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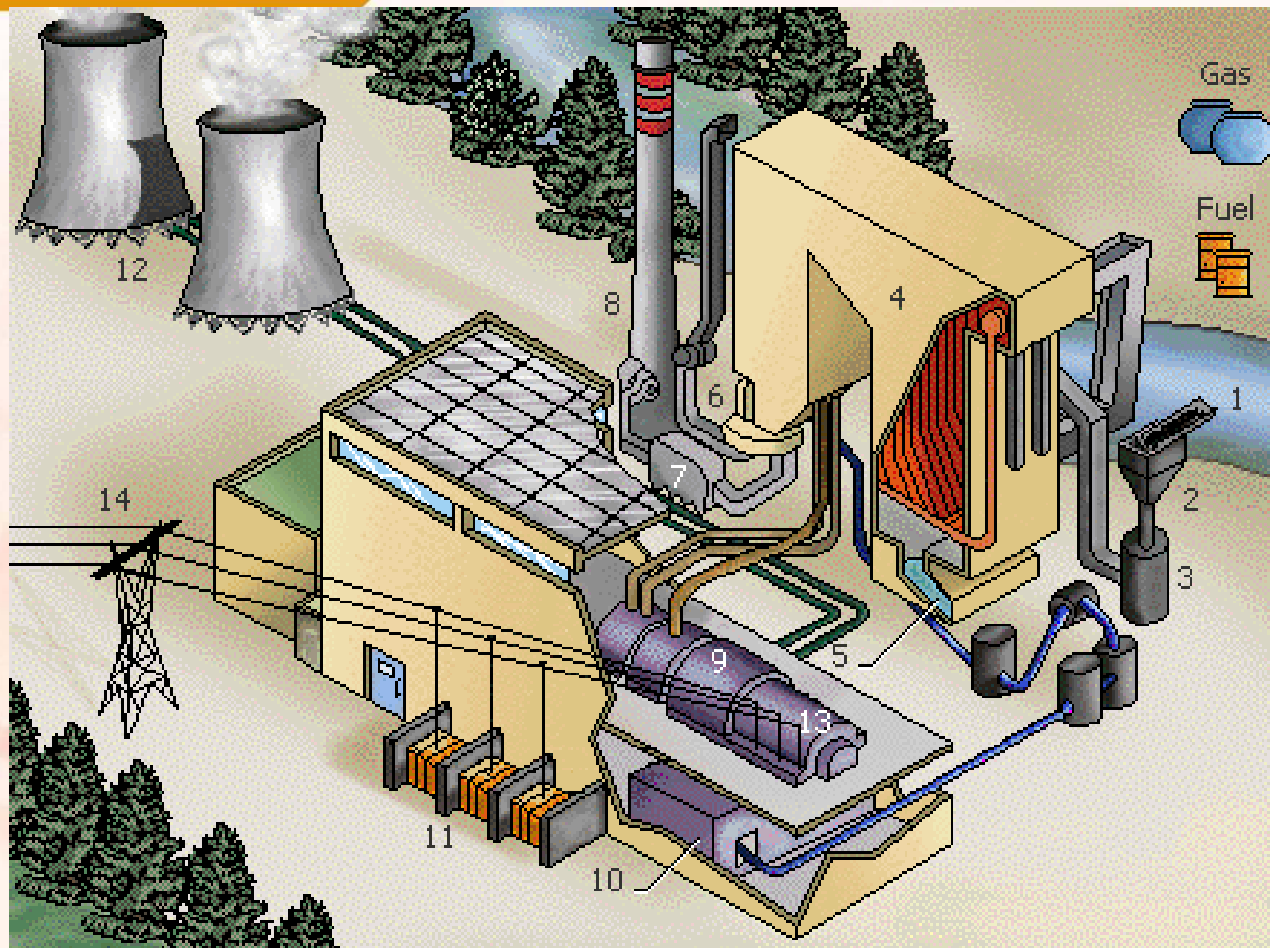
TOPIC 4

VAPOR POWER CYCLE

CHAPTER 10

INSPIRING CREATIVE AND INNOVATIVE MINDS

INTRODUCTION



Thermal power plant

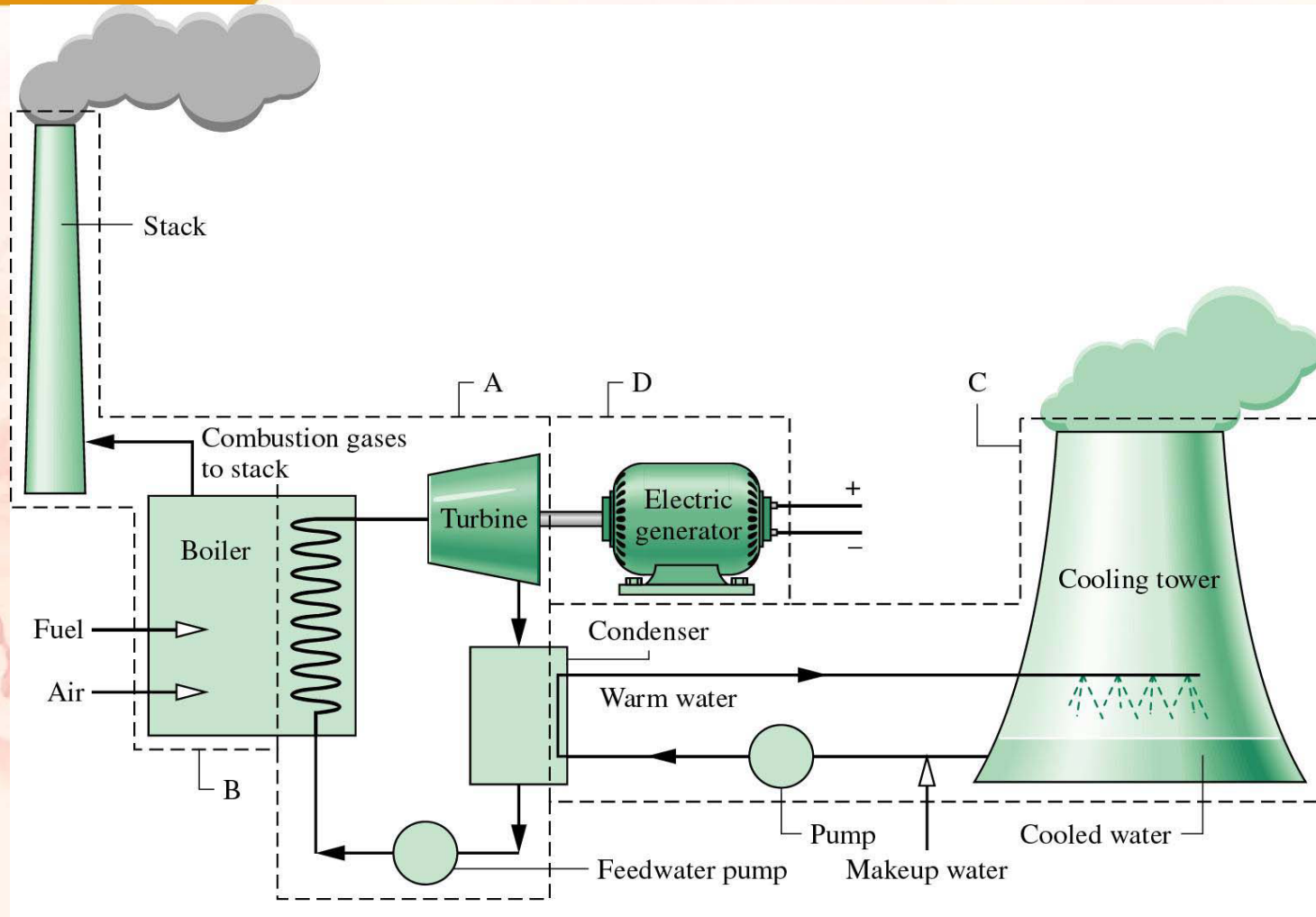
- 1 Coal conveyer
- 2 Stoker
- 3 Pulverizer
- 4 Boiler
- 5 Coal Ash
- 6 Air preheater
- 7 Electrostatic precipitator
- 8 Smokestack
- 9 Turbine
- 10 Condenser
- 11 Transformers
- 12 Cooling towers
- 13 Generator
- 14 High-voltage power lines



