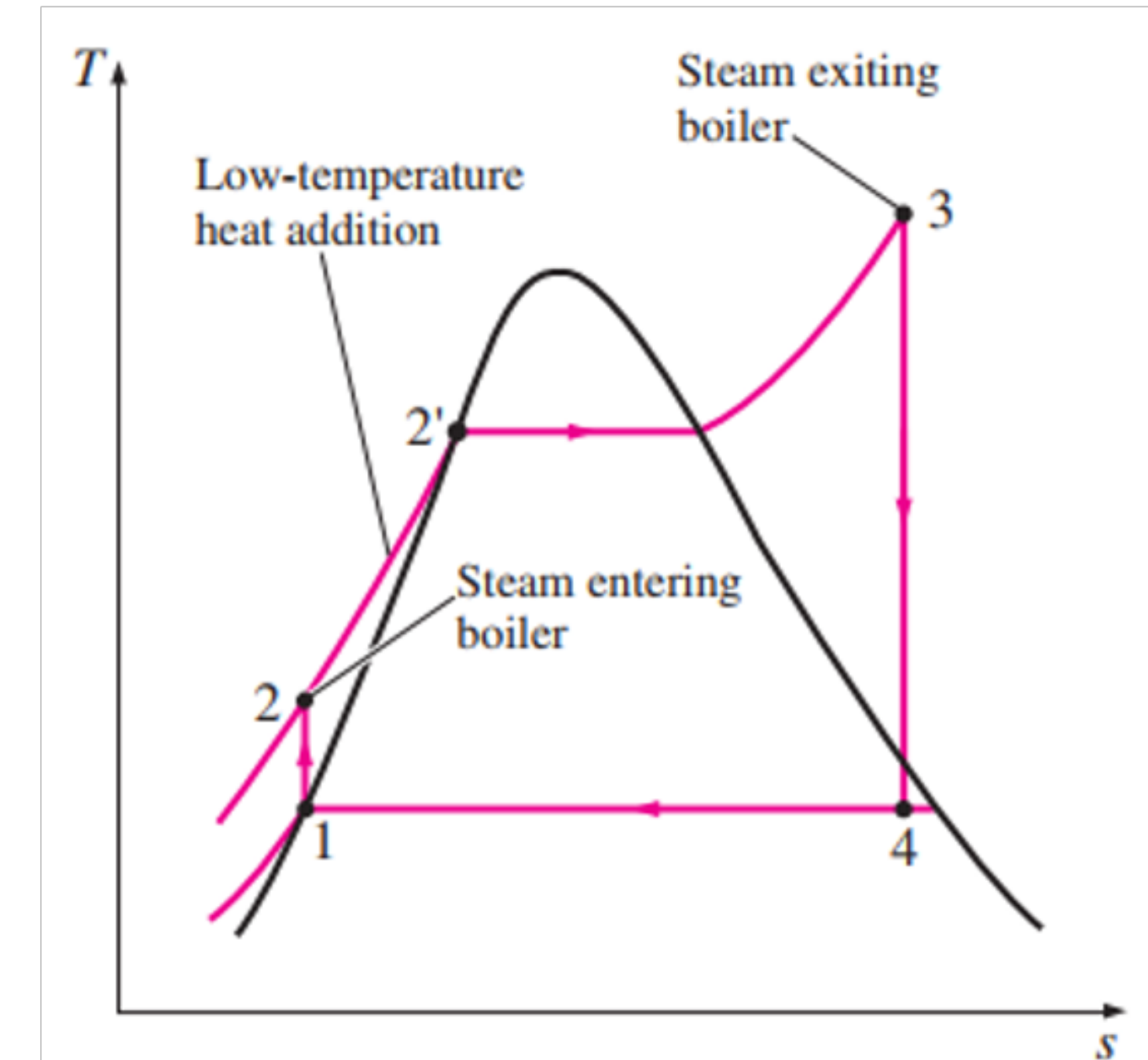
 Using air would drastically reduce net power output.

Water is used in the Rankine cycle instead of air because:

- its phase change allows large energy transfer with very low pumping work,
- has a very high expansion ratio. When boiled, one cup of water expands into about 1700 cups of steam.
- resulting in higher efficiency, smaller equipment, and practical power plant operation.

