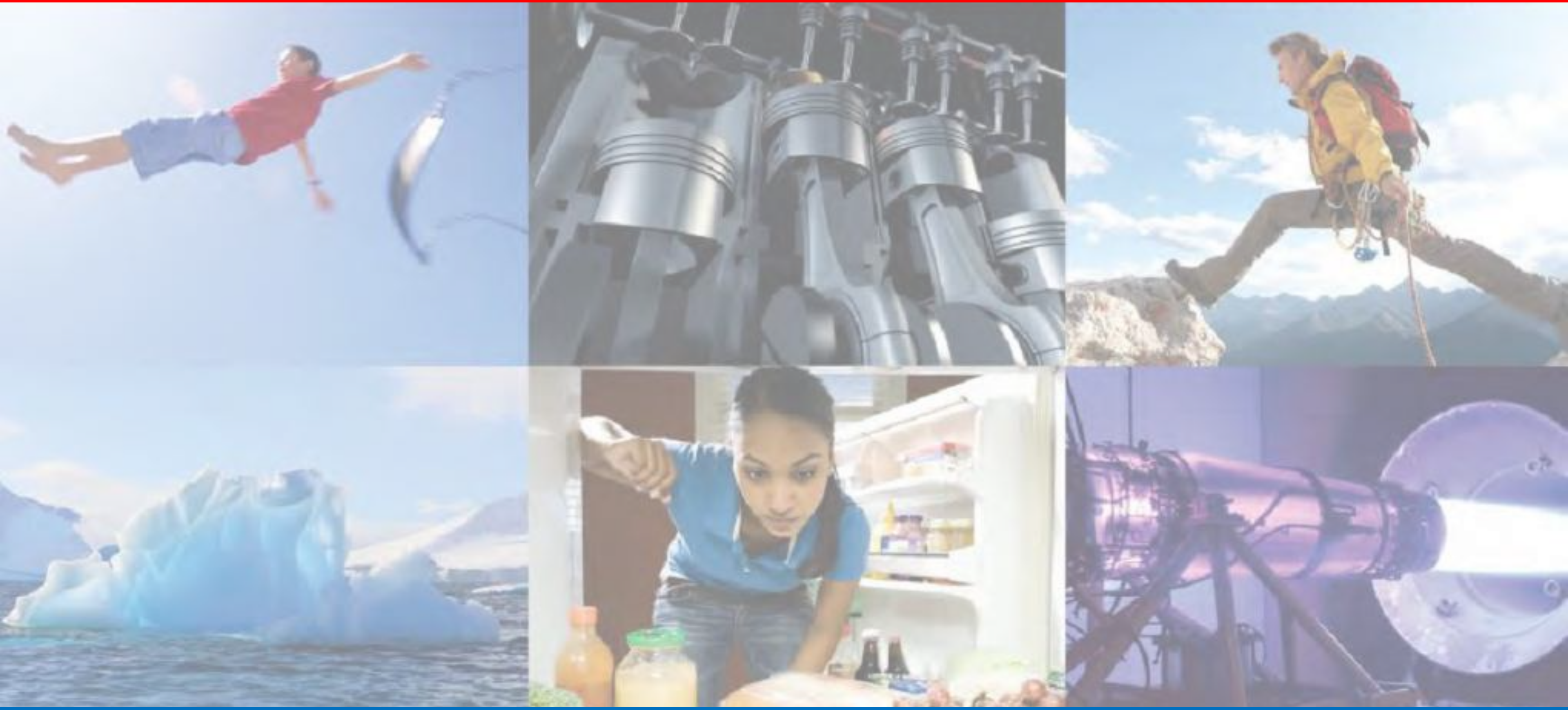


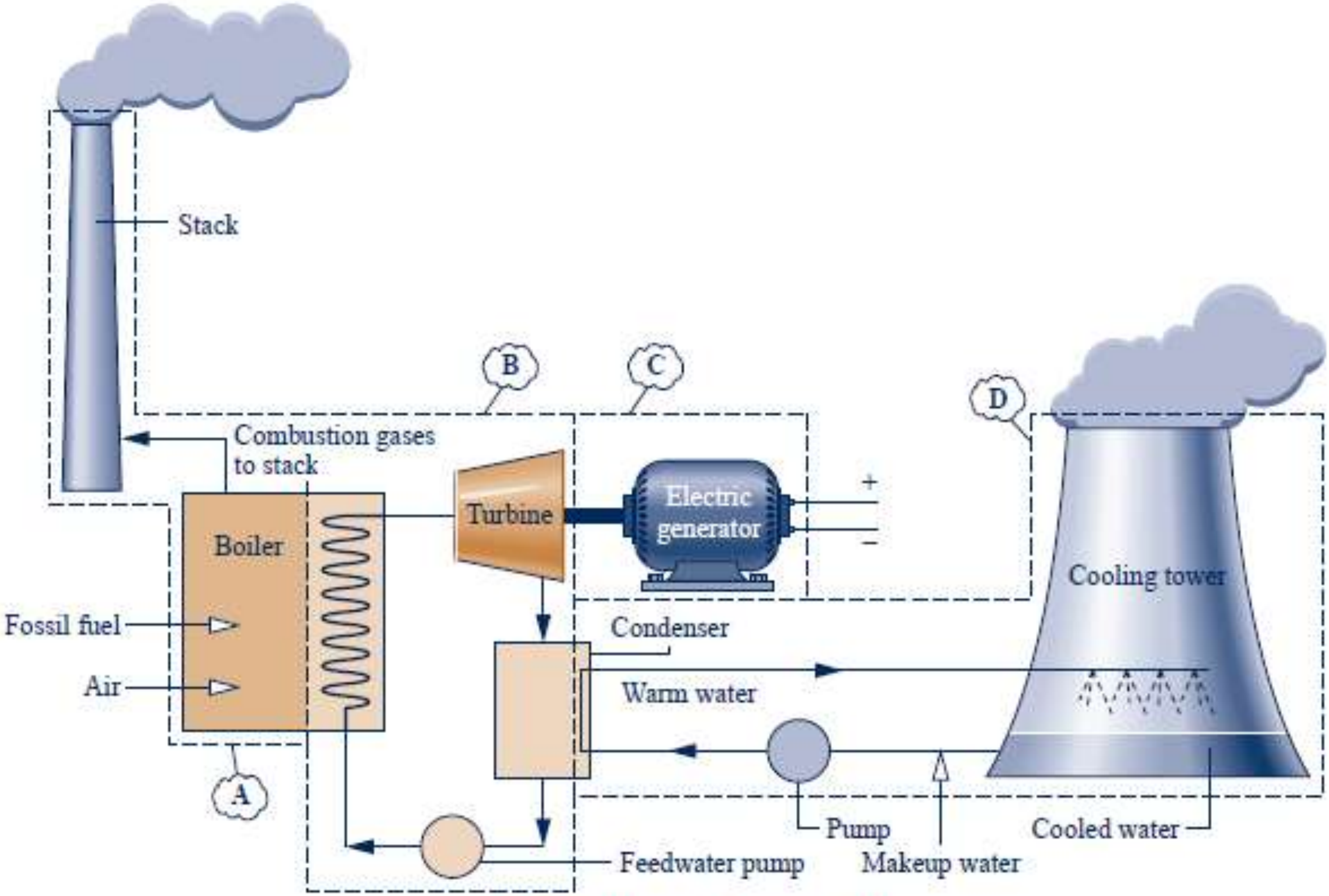
Vapor Power System

By Ertanto Vetra

Outlines

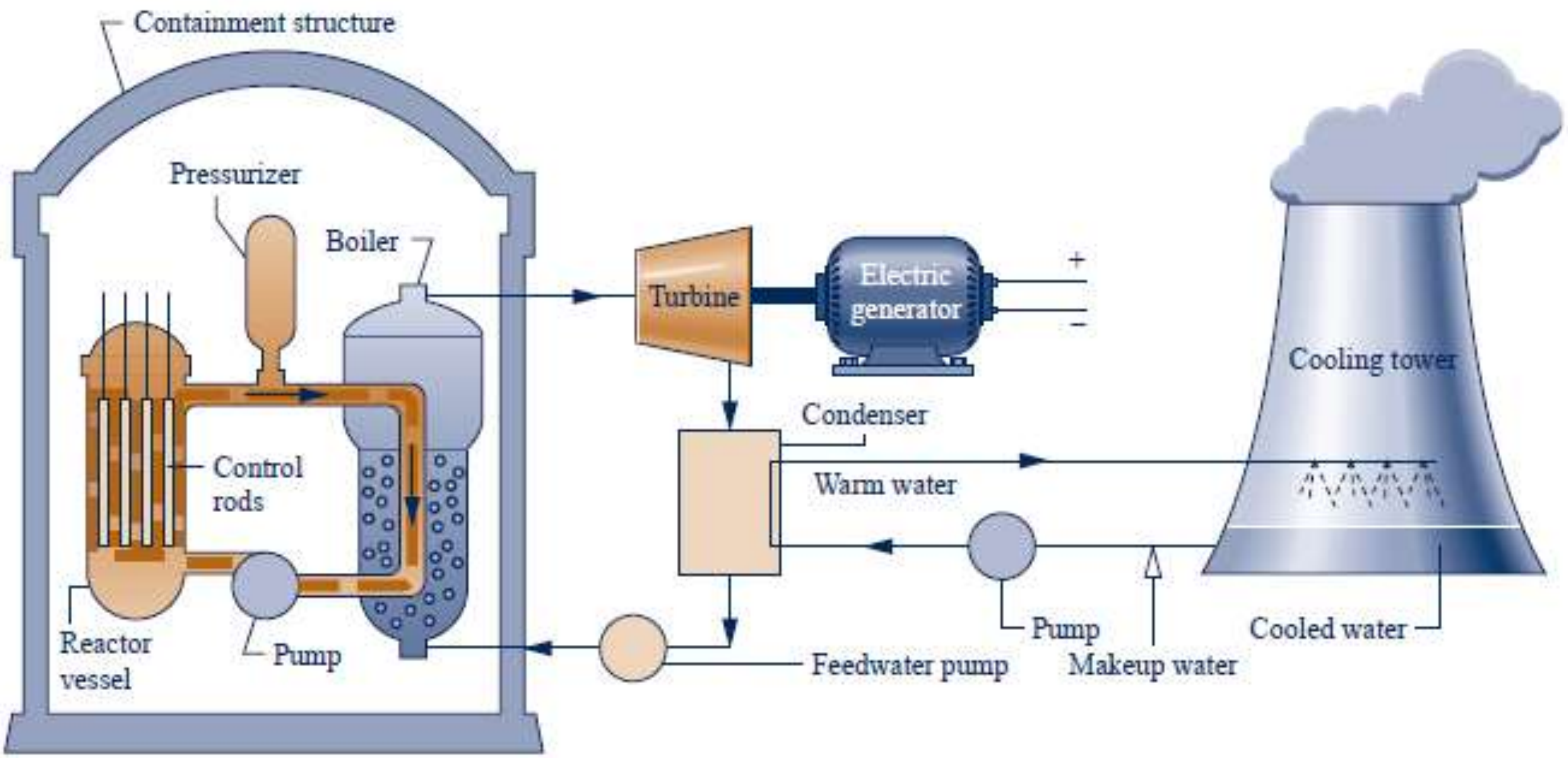
- Introduction to Vapor Power Plant
- Rankine Cycle
- Improve cycle performance – Superheat, Reheat, Supercritical
- Improve cycle performance – Regenerative Vapor Power Cycle
- Cogeneration Cycle