INTRODUCTION

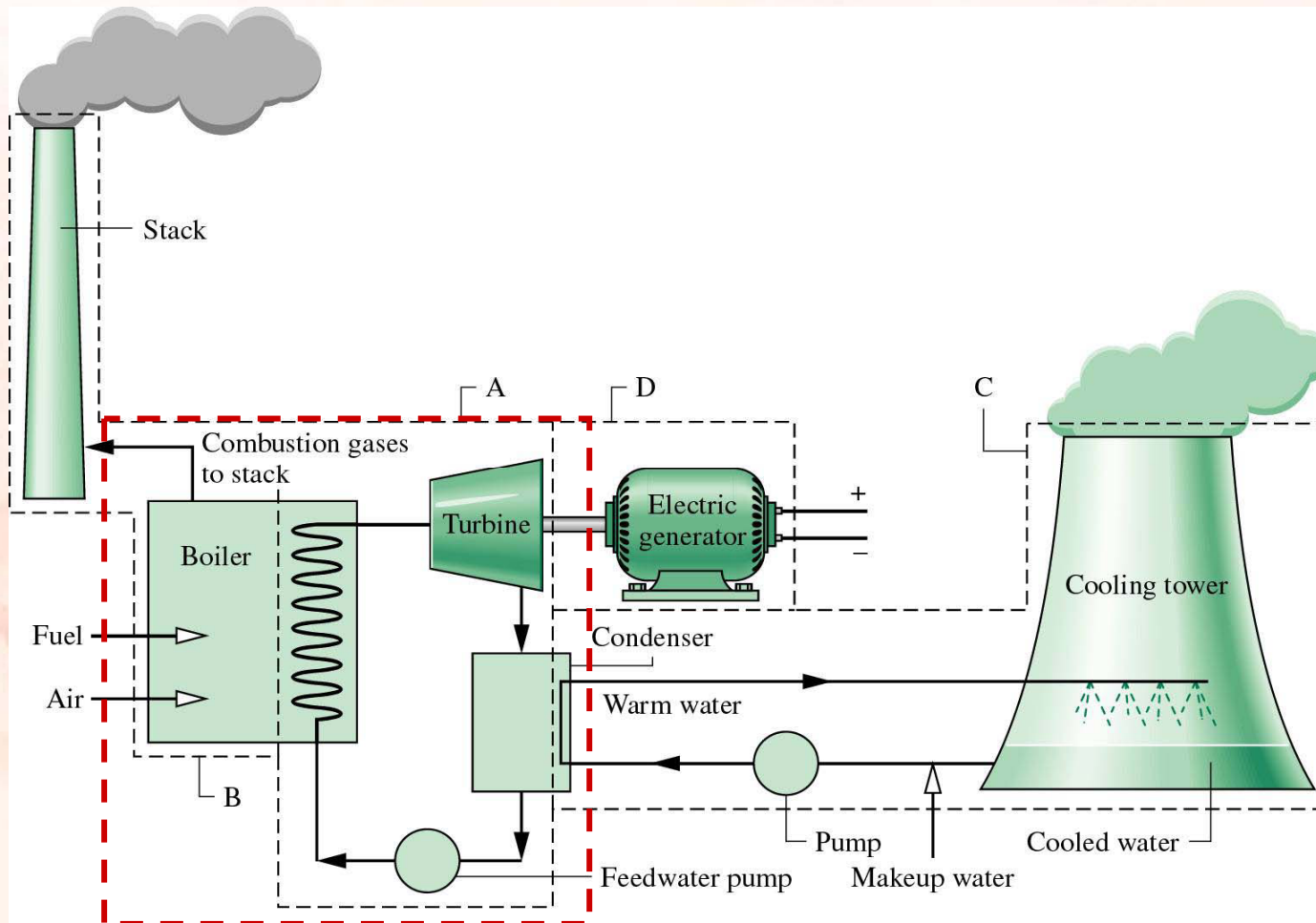
- The steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency from the use of multiple stages in the expansion of the steam
- The modern steam turbine was invented in 1884 by the Englishman [Sir Charles Parsons](#), whose first model was connected to a [dynamo](#) that generated 7.5 kW (10 hp) of electricity
- 86% of electric generation in the world is using steam turbine.

INTRODUCTION



TOPIC 4 : VAPOR POWER CYCLE

Our focus will be on sub-system A.



MAIN COMPONENTS OF SPP

Steam turbine

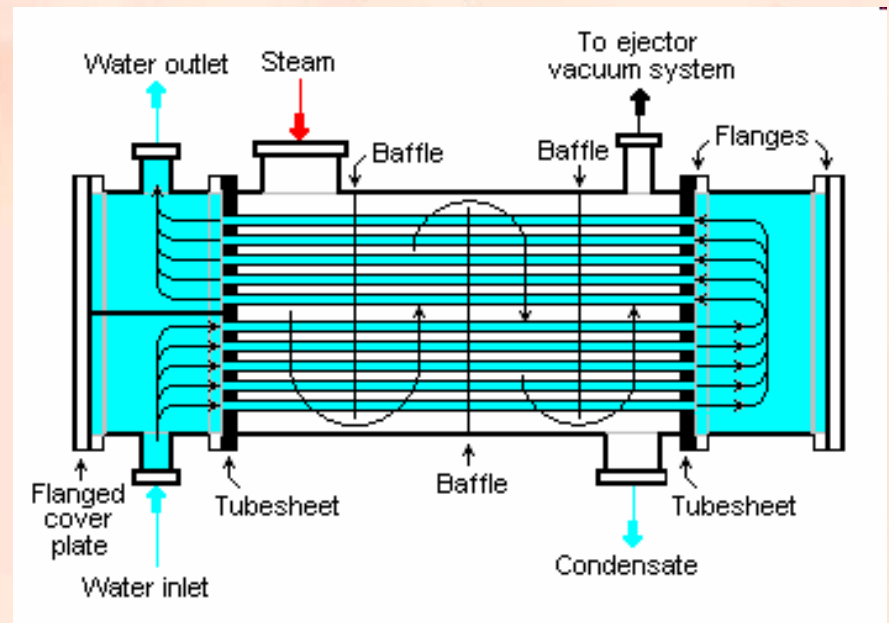
- Steam turbines are devices convert the energy stored in steam into rotational mechanical energy
- The steam turbine may consists of several stages.
- Each stage can be described by analyzing the expansion of steam from a higher pressure to a lower pressure
- The steam may be wet, dry saturated or superheated



MAIN COMPONENTS OF SPP

Condenser

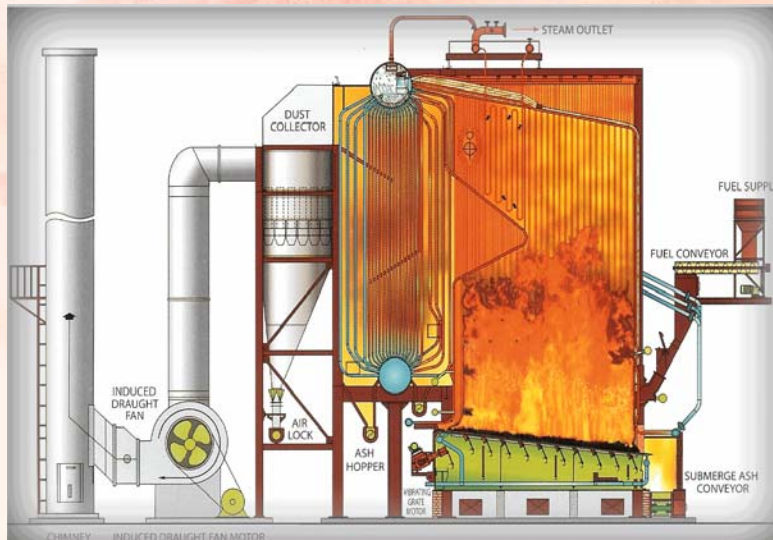
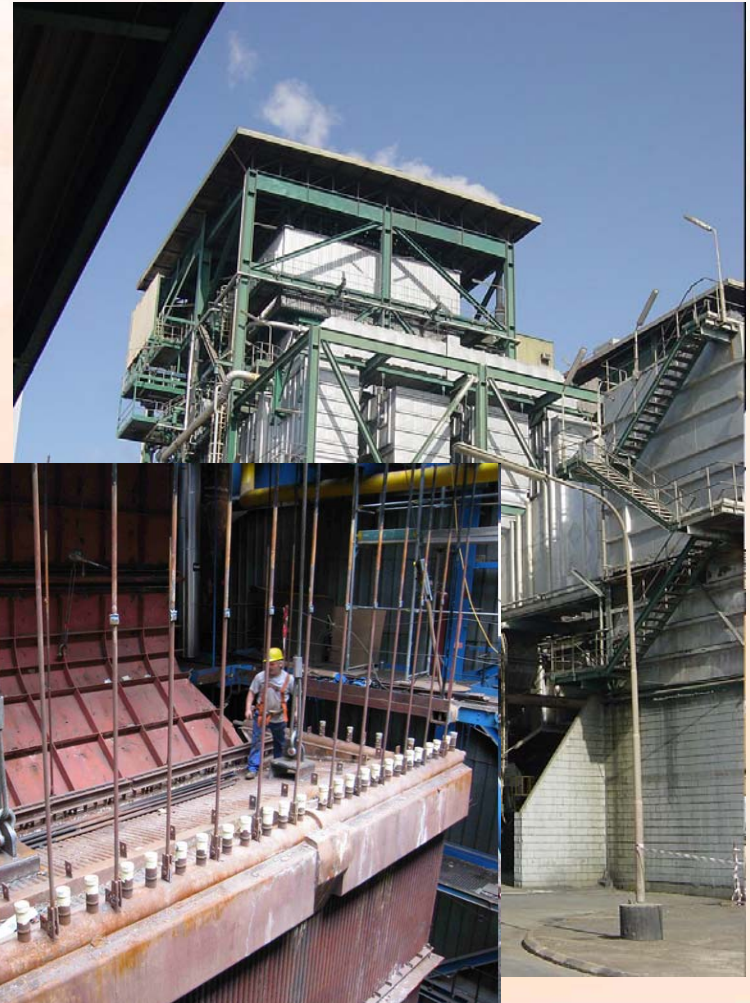
- To convert the exhaust steam from the low pressure turbine to condensate (water) by flowing over the tubes.
- Normally, surface condenser is used in SPP i.e: [shell and tube heat exchanger](#) - in which cooling water is circulated through the tubes.