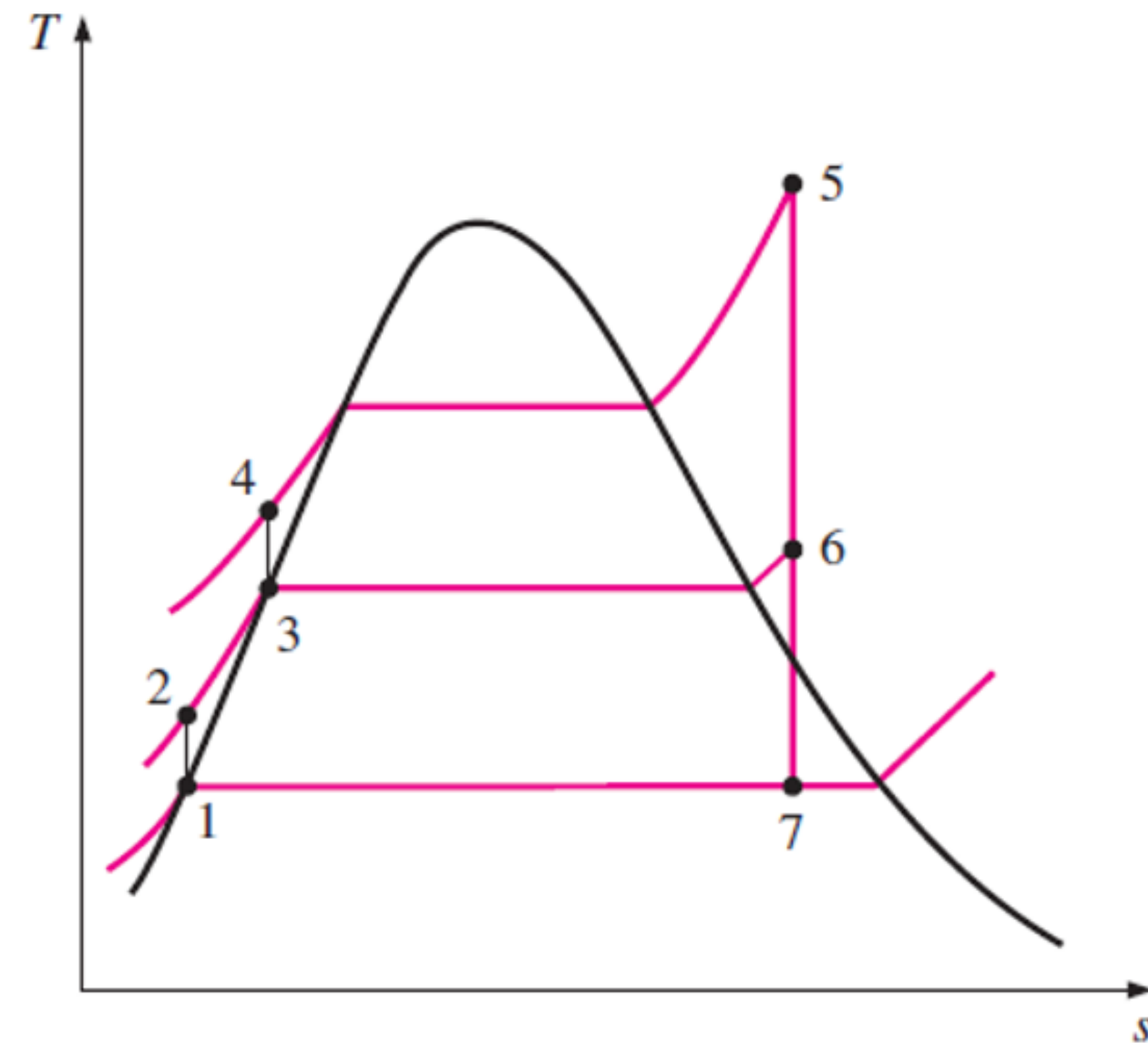
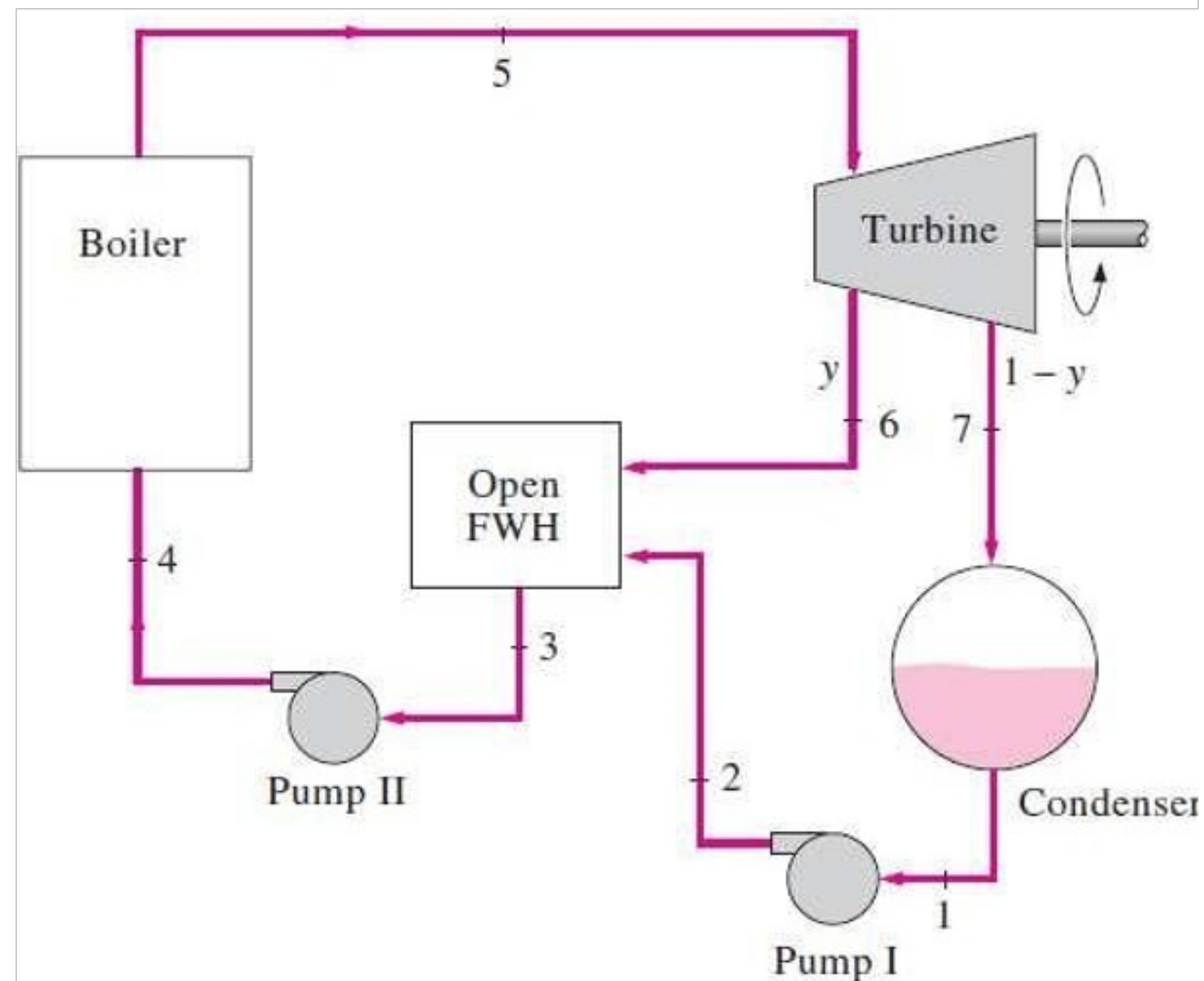
Regenerator