Fossil Fueled Vapor Power Plant



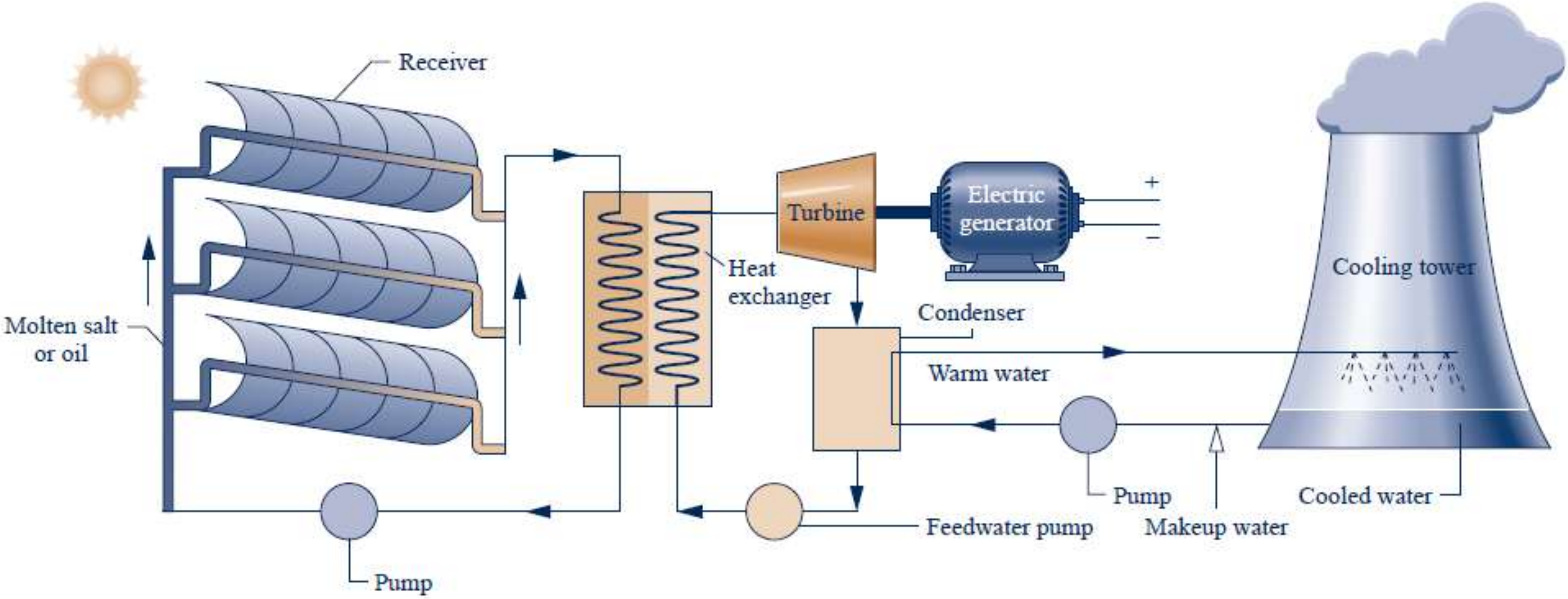
(*a*) Fossil-fueled vapor power plant.

Nuclear Vapor Power Plant

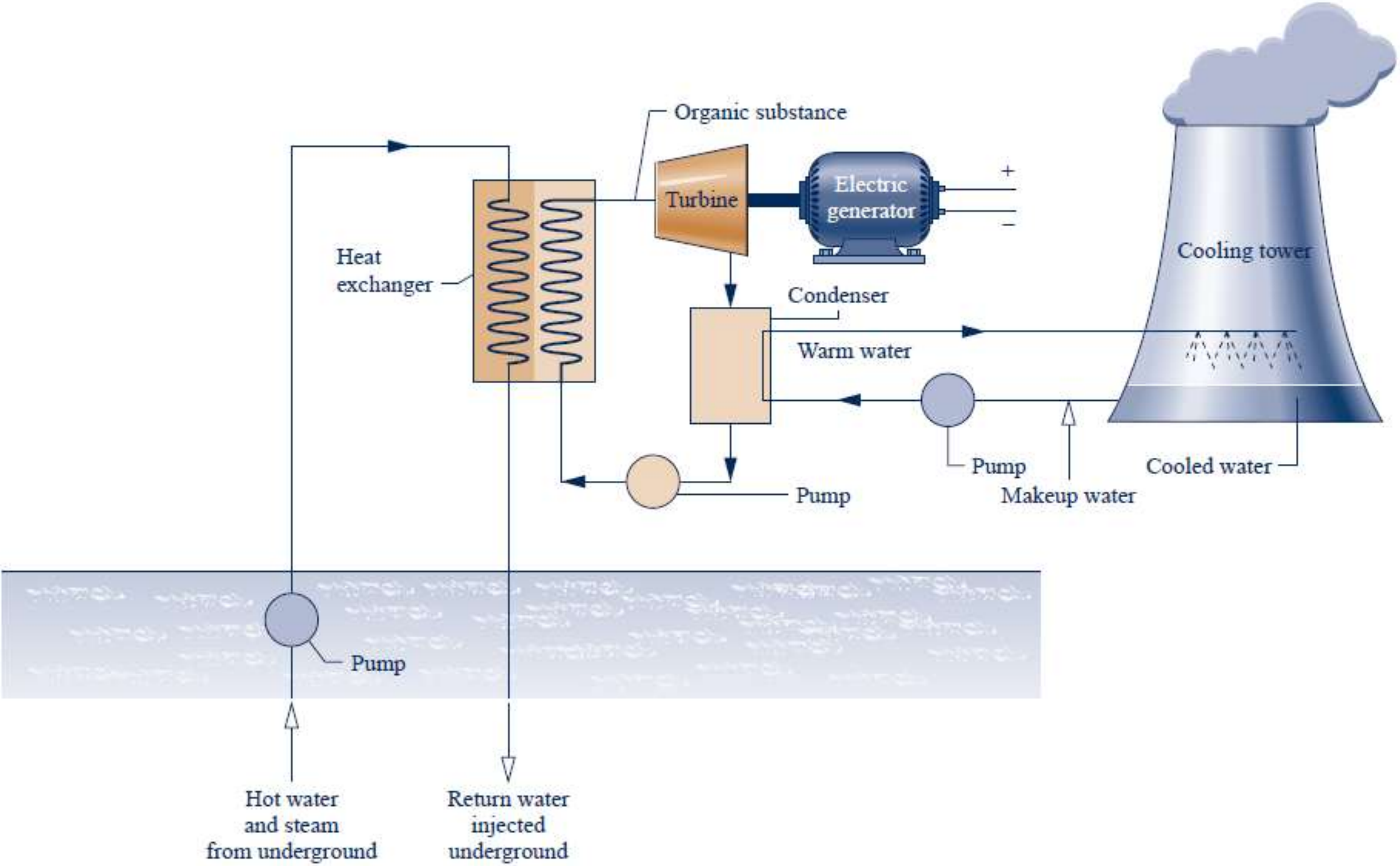


(*b*) Pressurized-water reactor nuclear vapor power plant.

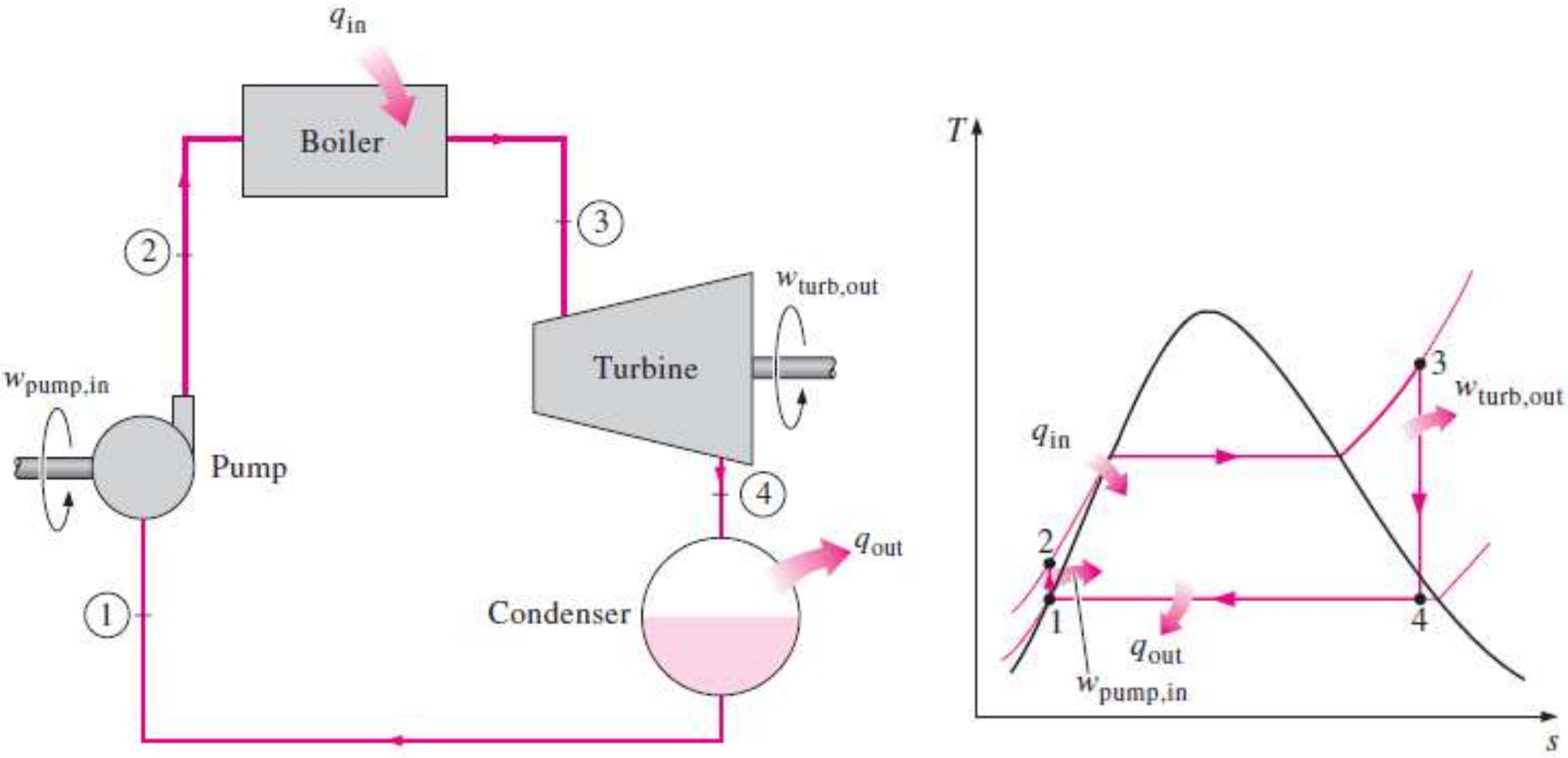
Solar Thermal Vapor Power Plant



Geothermal Vapor Power Plant



Ideal Rankine Cycle



1-2 Isentropic compression in a pump
2-3 Constant pressure heat addition in a boiler
3-4 Isentropic expansion in a turbine
4-1 Constant pressure heat rejection in a condenser