MAIN COMPONENTS OF SPP

Boiler

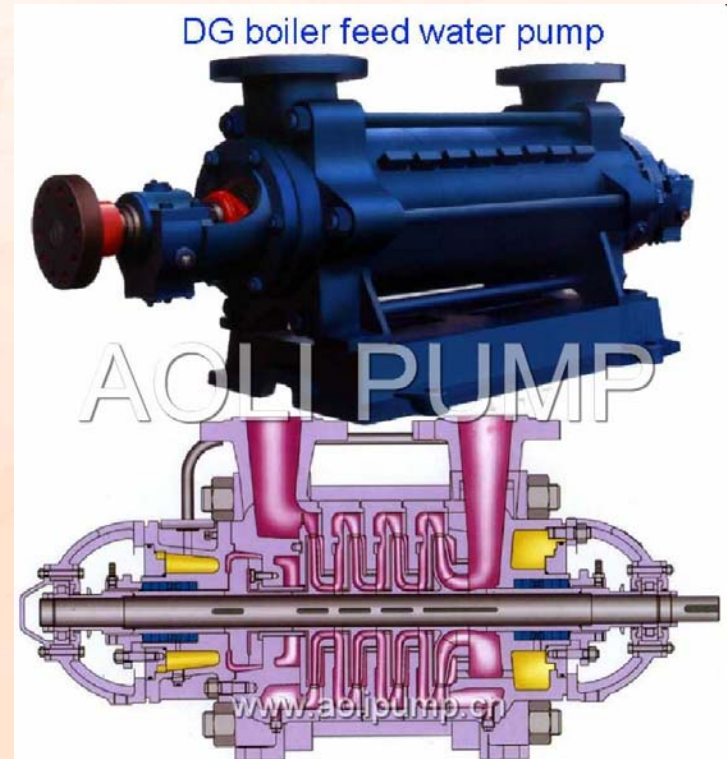
- The heat from combustion of fuel (coal, natural gas or diesel) boils water in the boiler to produce steam at a high pressure and temperature.
- More than half of the electricity generated in the world is by using coal as the primary fuel.



MAIN COMPONENTS OF SPP

Feed Water Pump

- A **boiler feed water pump** is a specific type of pump used to pump feedwater into a steam boiler.
- The water may be freshly supplied or returning condensate produced as a result of the condensation of the steam produced by the boiler.
- These pumps are normally high pressure units
- Can be of the centrifugal pump type or positive displacement type





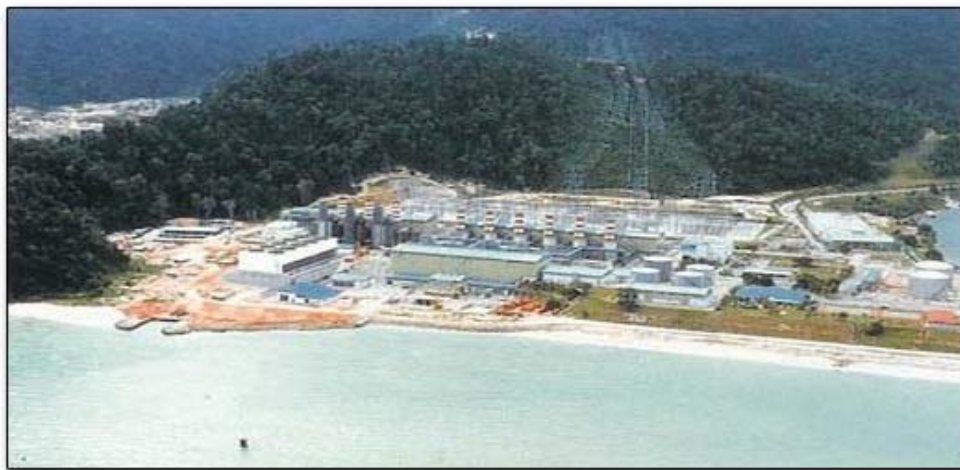
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INTRODUCTION

Lumut Power Plant

Also known as Segari Power Plant is a combine cycle power plant. Owned by Segari Energy Ventures Sdn Bhd (SEV), a subsidiary company of Malakoff Berhad. Located at Mukim Pengkalan Baru, District of Manjung in Lumut Perak with 80 acre site on old tin mining land. Coal Fired 3 x 700 MW Power Plant which owned by Tenaga Nasional Berhad. Segari combine cycle power plant is designed with net output 1,300 MW power generation making it is the biggest gas fired power plant in Malaysia. _



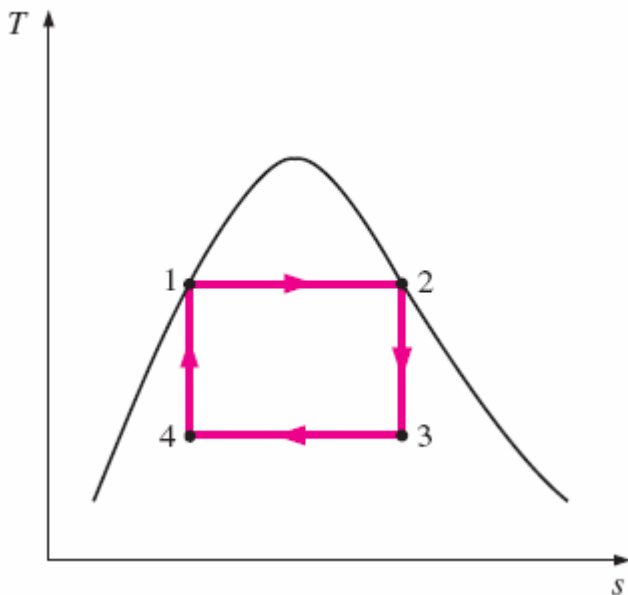
Mohd Kamal Ariffin, FKM, UTM, 2010

CARNOT VAPOR CYCLE

- Carnot cycle is the most efficient power cycle operating between two specified temperature limits
- We can adopt the Carnot cycle first as a prospective ideal cycle for vapor power plants.

Sequence of Processes:

- 1-2 Reversible and isothermal heating (in a boiler);
- 2-3 Isentropic expansion (in a turbine);
- 3-4 Reversible and isothermal condensation (in a condenser); and
- 4-2 Isentropic compression (in a compressor).



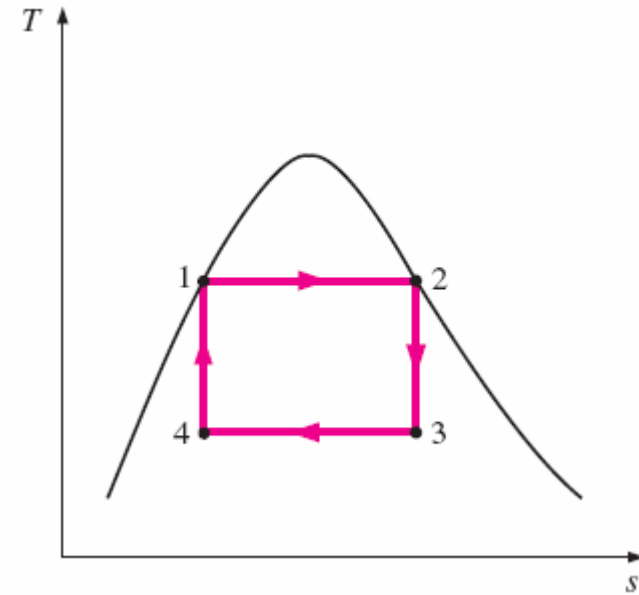
IS CARNOT CYCLE PRACTICAL?

The Carnot cycle is NOT a suitable model for actual power cycles because of several impracticalities associated with it:

Process 1-2 : Limiting the heat transfer processes to two-phase systems severely limits the maximum temperature that can be used in the cycle (374°C for water).

Process 2-3 : The turbine cannot handle steam with a high moisture content because of the impingement of liquid droplets on the turbine blades causing erosion and wear.