- 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.
- To remedy this shortcoming, the temperature of the liquid leaving the pump (called the feedwater) can be raised before it enters the boiler.
- **A practical regeneration process in steam power plants is accomplished by extracting, or “bleeding,” steam from the turbine at various points.** This steam, which could have produced more work by expanding further in the turbine, 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).**



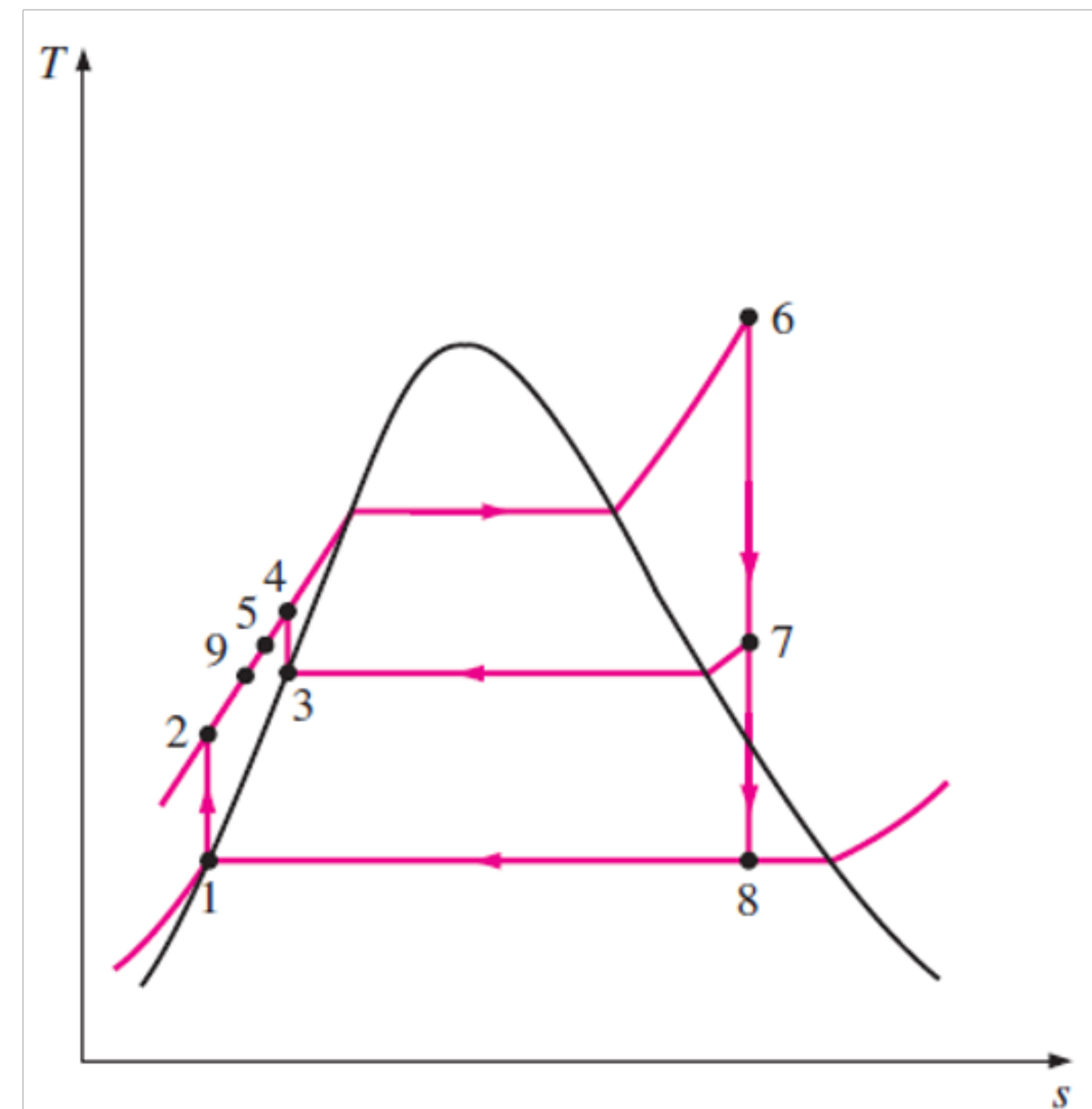
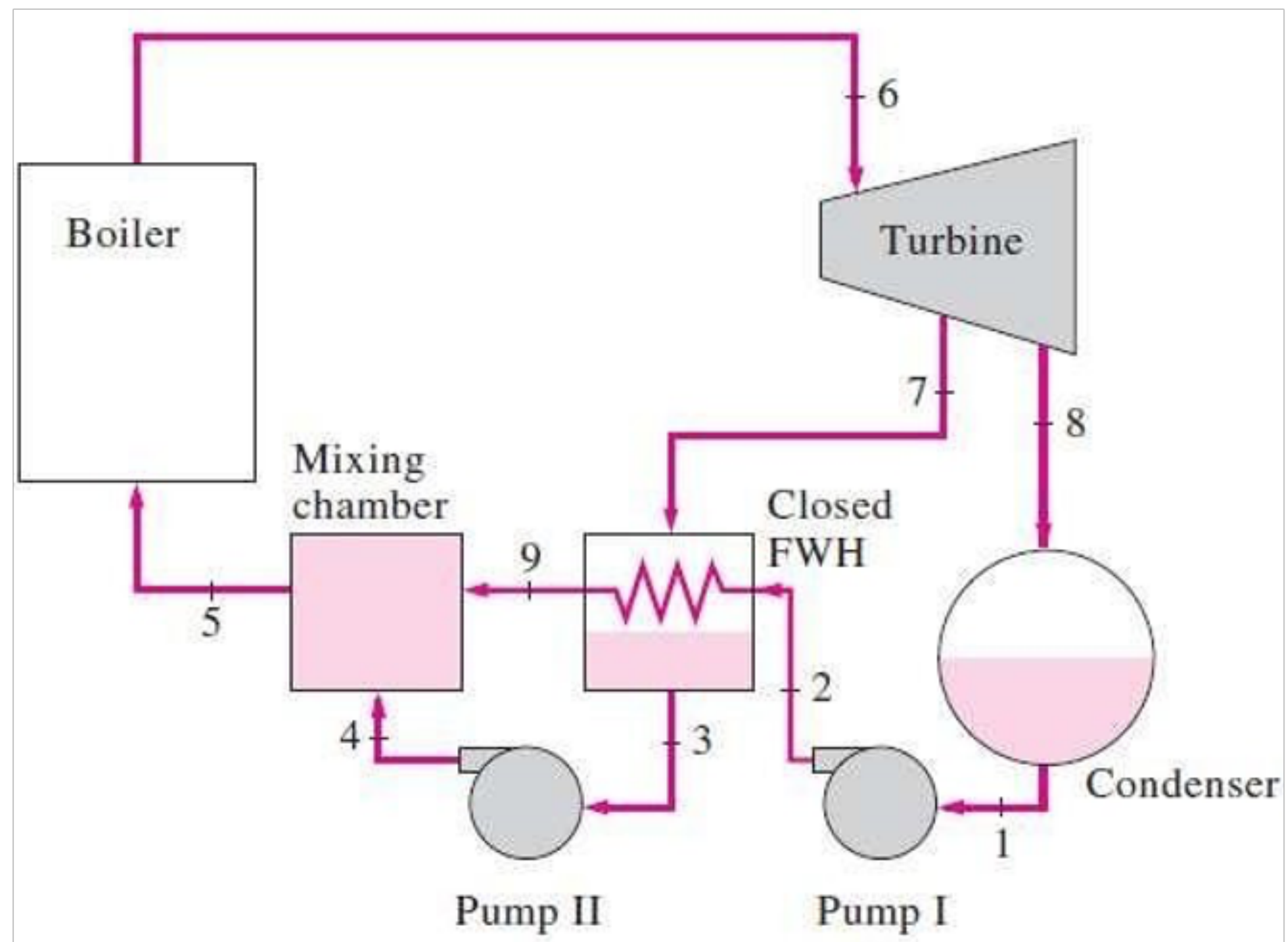
Regenerative Rankine cycle with open feed water heater