Energy Analysis of Ideal Rankine Cycle

- Boiler
  - Does not produce any work
  - Receives Heat (Q_{in})
  - No Pressure Drop
- Condenser
  - Does not produce any work
  - Rejects Heat (Q_{out})
  - No Pressure Drop
- Pump
  - Adiabatic reversible / Isentropic
  - Receives Work (W_{in})
- Turbine
  - Adiabatic reversible / Isentropic
  - Produces Work (W_{out})

- In general
  - Steady state is assumed
  - Kinetic & Potential Energy changes is neglected

Energy Analysis of Ideal Rankine Cycle

Unit	Q direction	W direction	Value
Boiler	+	0	$h_{\text{boiler out}} - h_{\text{boiler in}}$
Condenser	-	0	$h_{\text{cond, out}} - h_{\text{cond, in}}$
Pumps	0	+	$h_{\text{pump, out}} - h_{\text{pump, in}}$ or $V\,(P_{out}-P_{in})$
Turbine	0	-	$h_{\text{turb, out}} - h_{\text{turb, in}}$

+ = In **- = Out**

Energy Analysis of Ideal Rankine Cycle

Thermal Efficiency

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

Since it is a closed Cycle:

$$\Delta U = 0$$
$$Q_{net} = -W_{net}$$
$$Q_{in} - Q_{out} = -(W_{out} - W_{in})$$
$$Q_{boiler} - Q_{cond} = -(W_{turb} - W_{pump})$$

$Q_{in} > Q_{out}$ and $W_{out} > W_{in}$

Or sometimes described as:

$$\eta_{th} = \frac{3412\ (\text{Btu/kWh})}{\text{Heat rate}\ (\text{Btu/kWh})}$$

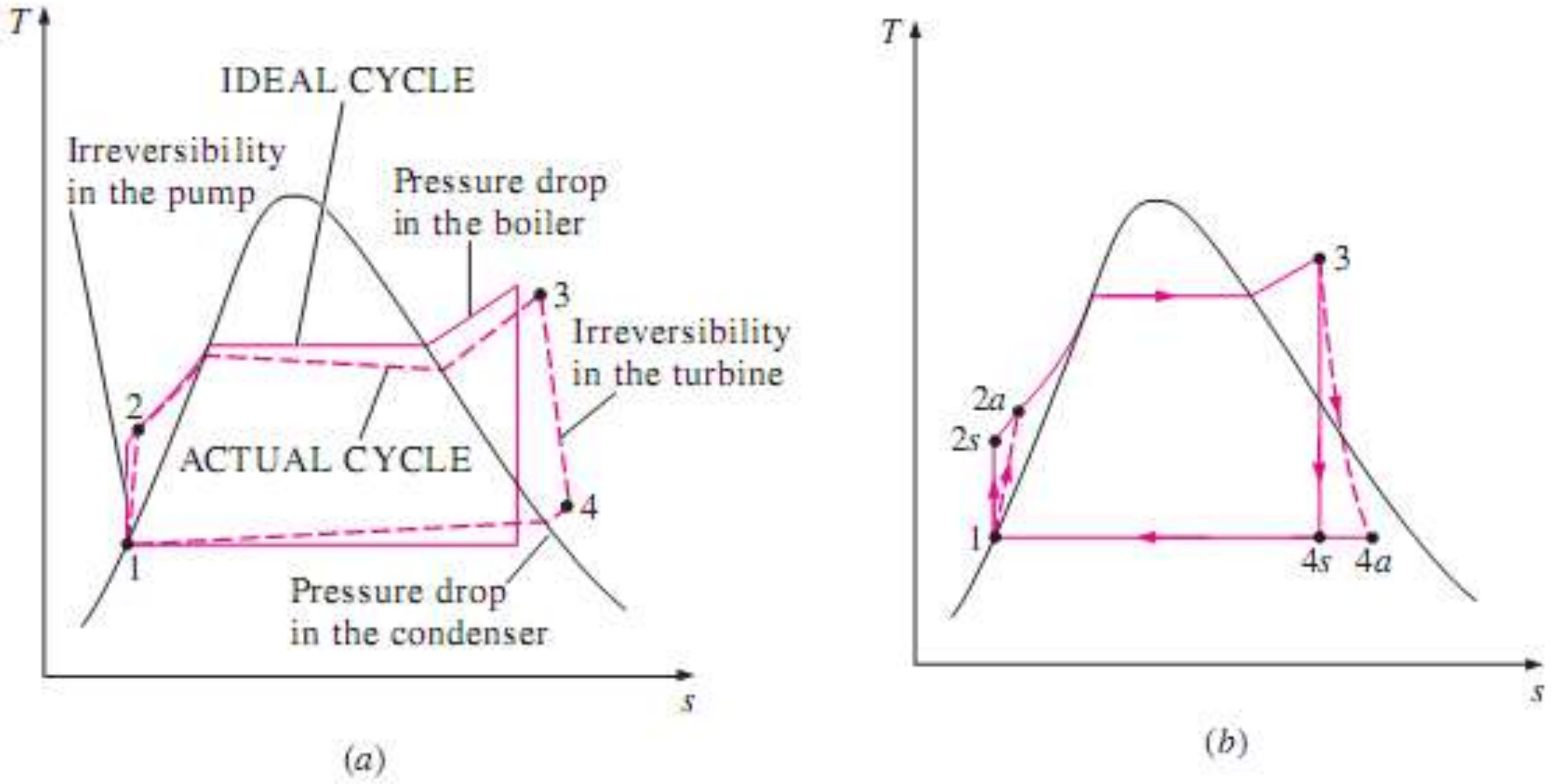
Heat rate = the amount of heat supplied, In Btu, to generate 1 kWh of electricity.

DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES

Real Cycles

- Pressure Drops Losses inside Exchangers and Piping System
- For Pump and Turbine, the entropy is always increased
- Condenser outlet is sub cooled to prevent cavitation

DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES



DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES

- The deviation of actual pumps and turbines from the isentropic ones can be accounted for by utilizing isentropic efficiencies:

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

HOW CAN WE INCREASE THE EFFICIENCY?

BASIC IDEAS

- 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.

T boiler as high as possible

T condenser as low as possible

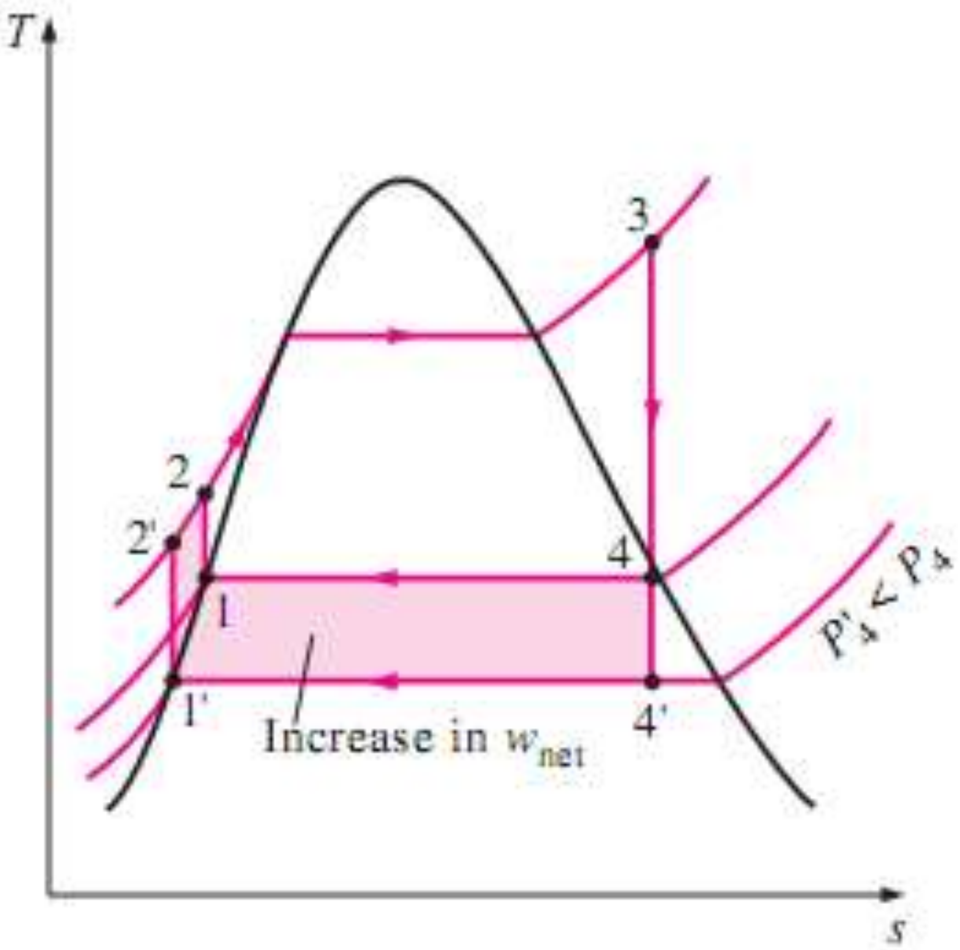
Efficiency Improvements

- Lowering the Condenser Pressure (Lowers $T_{low,avg}$)
- Superheating the Steam to High Temperatures (Increases $T_{high,avg}$)
- Increasing the Boiler Pressure (Increases $T_{high,avg}$)

Constraints:

- Available Cooling Media
- Material of Construction Selection

Lowering the Condenser Pressure

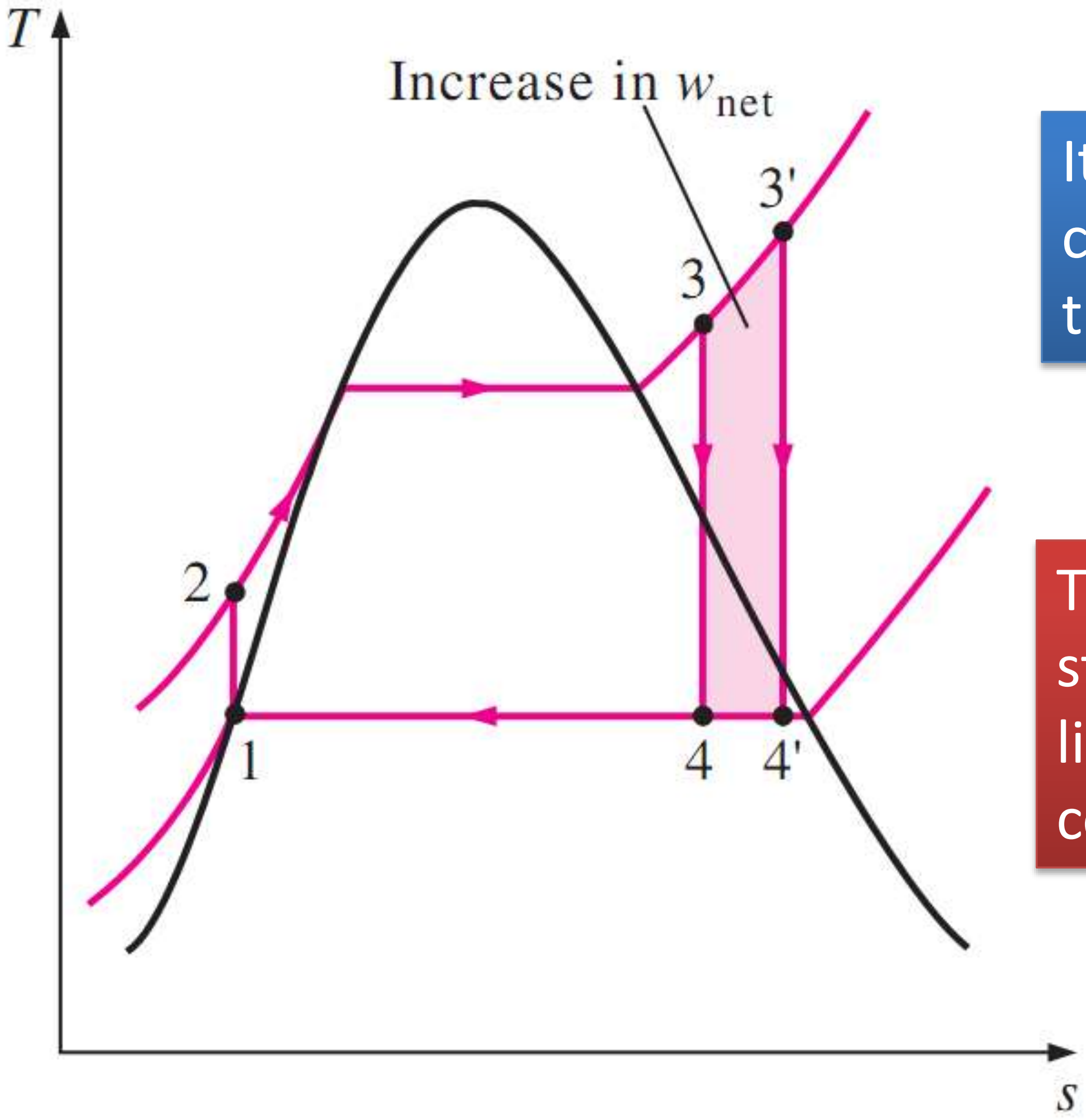


- The condensers of steam power plants usually operate well below the atmospheric pressure (Vacuum)
- However, there is a lower limit on the condenser pressure that can be used.
- It cannot be lower than the saturation pressure corresponding to the temperature of the cooling medium

side effects:

- possibility of air leakage into the condenser.
- increased moisture content of the steam at the final stages of the turbine

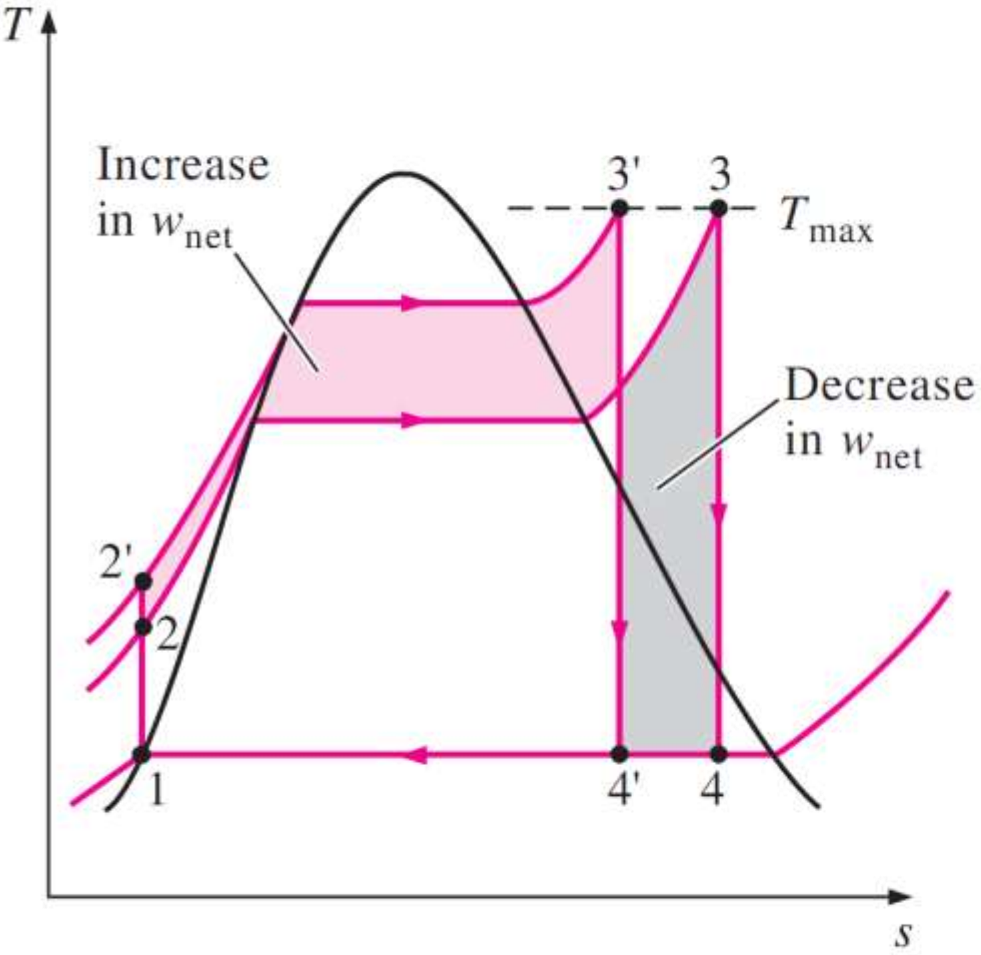
Superheating the Steam to High Temperatures

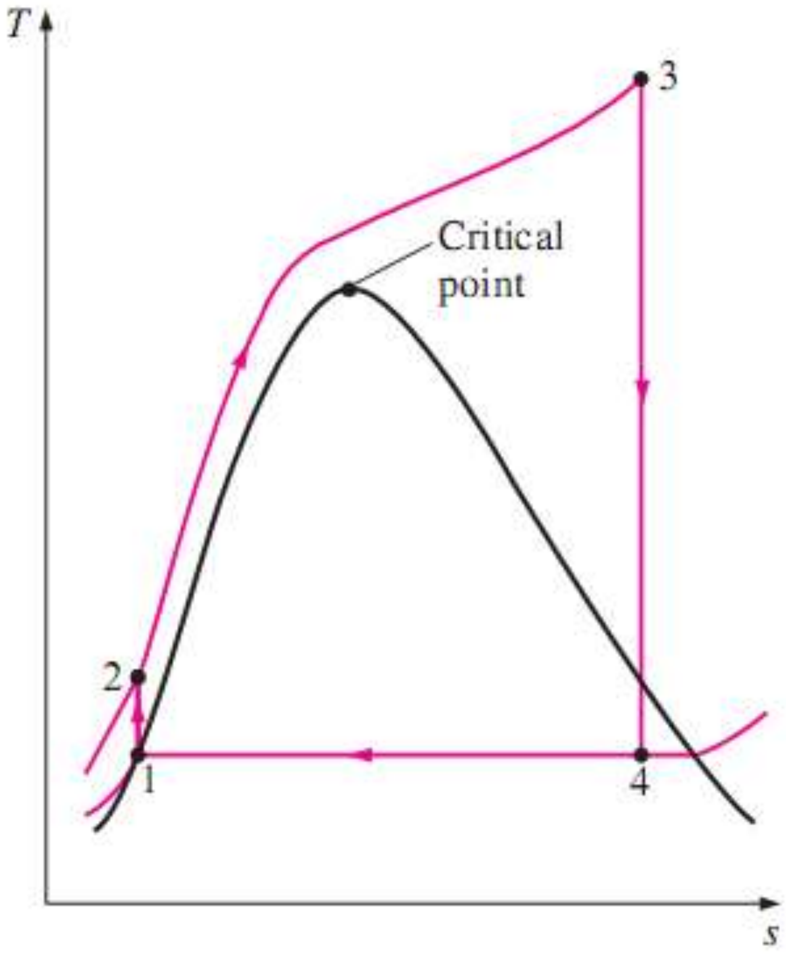


It decreases the moisture content of the steam at the turbine exit

The temperature to which steam can be superheated is limited by metallurgical considerations.

Increasing the Boiler Pressure





The moisture content at the turbine outlet is increased

Example: Effect of Boiler Pressure and Temperature on Efficiency

Consider a steam power plant operating on the ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 10 kPa.

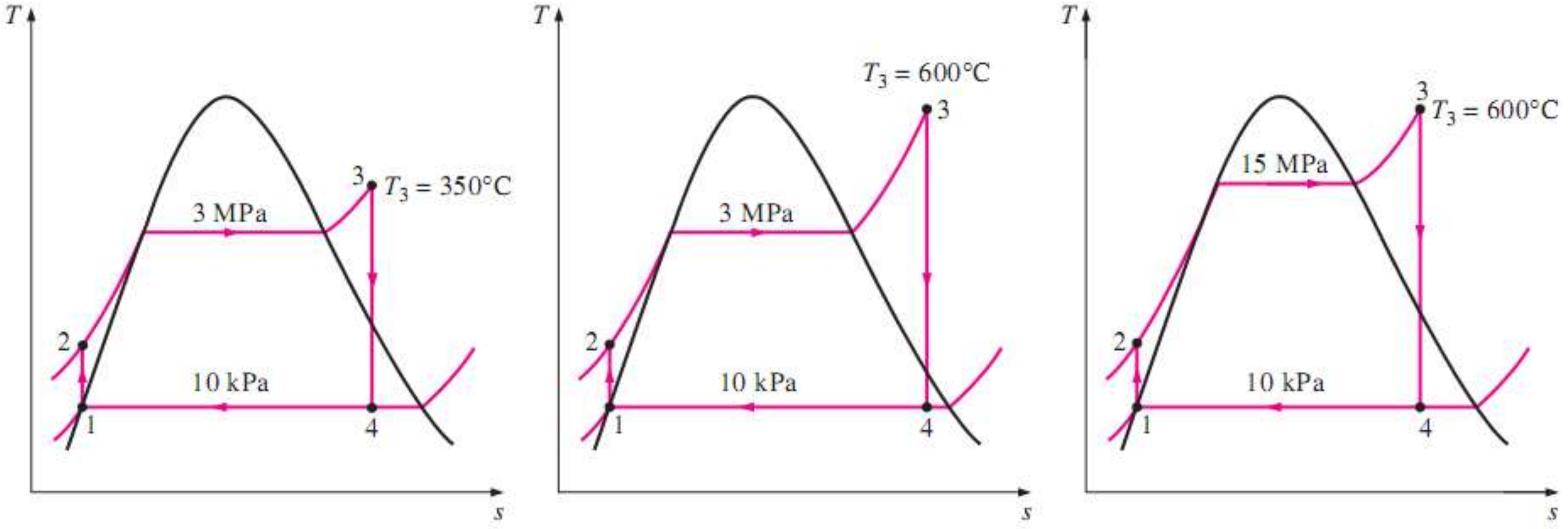
Determine:

(a) the thermal efficiency of this power plant,

(b) the thermal efficiency if steam is superheated to 600°C instead of 350°C, and

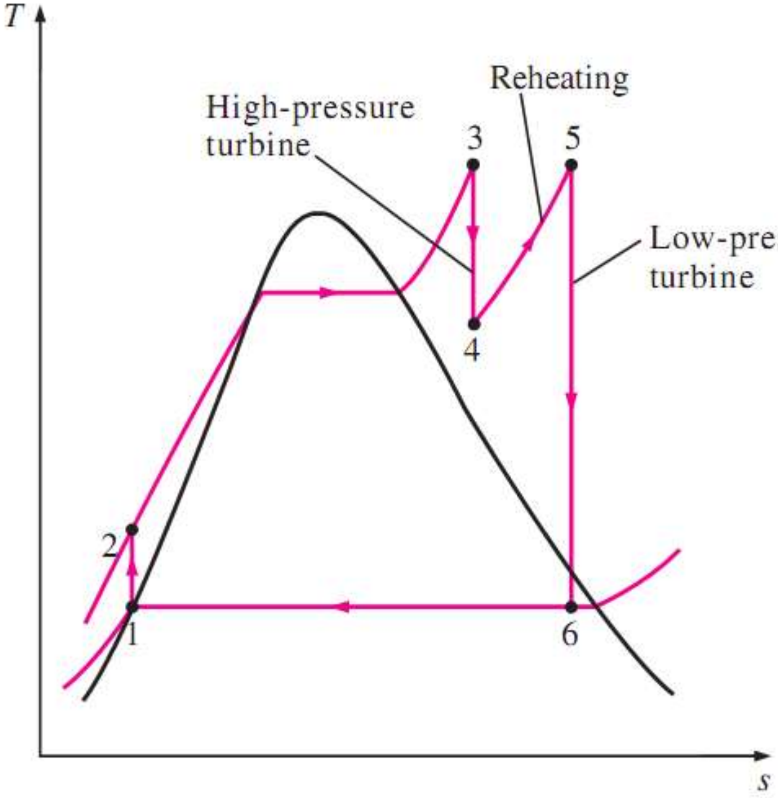
(c) the thermal efficiency if the boiler pressure is raised to 15 MPa while the turbine inlet temperature is maintained at 600°C.

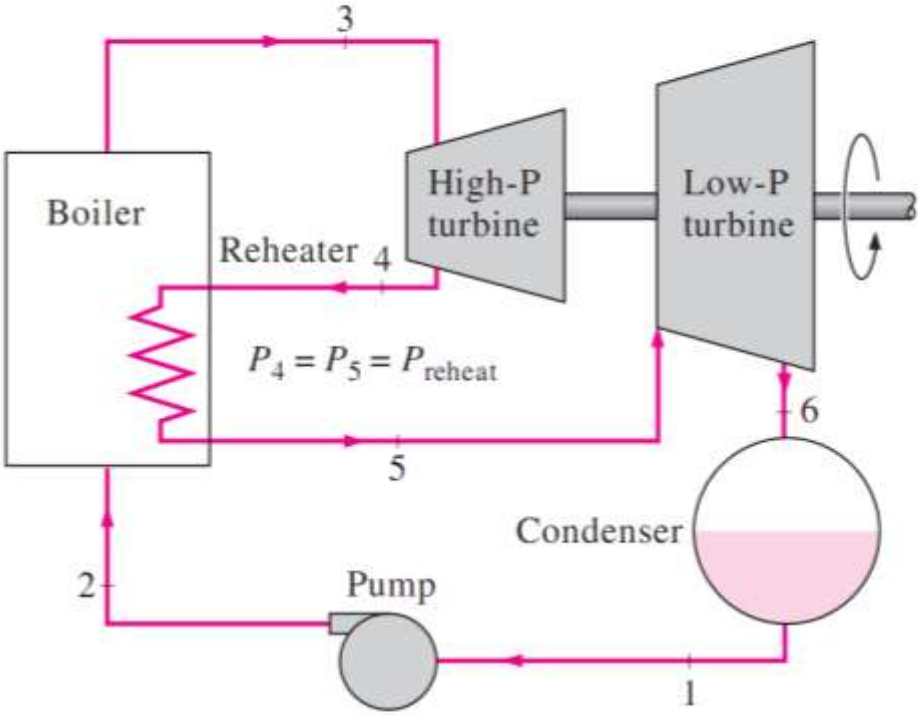
Example: Effect of Boiler Pressure and Temperature on Efficiency



(a) (b) (c)

Ideal Reheat Rankine Cycles



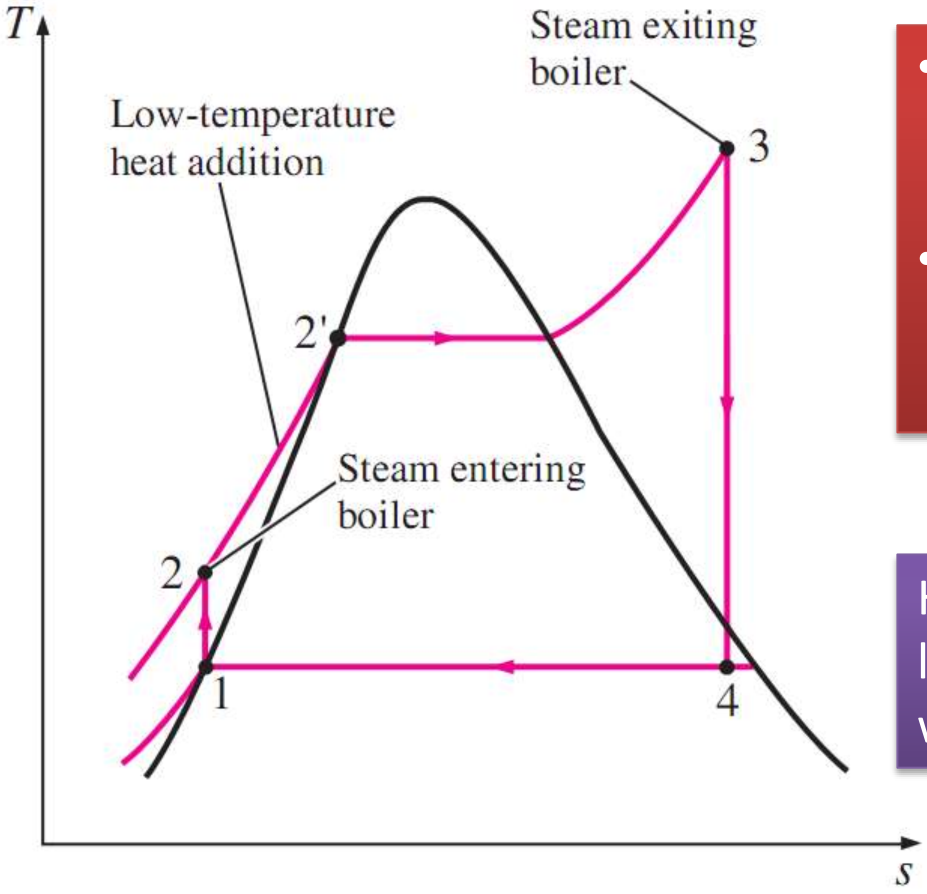


$$q_{\text{in}} = q_{\text{primary}} + q_{\text{reheat}}$$

$$w_{\text{turb,out}} = w_{\text{turb,I}} + w_{\text{turb,II}}$$

Example

The Ideal Regenerative Rankine Cycle

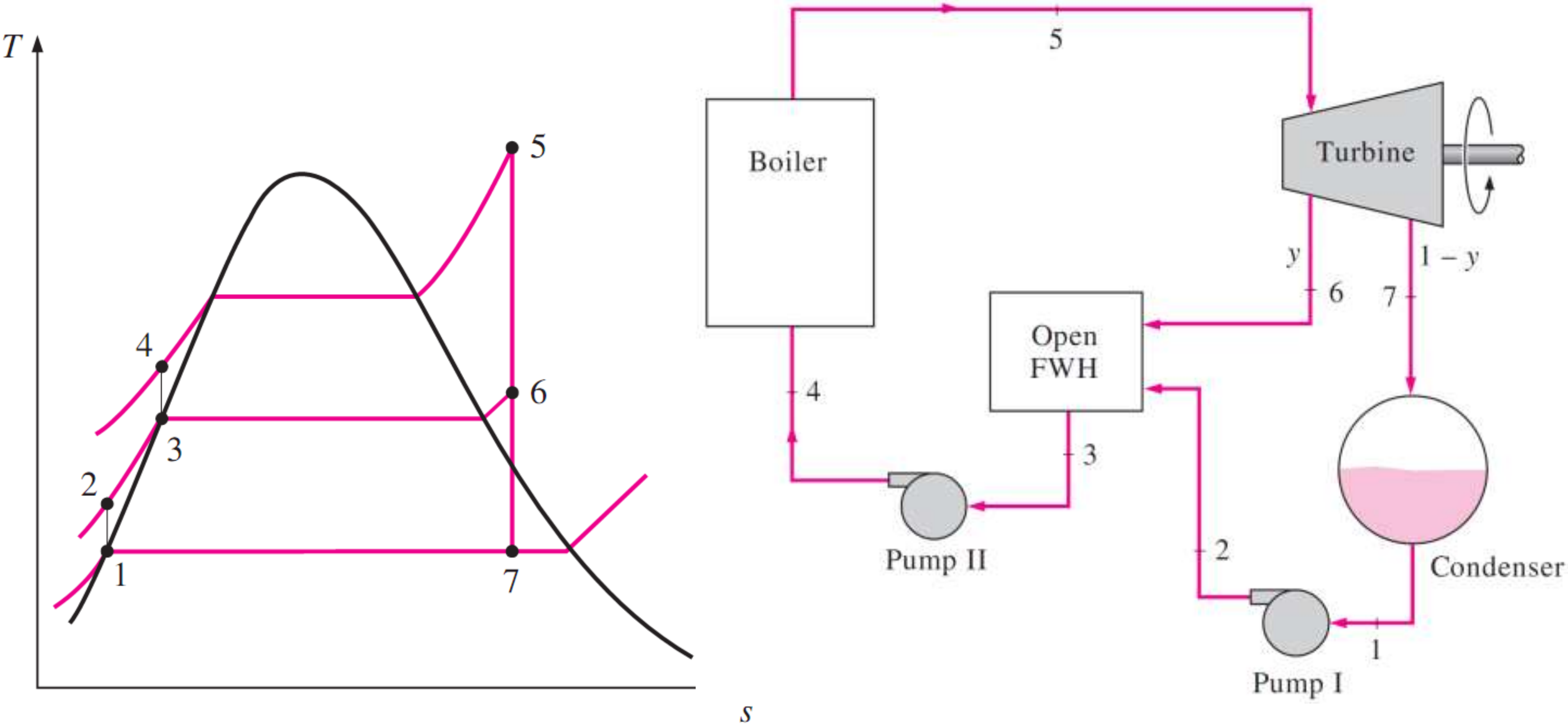


- Heat is transferred to the working fluid during process 2-2’ at a relatively low temperature.
- This lowers the average heat addition temperature and thus the cycle efficiency