Process 4-1 : It is not practical to design a compressor that handles two phases.



THE IDEAL RANKINE CYCLE

- Many of the impracticalities associated with the Carnot cycle can be eliminated by:
 - superheating the steam in the boiler
 - condensing the steam **completely** in the condenser.
- The modified Carnot cycle is called the Rankine cycle, which is the ideal and practical cycle for vapor power plants
- This ideal cycle does not involve any internal irreversibilities.

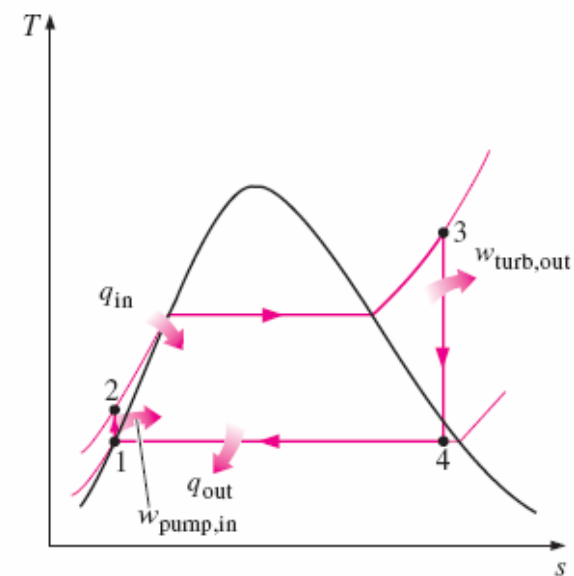
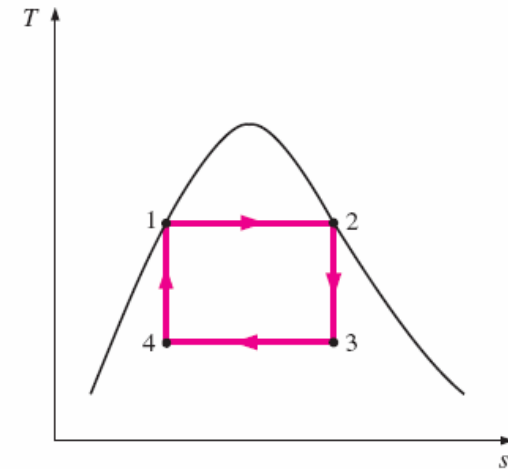


FIGURE 10-2

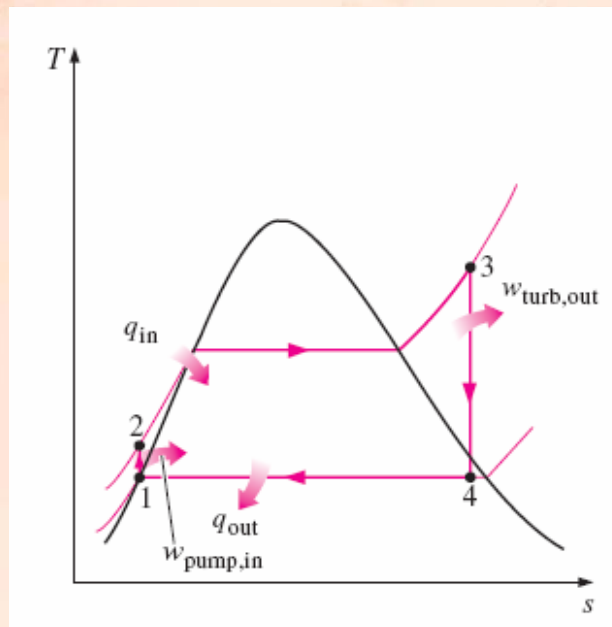
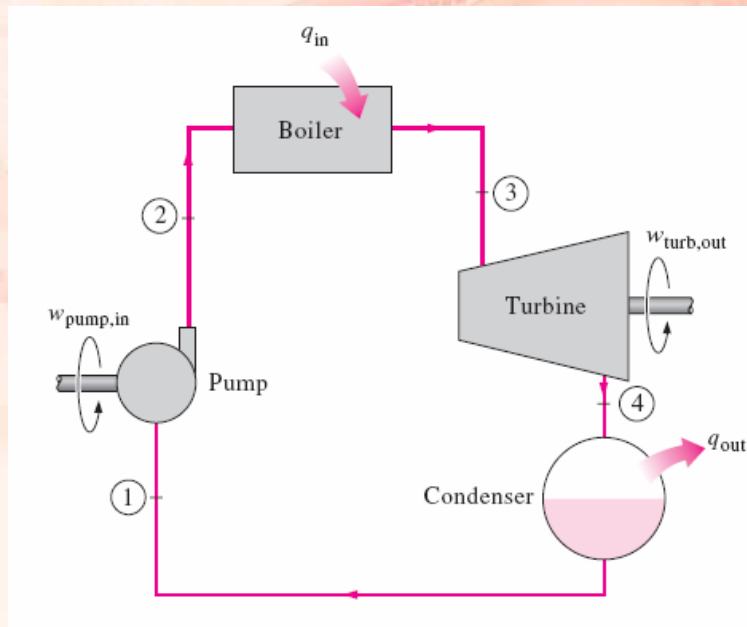
The simple ideal Rankine cycle.

THE IDEAL RANKINE CYCLE

Sequence of Processes

The ideal Rankine cycle consists of four processes:

- 1-2 Isentropic compression in a water 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.

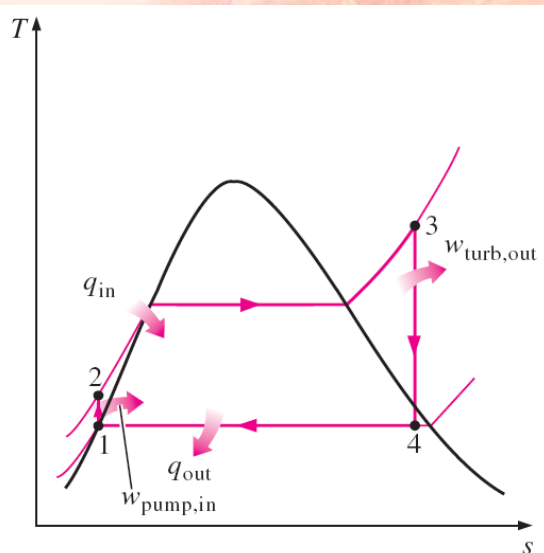


THE RANKINE CYCLE

Energy Analysis of Ideal Rankine Cycle

- The pump, boiler, turbine, and condenser are steady-flow devices. Thus the ideal Rankine cycle can be analyzed as steady-flow processes.
- The kinetic and potential energy changes of the steam are usually small. Thus the Steady-flow Energy Equation per unit mass of steam reduces to:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$



Energy Interactions

The boiler and condenser do not involve any work but both involve with heat interactions.

The pump and the turbine are assumed to be isentropic and both involve work interactions.