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. Ideally, the mixture leaves the heater as a saturated liquid at the heater pressure.



Regenerative Rankine cycle with closed feed water heater

A **closed feedwater heater** is one, in which heat is transferred from the extracted steam to the feedwater without any mixing taking place. The two streams now can be at different pressures, since they do not mix.



Combined gas-steam power plant

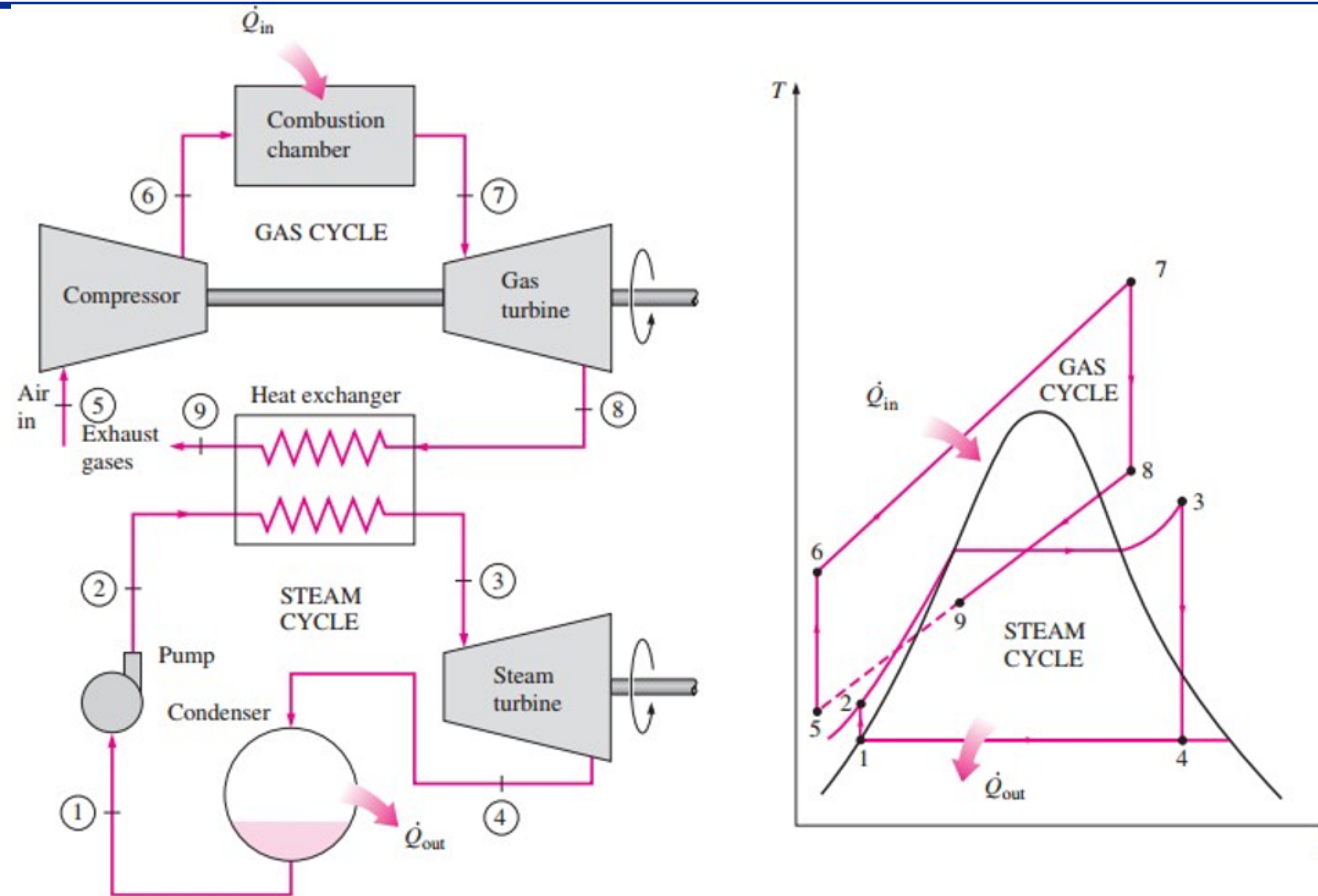
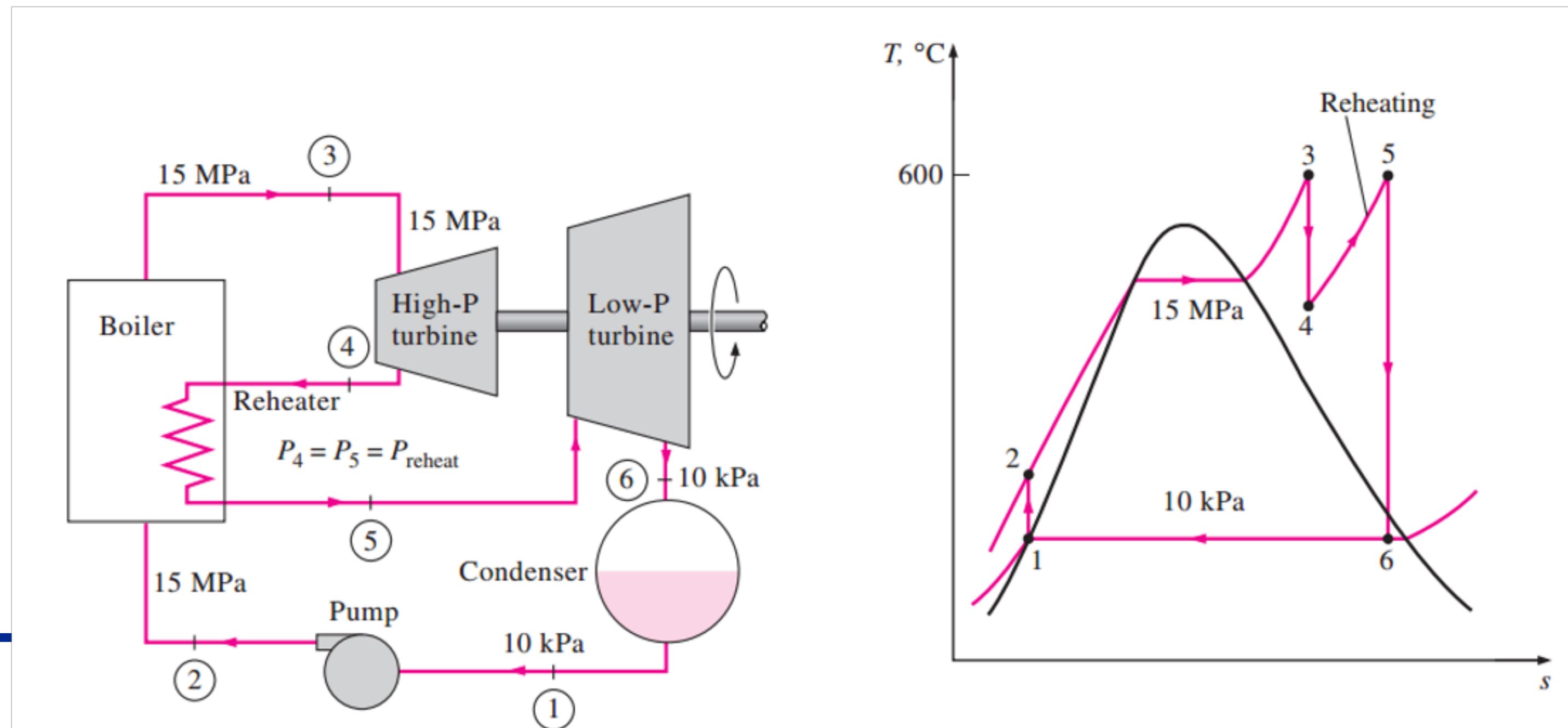


FIGURE 10-24

Combined gas-steam power plant.