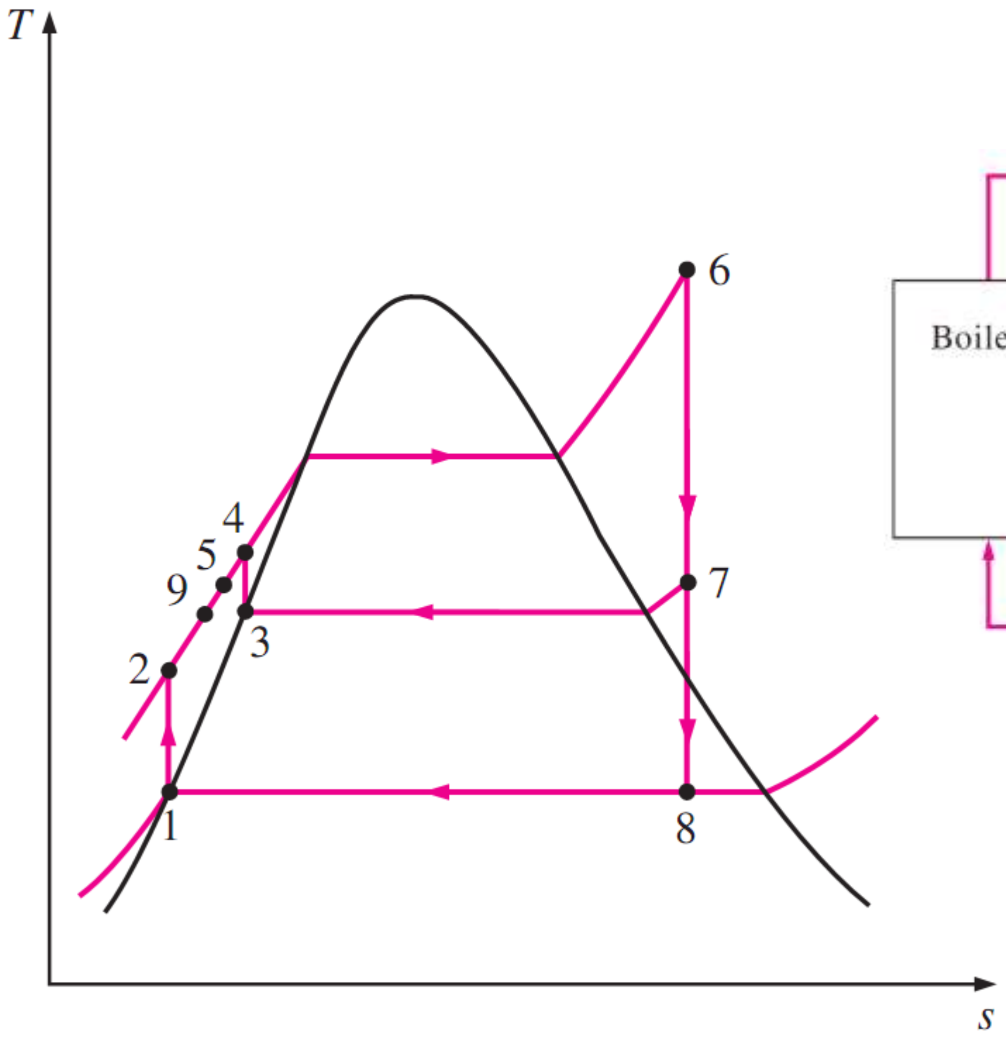
How can we raise the temperature of the liquid leaving the pump (called the feed water) before it enters the boiler?

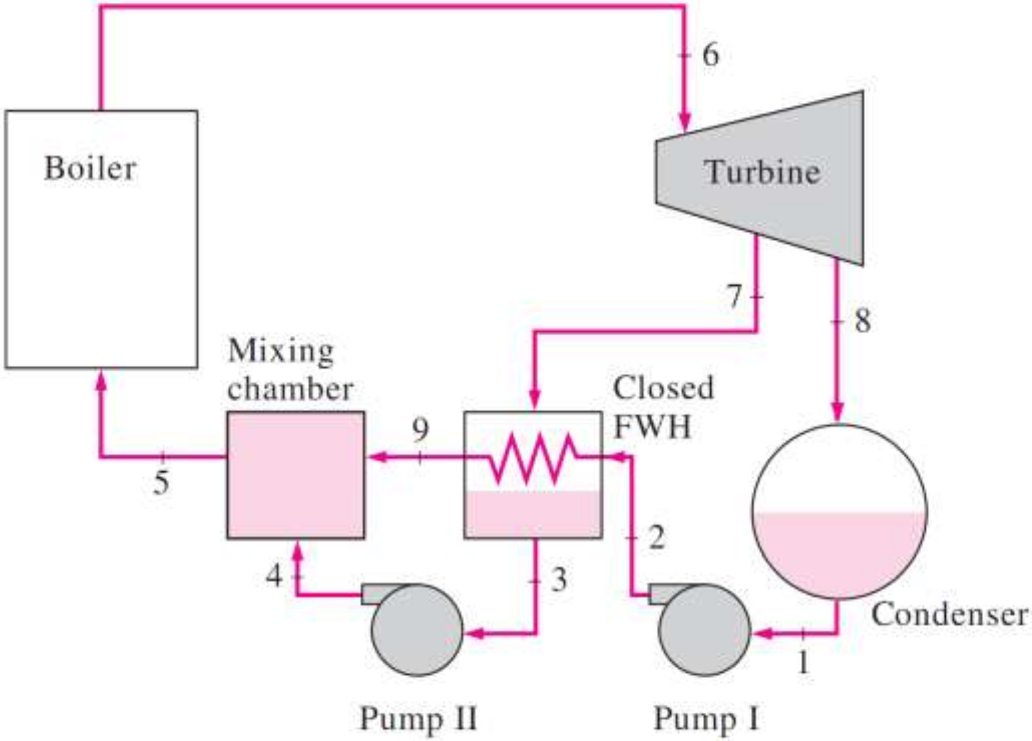
Regenerators/Feed Water Heater : HX from the steam (extracted from turbine) to the feed water either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters)