THE RANKINE CYCLE

Energy Interactions in Each Device

Pump: The work needed to operate the water pump,

$$w_{pump} = h_2 - h_1 = v(P_2 - P_1)$$

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

Boiler: The amount of heat supplied in the steam boiler,

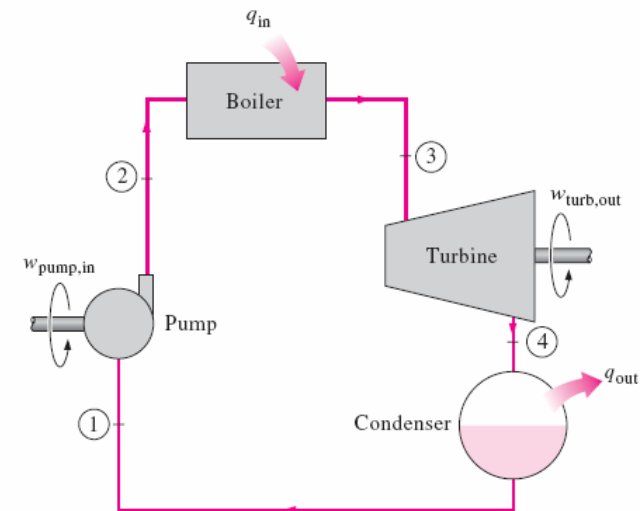
$$q_{in} = h_3 - h_2$$

Turbine: The amount of work produced by the turbine,

$$w_{turb} = h_3 - h_4$$

Condenser: The amount of heat rejected from condenser,

$$q_{out} = h_4 - h_1$$



THE RANKINE CYCLE

Performance of Ideal Rankine Cycle

Thermal Efficiency

The thermal efficiency of the Rankine cycle is determined from,

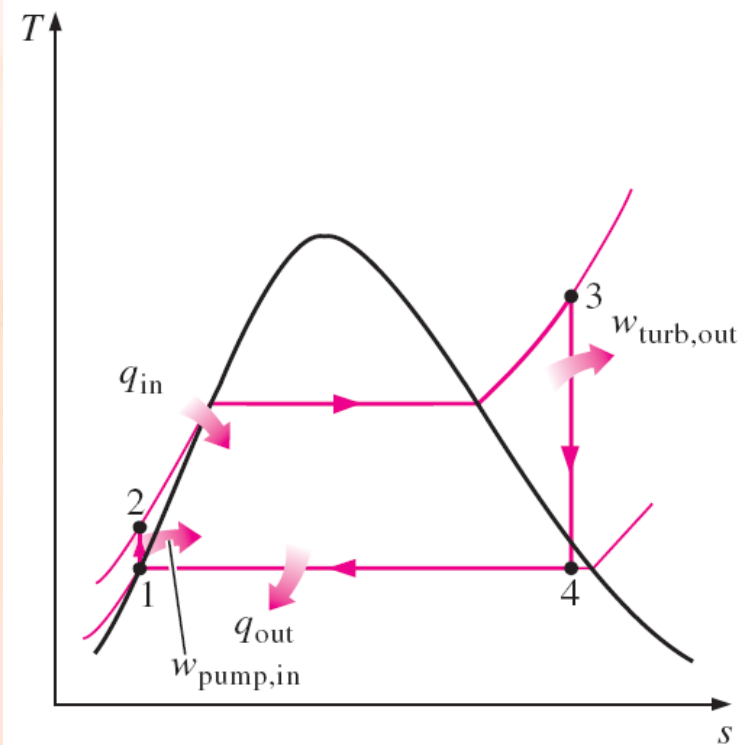
$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

where the net work output,

$$w_{net} = q_{in} - q_{out} = w_{turb} - w_{pump}$$

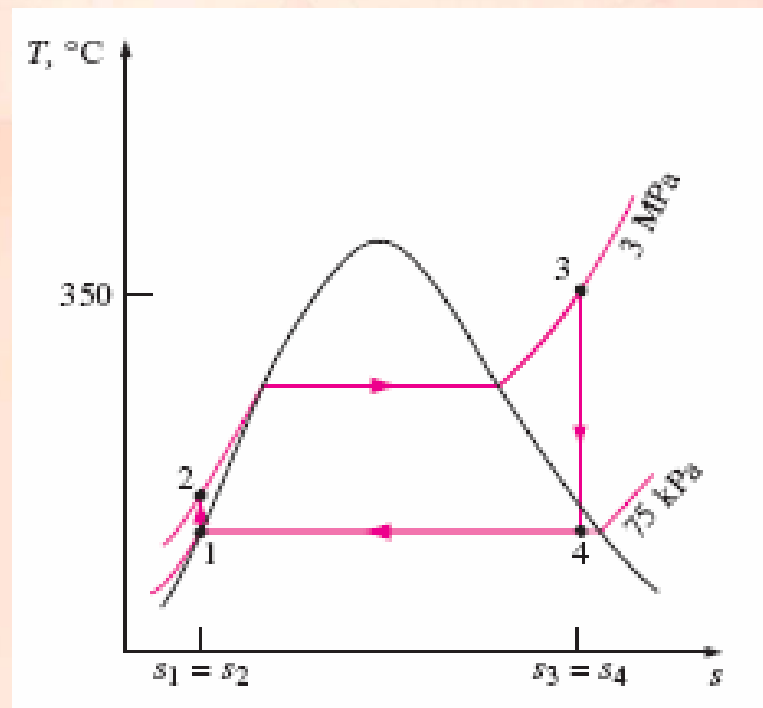
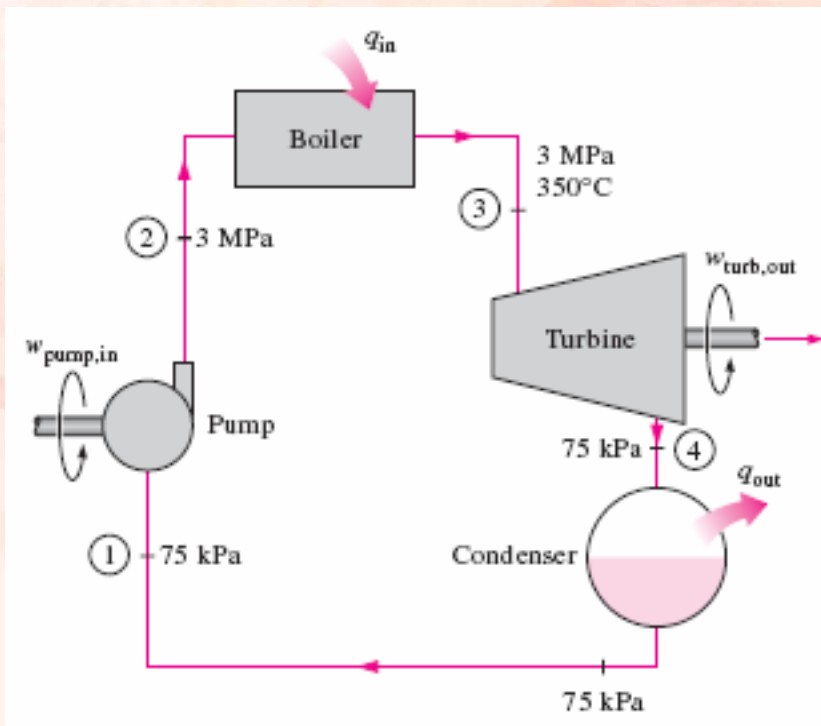
Note: +ve quantities only!

Thermal efficiency of Rankine cycle can also be interpreted as the ratio of the area enclosed by the cycle on a T - s diagram to the area under the heat-addition process.



EXAMPLE 10-1 Pg 569

Consider a steam power plant operating on the simple ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 75 kPa. Determine the thermal efficiency of this cycle.



EXAMPLE 10-1 Pg 569

$$\text{Thermal Efficiency, } \eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

$$\left. \begin{array}{l} P_1 = 75 \text{ kPa} \\ \text{Sat. Liquid} \end{array} \right\} \begin{array}{l} h_1 = h_f \text{ at } 75 \text{ kPa} = 384.44 \text{ kJ/kg} \\ v_1 = v_f \text{ at } 75 \text{ kPa} = 0.001037 \text{ m}^3 / \text{kg} \end{array}$$

$$W_{pump} = h_2 - h_1 = v(P_2 - P_1) = 0.001037(3000 - 75) = 3.03 \text{ kJ/kg}$$

$$h_2 = 3.03 + 384.44 \text{ kJ/kg} = 387.47 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 3 \text{ MPa} \\ T_3 = 350^\circ\text{C} \end{array} \right\} \begin{array}{l} h_3 = 3116.1 \text{ kJ/kg} \\ s_3 = 6.7450 \text{ kJ/kgK} = s_4 \end{array}$$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.7450 - 1.2132}{6.2426} = 0.8861$$

$$\begin{aligned} h_4 &= h_f + x_4 h_{fg} = 384.44 + 0.8861(2278.0) \\ &= 2403.0 \text{ kJ/kg} \end{aligned}$$

$$\eta_{th} = \frac{(3116.1 - 2403.0) - 3.03}{3116.1 - 387.47} = 0.260 \text{ or } 26.0\%$$

$$\begin{aligned} \eta_{th, \text{carnot}} &= 1 - \frac{T_{min}}{T_{max}} \\ &= 1 - \frac{(91.76 + 273)}{350 + 273} \\ &= 0.415 \text{ or } 41.5\% \end{aligned}$$

THE RANKINE CYCLE

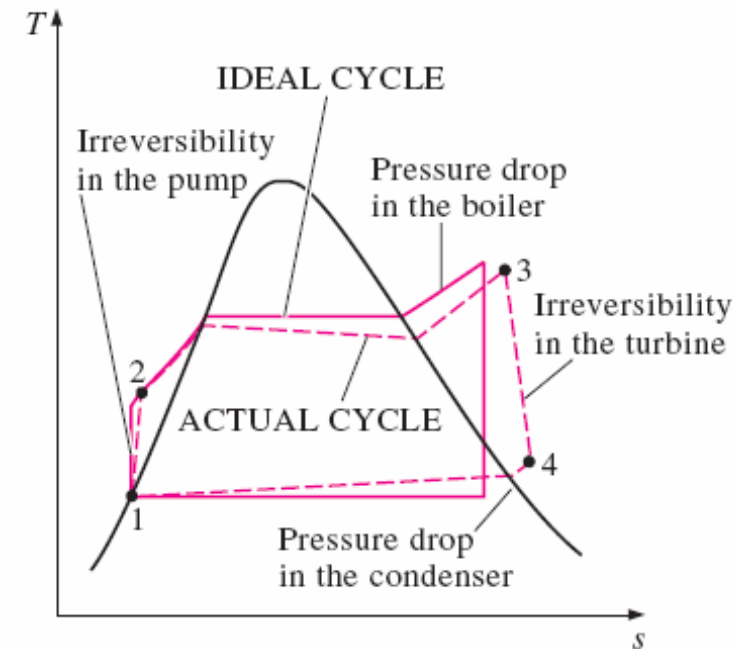
Actual Vapor Power Cycles

The actual vapor power cycle differs from the ideal Rankine cycle as a result of **irreversibilities** in various components. Two common sources of irreversibilities are: **(a) fluid friction, and (b) heat loss to the surroundings.**

Fluid friction causes pressure drops in the boiler, condenser, and the piping between various components. Water must be pumped to a **higher pressure** - requires a larger pump and larger work input.