Example 2

A steam power plant operates on an ideal reheat Rankine cycle between the pressure limits of 15 MPa and 10 kPa. The mass flow rate of steam through the cycle is 12 kg/s. Steam enters both stages of the turbine at 500°C. If the moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10 percent, determine (a) the pressure at which reheating takes place, (b) the total rate of heat input in the boiler, and (c) the thermal efficiency of the cycle. Also, show the cycle on a T-s diagram.



Example 2, cont'd

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

Analysis (a) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{\text{sat}@ 10 \text{ kPa}} = 191.81 \text{ kJ/kg}$$

$$\nu_1 = \nu_{\text{sat}@ 10 \text{ kPa}} = 0.00101 \text{ m}^3/\text{kg}$$

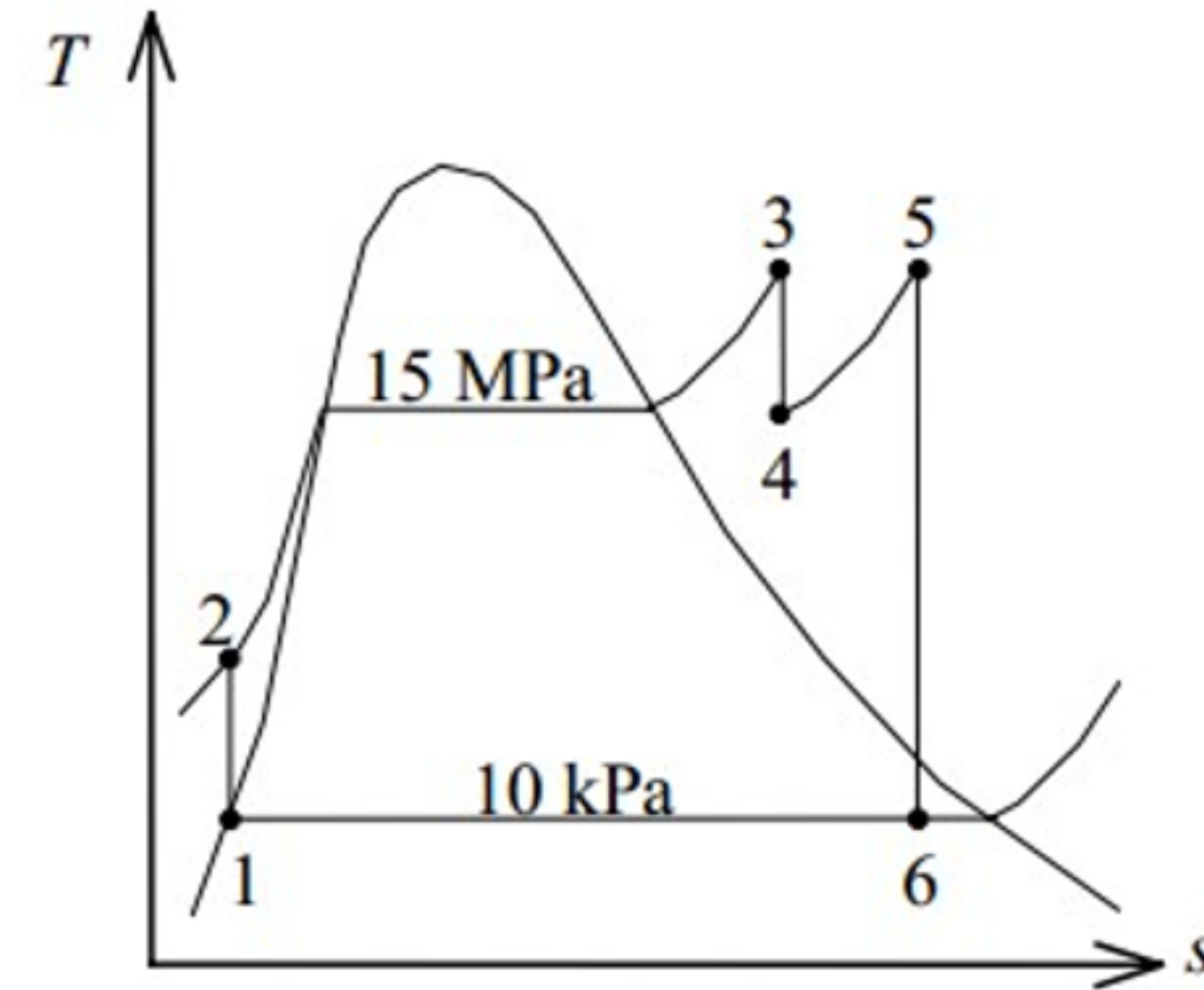
$$\begin{aligned} w_{p,\text{in}} &= \nu_1 (P_2 - P_1) \\ &= (0.00101 \text{ m}^3/\text{kg})(15,000 - 10 \text{ kPa}) \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \\ &= 15.14 \text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 15.14 = 206.95 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 15 \text{ MPa} \\ T_3 = 500^\circ\text{C} \end{array} \right\} \begin{array}{l} h_3 = 3310.8 \text{ kJ/kg} \\ s_3 = 6.3480 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_6 = 10 \text{ kPa} \\ s_6 = s_5 \end{array} \right\} \begin{array}{l} h_6 = h_f + x_6 h_{fg} = 191.81 + (0.90)(2392.1) = 2344.7 \text{ kJ/kg} \\ s_6 = s_f + x_6 s_{fg} = 0.6492 + (0.90)(7.4996) = 7.3988 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} T_5 = 500^\circ\text{C} \\ s_5 = s_6 \end{array} \right\} \begin{array}{l} P_5 = \mathbf{2161 \text{ kPa}} \text{ (the reheat pressure)} \\ h_5 = 3466.53 \text{ kJ/kg} \end{array}$$