Open Feedwater Heaters



Closed Feedwater Heaters





Combination of Closed & Open BFW Heaters

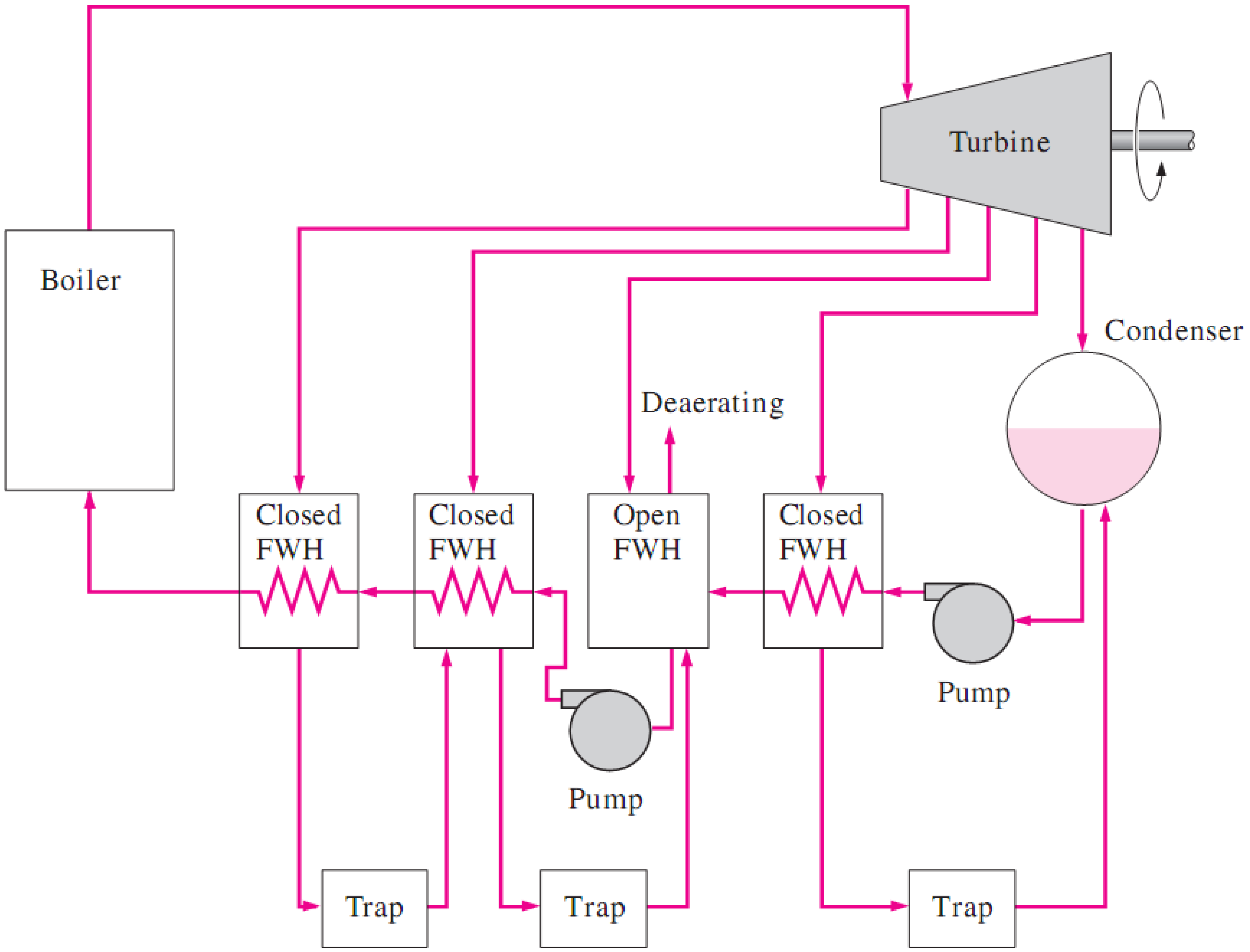


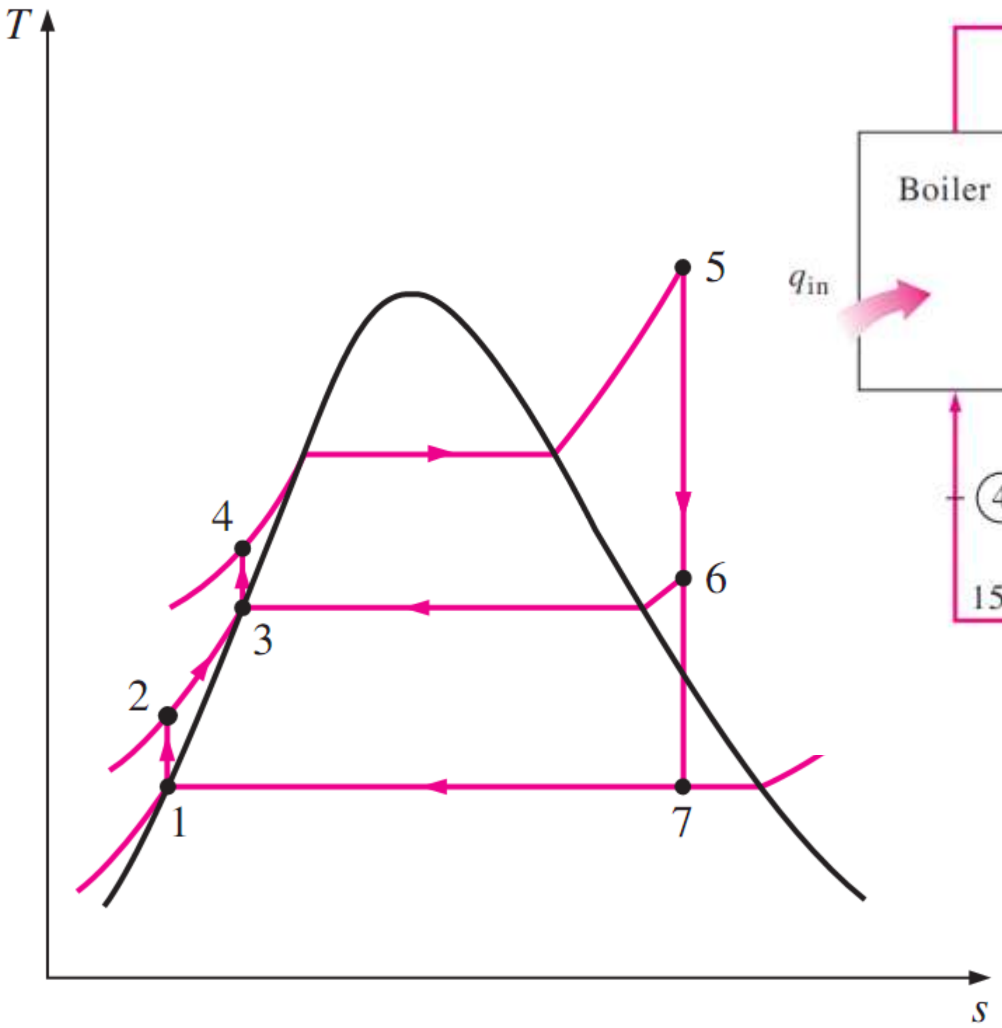
FIGURE 10–17

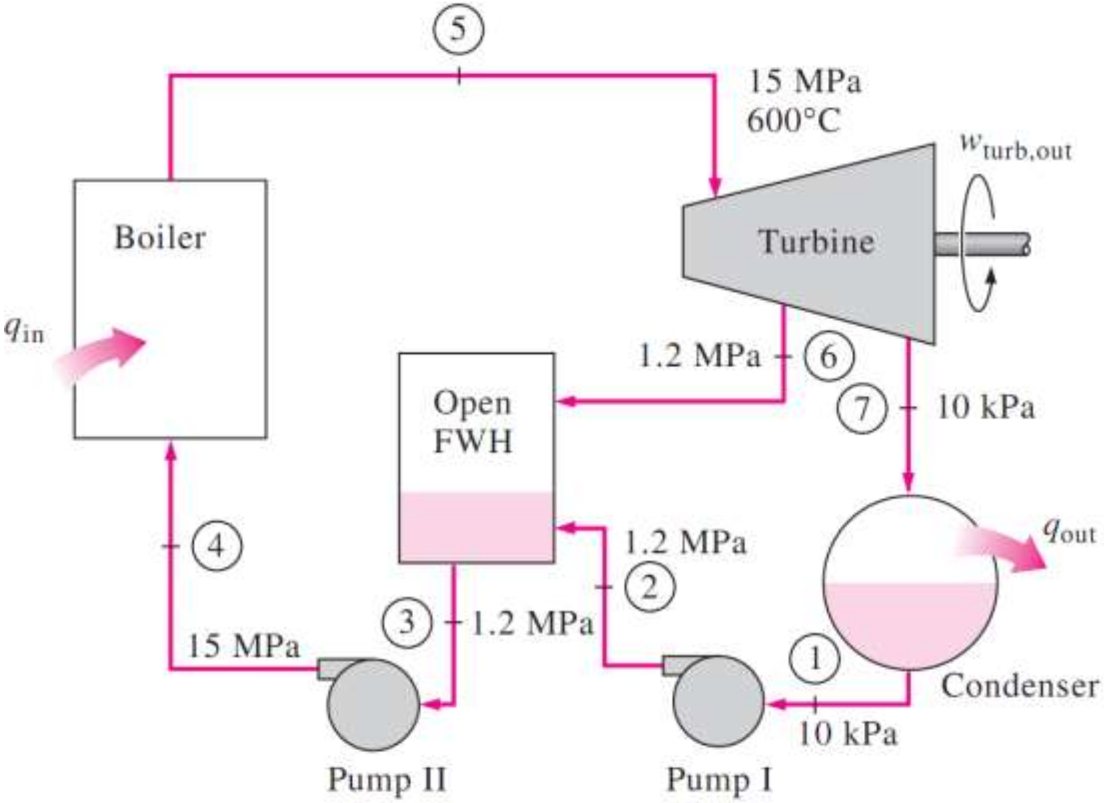
A steam power plant with one open and three closed feedwater heaters.

Example: The Ideal Regenerative Rankine Cycle

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.

Example: The Ideal Regenerative Rankine Cycle



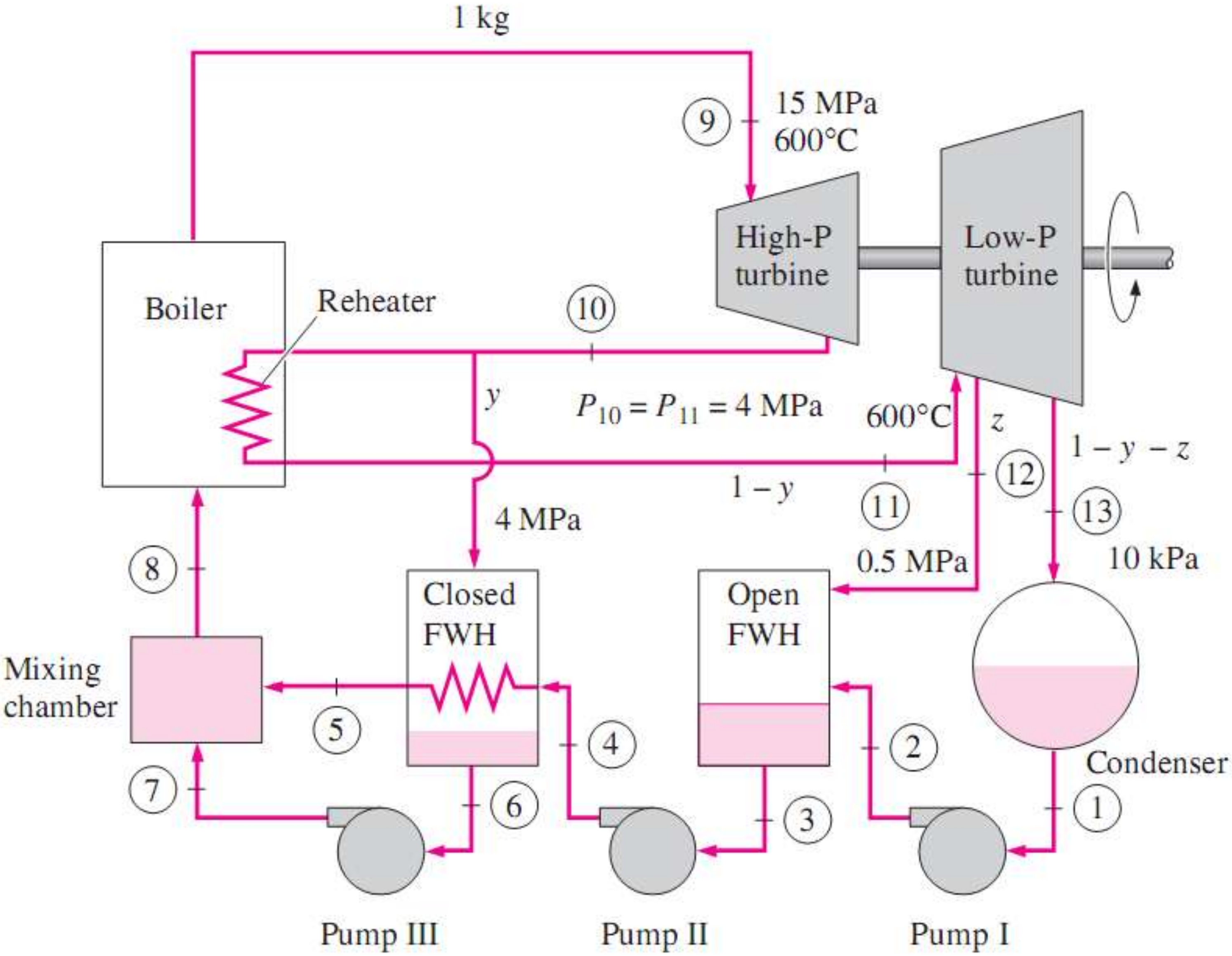


Example: The Ideal Reheat–Regenerative Rankine Cycle

Consider a steam power plant that operates on an ideal reheat–regenerative Rankine cycle with one open feedwater heater, one closed feedwater heater, and one reheater. Steam enters the turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. Some steam is extracted from the turbine at 4 MPa for the closed feedwater heater, and the remaining steam is reheated at the same pressure to 600°C. The extracted steam is completely condensed in the heater and is pumped to 15 Mpa before it mixes with the feedwater at the same pressure. Steam for the open feedwater heater is extracted from the low-pressure turbine at a pressure of 0.5 MPa.

Determine the fractions of steam extracted from the turbine as well as the thermal efficiency of the cycle.