More heat needs to be transferred to the steam in the boiler to compensate for the undesired heat losses from the steam to the surroundings.

As a result, the cycle thermal efficiency decreases.



(a)

FIGURE 10-4

(a) Deviation of actual vapor power cycle from the ideal Rankine cycle.

THE RANKINE CYCLE

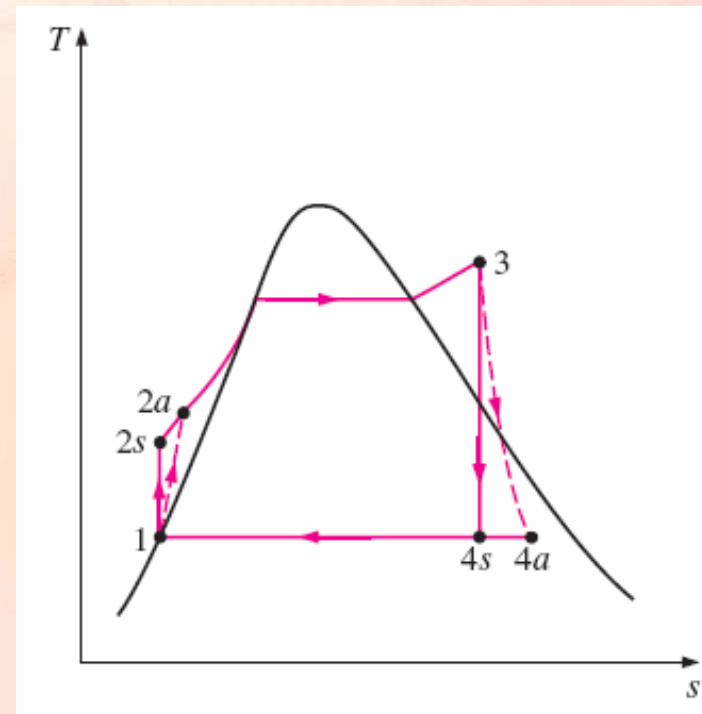
Isentropic Efficiencies

A pump requires a greater work input, and a turbine produces a smaller work output as a result of irreversibilities.

The deviation of actual pumps and turbines from the isentropic ones can be accounted for by utilizing isentropic efficiencies, defined as,

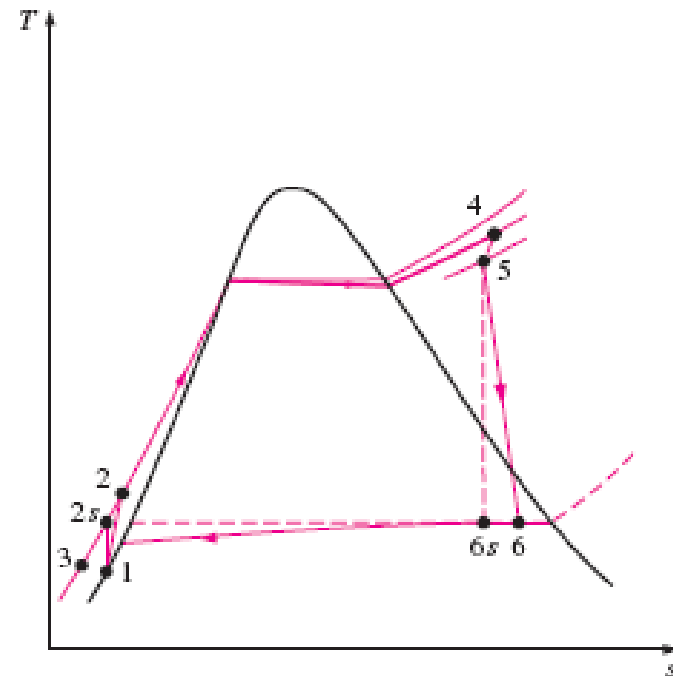
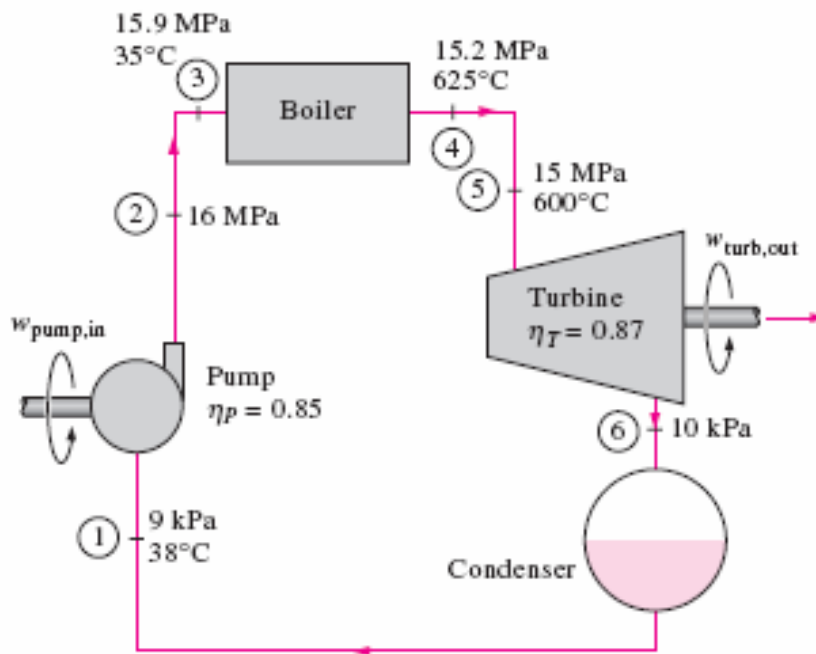
$$\text{Pump: } \eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

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



EXAMPLE 10-2 Pg 573

A steam power plant operates on the Rankine cycle. 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.



EXAMPLE 10-2 Pg 573

$$W_{pump} = \frac{W_{s,pump}}{\eta_P} = \frac{\nu(P_2 - P_1)}{0.85} = \frac{0.001009(16000 - 9)}{0.85} = 19.0 \text{ kJ/kg}$$

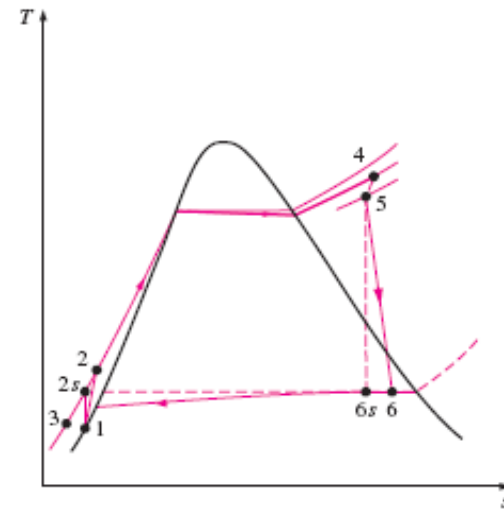
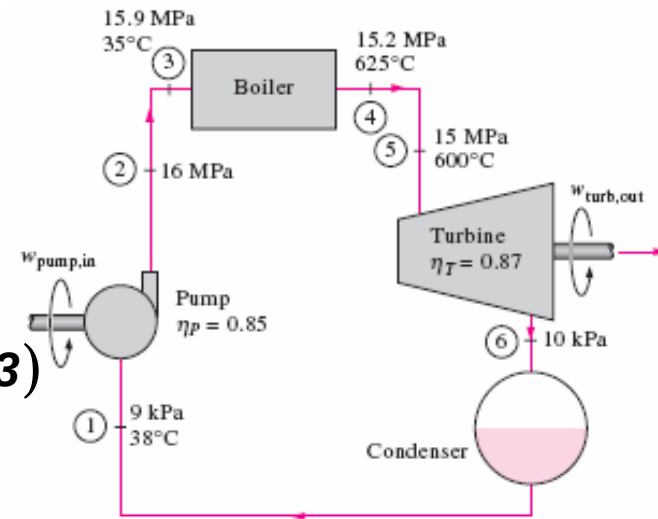
$$W_{turb} = \eta_T W_{s,turb} = \eta_T (h_5 - h_{6s}) = 0.87(3583.1 - 2115.3) = 1277.0 \text{ kJ/kg}$$

$$q_{in} = h_4 - h_3 = 3647.6 - 160.1 = 3487.5 \text{ kJ/kg}$$

$$W_{net} = W_{turb} - W_{pump} = 1277.0 - 19.0 = 1258.0 \text{ kJ/kg}$$

$$\eta_{th} = \frac{W_{net}}{q_{in}} = \frac{1258.0}{3487.5} = 0.361 \text{ or } 36.1\%$$