Example 2, cont'd

$$\left. \begin{array}{l} T_5 = 500^\circ\text{C} \\ s_5 = s_6 \end{array} \right\} \begin{array}{l} P_5 = \mathbf{2161\text{ kPa}} \text{ (the reheat pressure)} \\ h_5 = 3466.53\text{ kJ/kg} \end{array}$$

$$\left. \begin{array}{l} P_4 = 2.161\text{ MPa} \\ s_4 = s_3 \end{array} \right\} h_4 = 2817.2\text{ kJ/kg}$$

(b) The rate of heat supply is

$$\begin{aligned} \dot{Q}_{\text{in}} &= \dot{m}[(h_3 - h_2) + (h_5 - h_4)] \\ &= (12\text{ kg/s})(3310.8 - 206.95 + 3466.53 - 2817.2)\text{kJ/kg} = \mathbf{45,038\text{ kW}} \end{aligned}$$

(c) The thermal efficiency is determined from

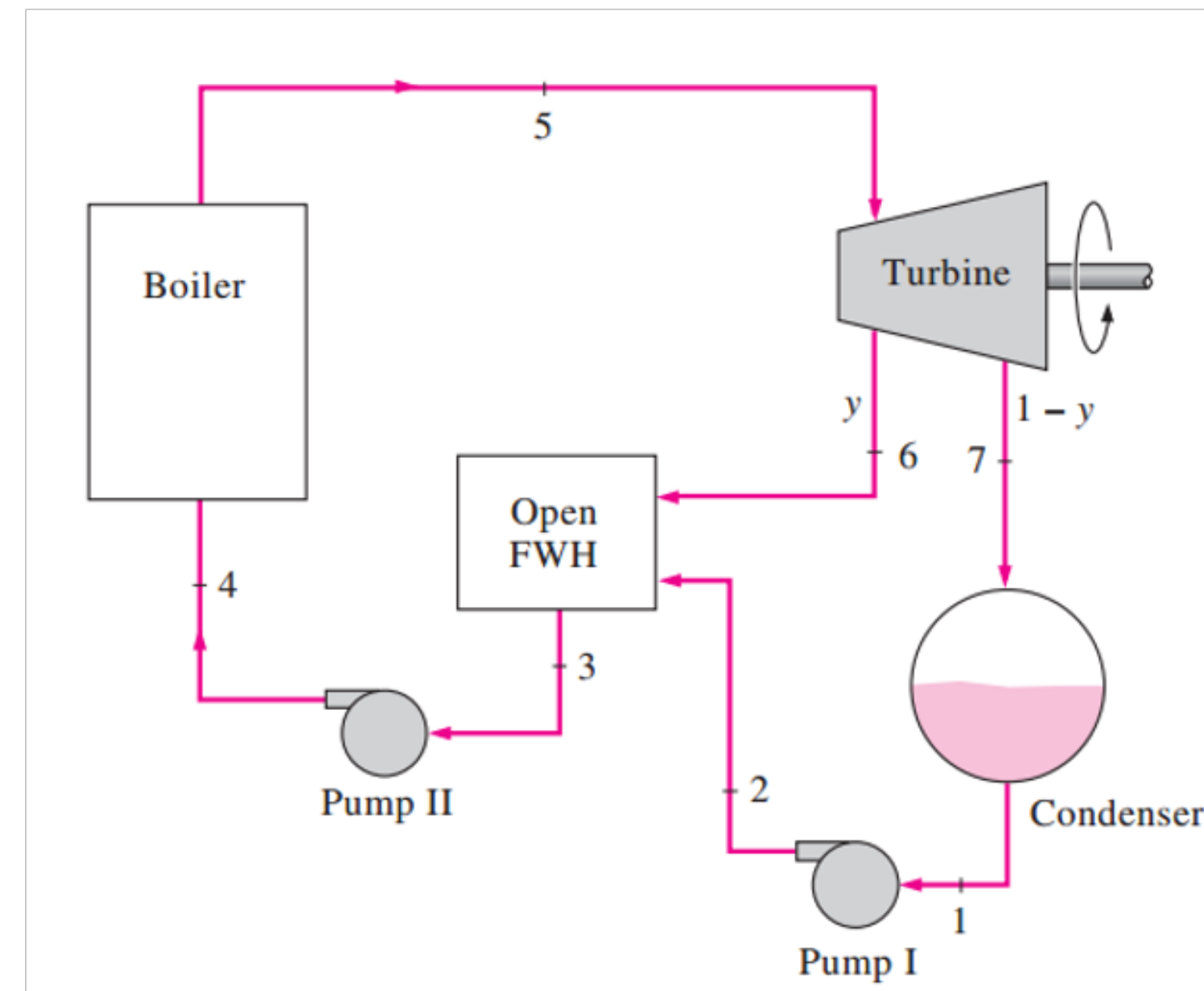
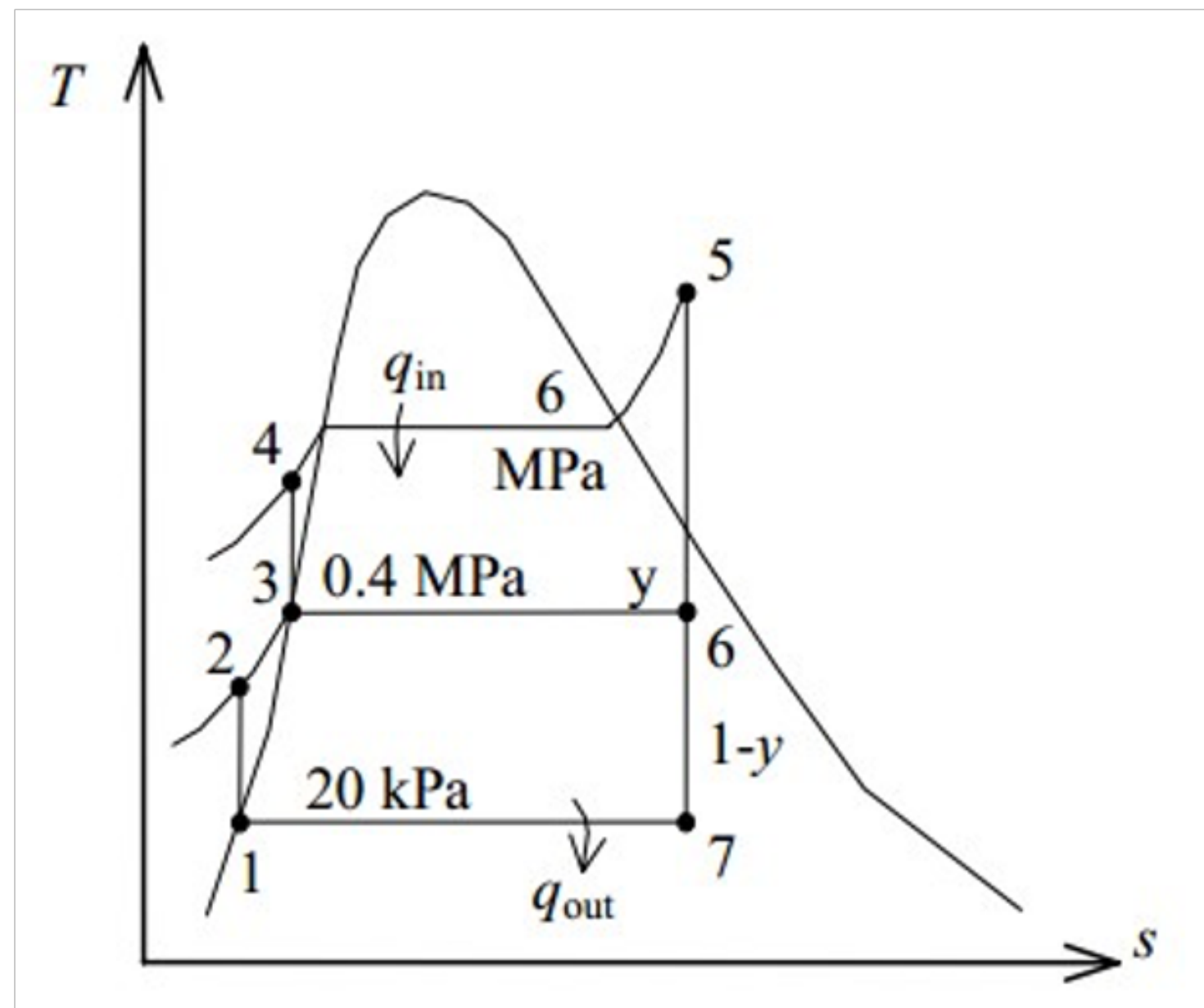
$$\dot{Q}_{\text{out}} = \dot{m}(h_6 - h_1) = (12\text{ kJ/s})(2344.7 - 191.81)\text{kJ/kg} = 25,835\text{ kJ/s}$$