Example: The Ideal Reheat–Regenerative Rankine Cycle



Cogeneration Cycle

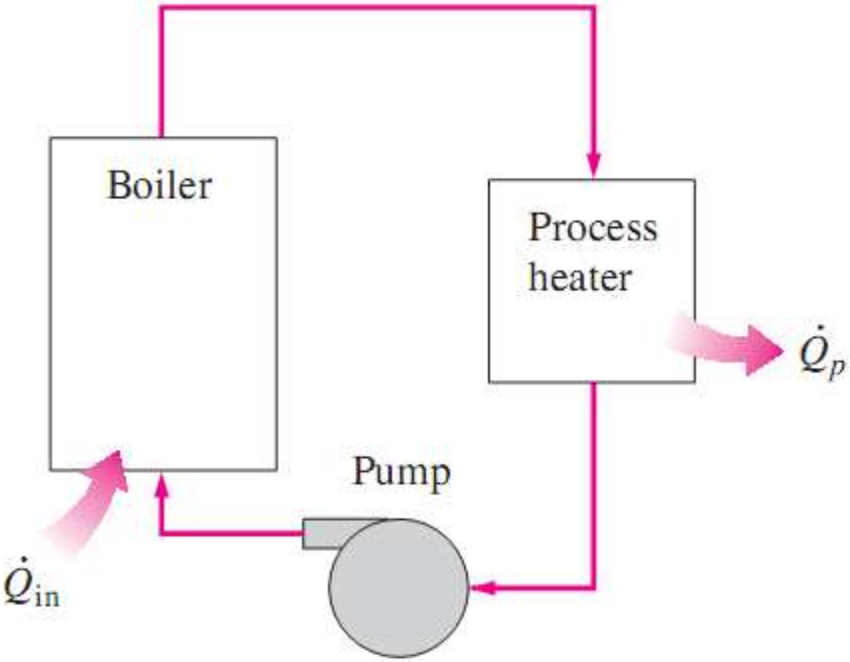


FIGURE 10–20

A simple process-heating plant.

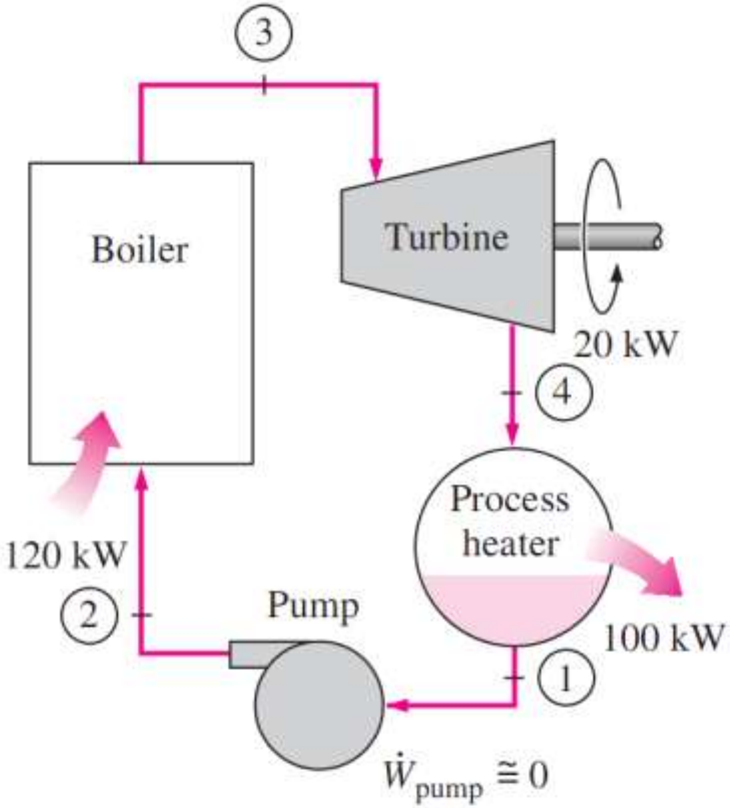


FIGURE 10–21

An ideal cogeneration plant.

Cogeneration Cycle

- ideal steam-turbine cogeneration plant shown in Fig. 10–21 does not have a condenser. Thus no heat is rejected from this plant as waste heat.
- All the energy transferred to the steam in the boiler is utilized as either process heat or electric power.
- Thus it is appropriate to define a **UTILIZATION FACTOR** for a cogeneration plant

$$\epsilon_u = \frac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{\text{net}} + \dot{Q}_p}{\dot{Q}_{\text{in}}}$$

Cogeneration Cycle

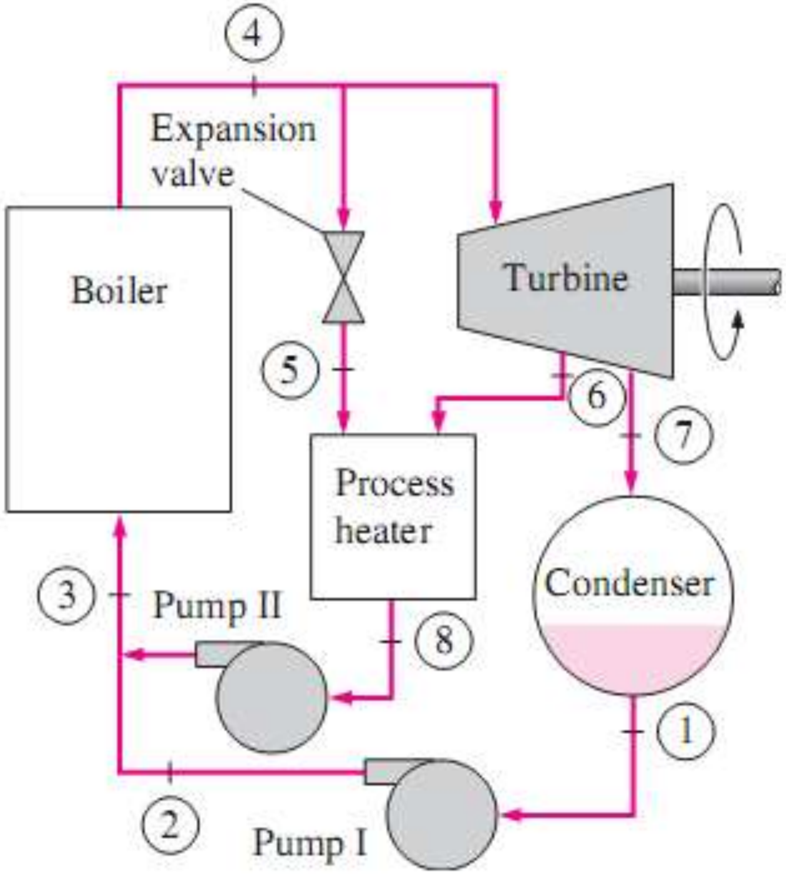


FIGURE 10–22

A cogeneration plant with adjustable loads.

- The ideal steam-turbine cogeneration plant described above is not practical because it cannot adjust to the variations in power and process-heat loads.
- The schematic of a more practical (but more complex) cogeneration plant is shown in Fig. 10–22.
- Under normal operation, some steam is extracted from the turbine at some predetermined intermediate pressure P6. The rest of the steam expands to the condenser pressure P7 and is then cooled at constant pressure. The heat rejected from the condenser represents the waste heat for the cycle.

Example

Consider the cogeneration plant shown in Fig. 10–23. Steam enters the turbine at 7 MPa and 500°C. Some steam is extracted from the turbine at 500 kPa for process heating. The remaining steam continues to expand to 5 kPa. Steam is then condensed at constant pressure and pumped to the boiler pressure of 7MPa. At times of high demand for process heat, some steam leaving the boiler is throttled to 500 kPa and is routed to the process heater. The extraction fractions are adjusted so that steam leaves the process heater as a saturated liquid at 500 kPa. It is subsequently pumped to 7 MPa. The mass flow rate of steam through the boiler is 15 kg/s. Disregarding any pressure drops and heat losses in the piping and assuming the turbine and the pump to be isentropic, determine:

(a) the maximum rate at which process heat can be supplied,

(b) the power produced and the utilization factor when no process heat is supplied, and

(c) the rate of process heat supply when 10 percent of the steam is extracted before it enters the turbine and 70 percent of the steam is extracted from the turbine at 500 kPa for process heating.

Example

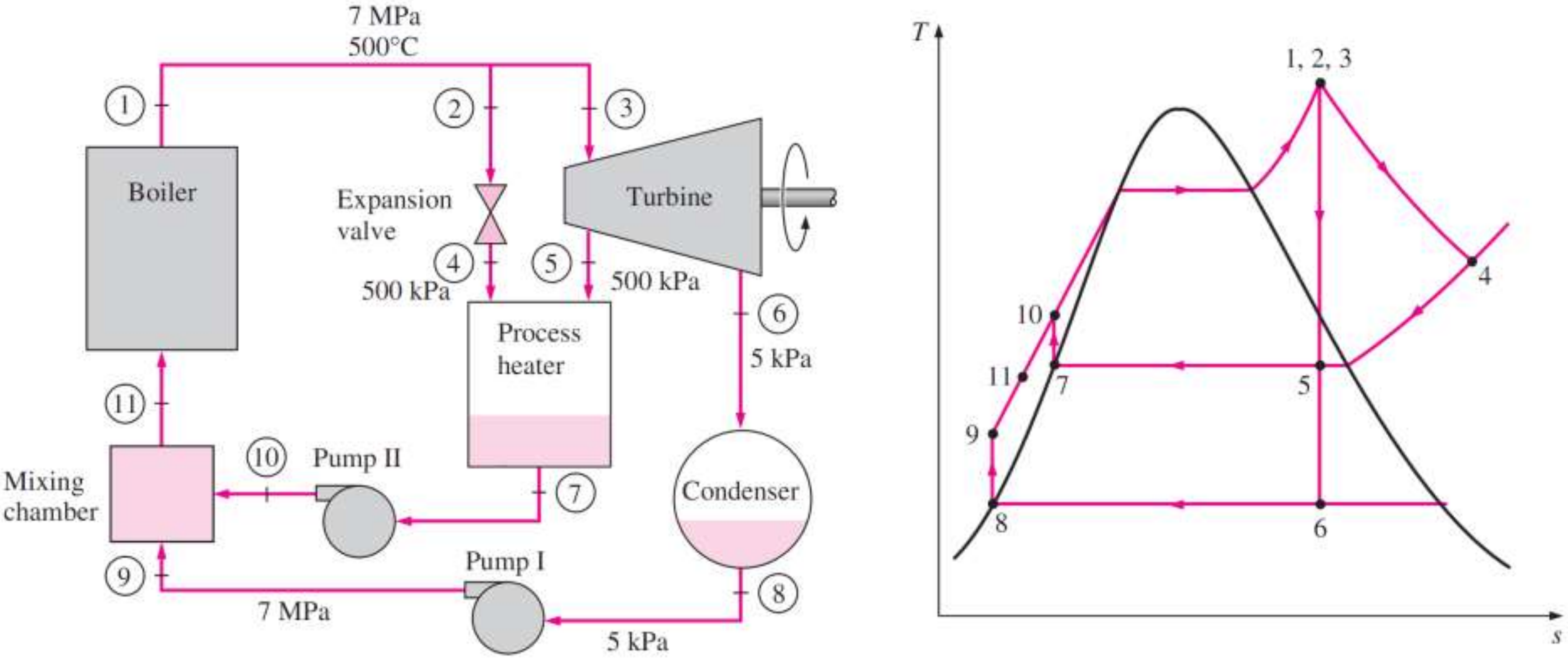


FIGURE 10–23

Schematic and *T-s* diagram for Example 10–8.