$$\dot{W}_{net} = \dot{m} W_{net} = 15(1258.0) = 18.9 \text{ MW}$$



THE RANKINE CYCLE

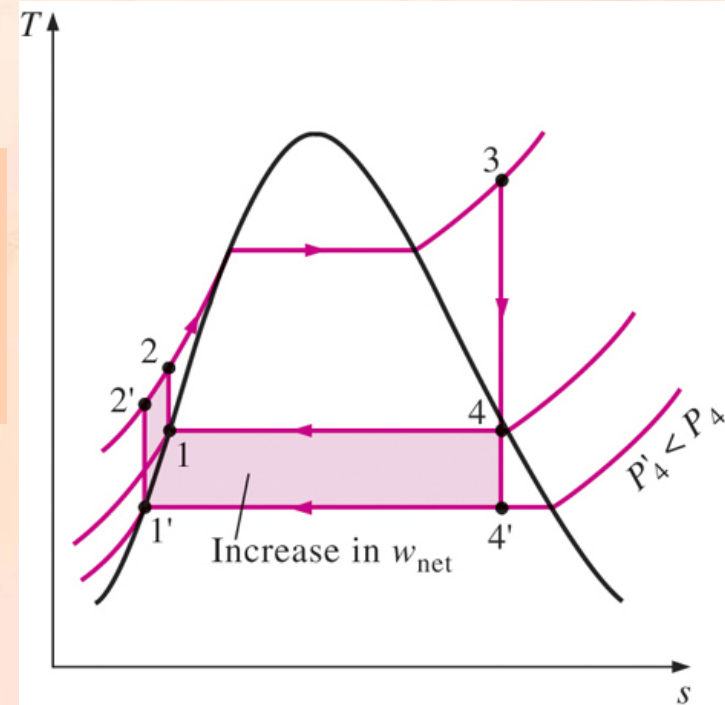
Increasing Efficiency of Rankine Cycle

Thermal efficiency of the ideal Rankine cycle can be increased by:

- Increasing the average temperature at which heat is transferred to the working fluid in the boiler, or
- decreasing the average temperature at which heat is rejected from the working fluid in the condenser.

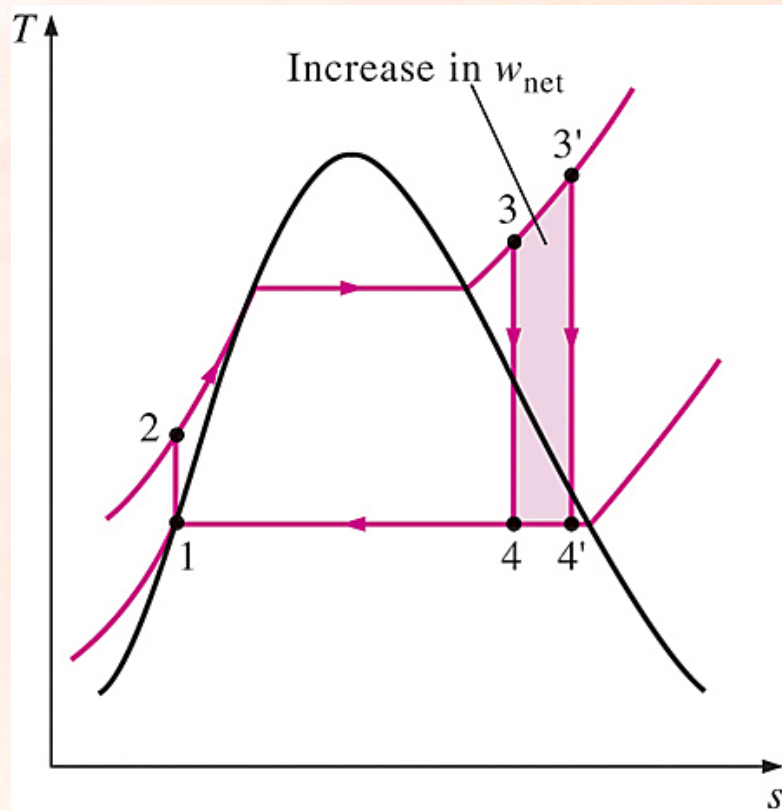
Lowering the Condenser Pressure

Side effect: Lowering the condenser pressure increases the moisture content of the steam at the final stages of the turbine – can cause blade damage, decreasing isentropic efficiency.



THE RANKINE CYCLE

Superheating the Steam to High Temperatures



Superheating the steam increases both the net work output and heat input to the cycle. The overall effect is an increase in thermal efficiency of the cycle.

Superheating to higher temperatures will decrease the moisture content of the steam at the turbine exit, which is desirable – avoid erosion of turbine blades.

The superheating temperature is limited by metallurgical considerations. Presently the highest steam temperature allowed at the turbine inlet is about 620°C.

THE RANKINE CYCLE

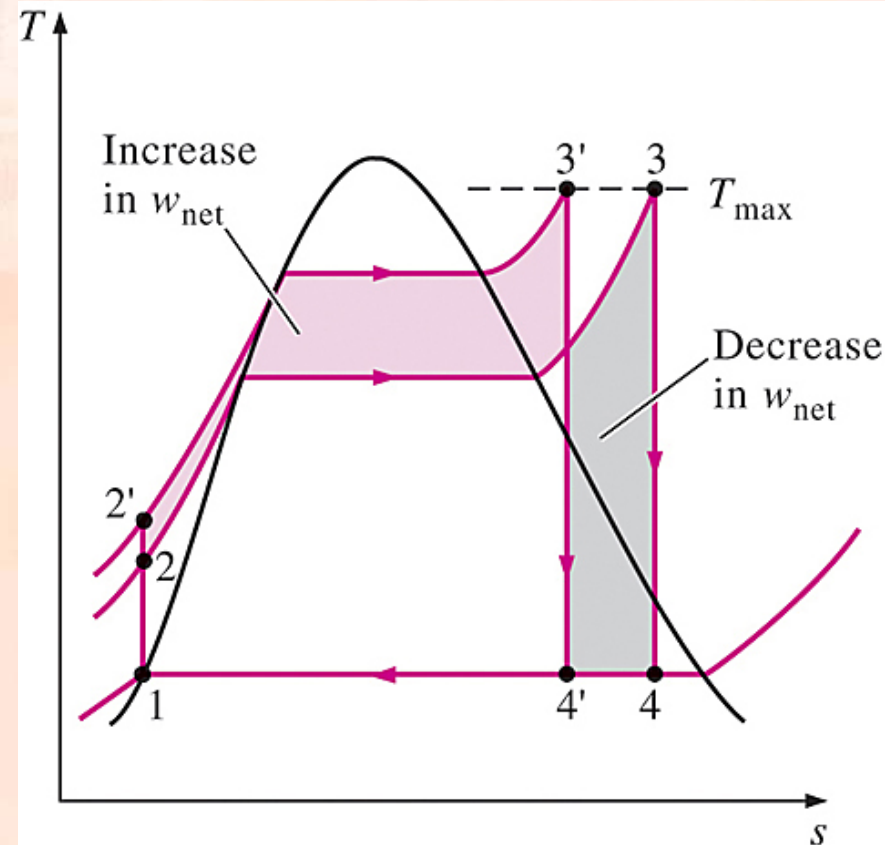
Increasing the Boiler Pressure

Increasing the boiler pressure raises the average temperature at which heat is transferred to the steam. This, in turns increases the **thermal efficiency** of the cycle.