Thus,

$$\eta_{\text{th}} = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} = 1 - \frac{25,834\text{ kJ/s}}{45,039\text{ kJ/s}} = \mathbf{42.6\%}$$

Example 3

A steam power plant operates on an ideal regenerative Rankine cycle. Steam enters the turbine at 6 MPa and 450°C and is condensed in the condenser at 20 kPa. Steam is extracted from the turbine at 0.4 MPa to heat the feedwater in an open feedwater heater. Water leaves the feedwater heater as a saturated liquid. Show the cycle on a T - s diagram, and determine (a) the net work output per kilogram of steam flowing through the boiler and (b) the thermal efficiency of the cycle.



Example 3, cont'd

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

Analysis (a) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@ 20 \text{ kPa}} = 251.42 \text{ kJ/kg}$$

$$\nu_1 = \nu_{f@ 20 \text{ kPa}} = 0.001017 \text{ m}^3/\text{kg}$$

$$\begin{aligned} w_{pI,\text{in}} &= \nu_1 (P_2 - P_1) \\ &= (0.001017 \text{ m}^3/\text{kg})(400 - 20 \text{ kPa}) \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \\ &= 0.39 \text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{pI,\text{in}} = 251.42 + 0.39 = 251.81 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 0.4 \text{ MPa} \\ \text{sat.liquid} \end{array} \right\} \begin{array}{l} h_3 = h_{f@ 0.4 \text{ MPa}} = 604.66 \text{ kJ/kg} \\ \nu_3 = \nu_{f@ 0.4 \text{ MPa}} = 0.001084 \text{ m}^3/\text{kg} \end{array}$$

$$w_{pII,\text{in}} = \nu_3 (P_4 - P_3) = (0.001084 \text{ m}^3/\text{kg})(6000 - 400 \text{ kPa}) \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = 6.07 \text{ kJ/kg}$$

$$h_4 = h_3 + w_{pII,\text{in}} = 604.66 + 6.07 = 610.73 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_5 = 6 \text{ MPa} \\ T_5 = 450^\circ\text{C} \end{array} \right\} \begin{array}{l} h_5 = 3302.9 \text{ kJ/kg} \\ s_5 = 6.7219 \text{ kJ/kg} \cdot \text{K} \end{array}$$