Note:

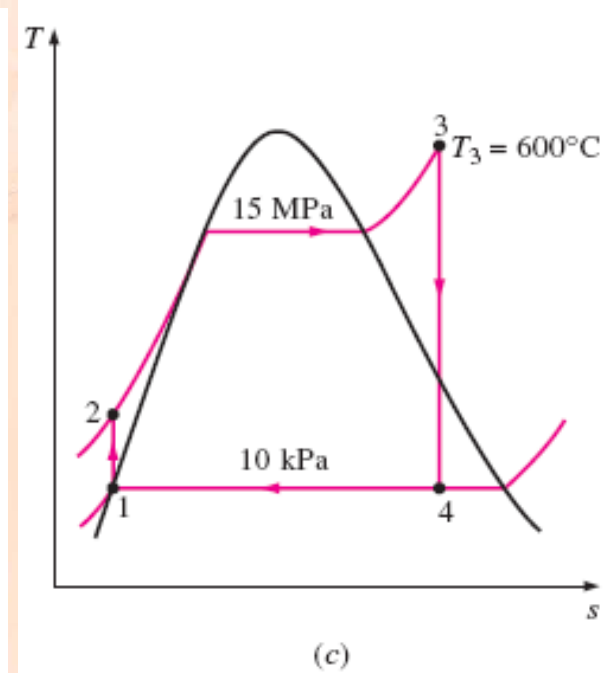
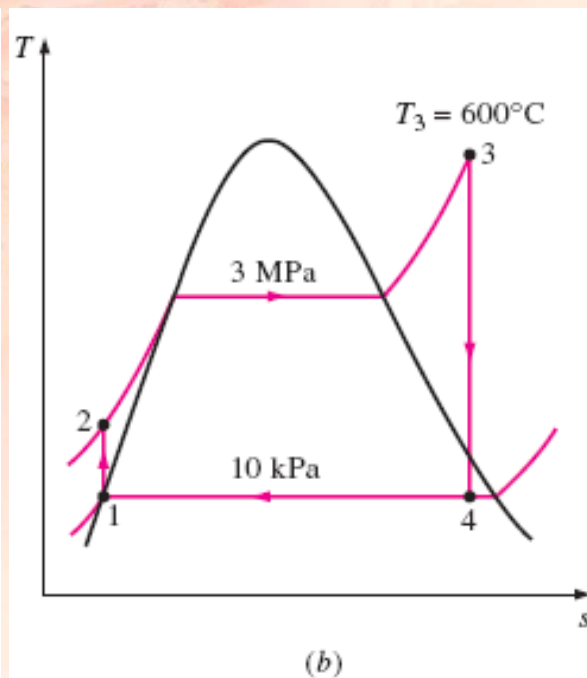
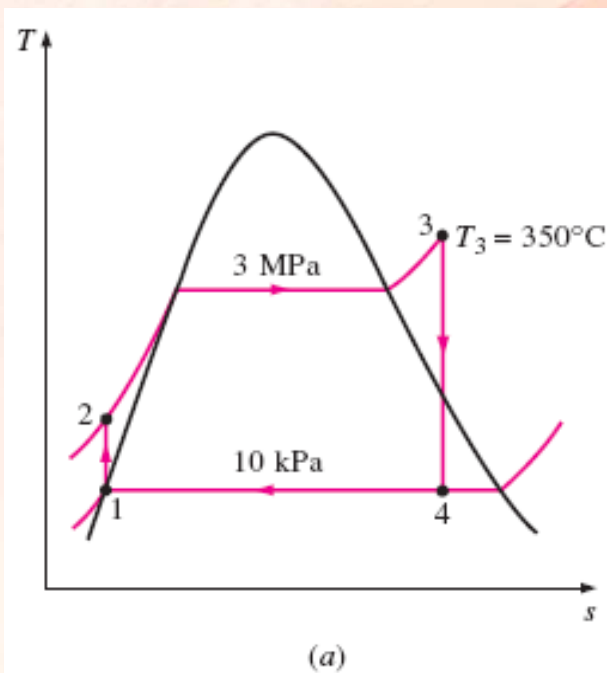
For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases.

This side effect can be corrected by reheating the steam.



EXAMPLE 10-3 Pg 562

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 turbine inlet temperature is maintained at 600°C.



EXAMPLE 10-3 Pg 562

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$$\left. \begin{array}{l} P_1 = 10 \text{ kPa} \\ \text{Sat. Liquid} \end{array} \right\} \begin{array}{l} h_1 = h_f \text{ at } 10 \text{ kPa} = 191.81 \text{ kJ/kg} \\ v_1 = v_f \text{ at } 10 \text{ kPa} = 0.00101 \text{ m}^3 / \text{kg} \end{array}$$

$$W_{\text{pump}} = h_2 - h_1 = v(P_2 - P_1) = 0.001017(3000 - 105) = 3.02 \text{ kJ/kg}$$

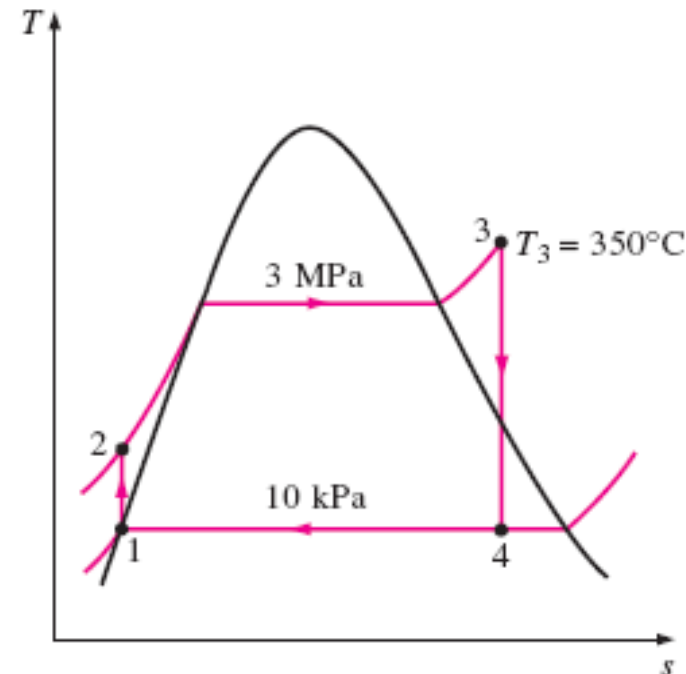
$$h_2 = 3.02 + 191.81 \text{ kJ/kg} = 198.83 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 3 \text{ MPa} \\ T_3 = 350^\circ\text{C} \end{array} \right\} \begin{array}{l} h_3 = 3116.1 \text{ kJ/kg} \\ s_3 = 6.7450 \text{ kJ/kgK} = s_4 \end{array}$$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.7450 - 0.6492}{7.4996} = 0.8128$$

$$\begin{aligned} h_4 &= h_f + x_4 h_{fg} = 191.81 + 0.8128(2391.1) \\ &= 2136.3 \text{ kJ/kg} \end{aligned}$$

$$\eta_{\text{th}} = \frac{(3116.1 - 2136.3) - 3.02}{3116.1 - 191.81} = 0.334 \text{ or } 33.4\%$$



(a)

EXAMPLE 10-3 Pg 562

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$$\left. \begin{array}{l} P_1 = 10 \text{ kPa} \\ \text{Sat. Liquid} \end{array} \right\} \begin{array}{l} h_1 = h_f \text{ at } 10 \text{ kPa} = 191.81 \text{ kJ/kg} \\ v_1 = v_f \text{ at } 10 \text{ kPa} = 0.00101 \text{ m}^3 / \text{kg} \end{array}$$

$$W_{\text{pump}} = h_2 - h_1 = v(P_2 - P_1) = 0.00101(3000 - 105) = 3.02 \text{ kJ/kg}$$

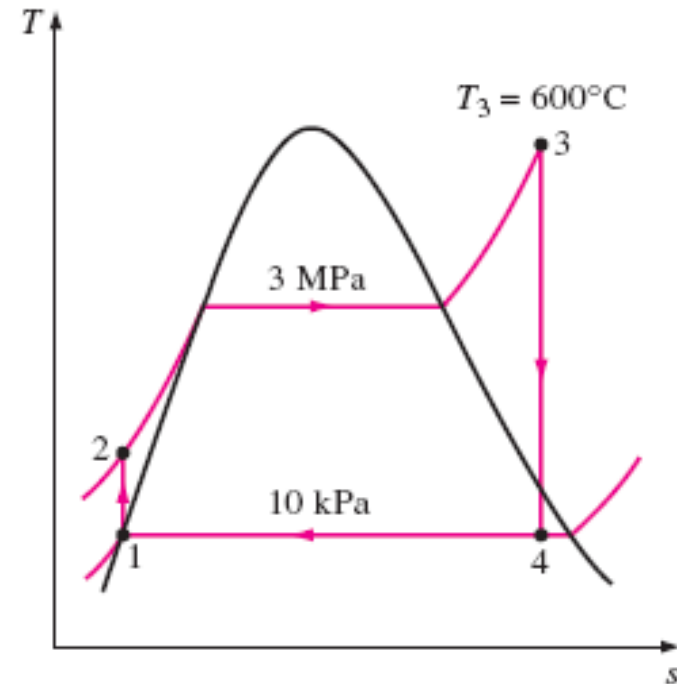
$$h_2 = 3.02 + 191.81 \text{ kJ/kg} = 198.83 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 3 \text{ MPa} \\ T_3 = 600^\circ\text{C} \end{array} \right\} \begin{array}{l} h_3 = 3682.8 \text{ kJ/kg} \\ s_3 = s_4 \end{array}$$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = 0.915$$

$$\begin{aligned} h_4 &= h_f + x_4 h_{fg} = 191.81 + 0.915(2391.1) \\ &= 2380.3 \text{ kJ/kg} \end{aligned}$$

$$\eta_{\text{th}} = \frac{(3682.8 - 2380.3) - 3.02}{3682.8 - 191.81} = 0.373 \text{ or } 37.3\%$$



(b)

EXAMPLE 10-3 Pg 562

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$$\left. \begin{array}{l} P_1 = 10 \text{ kPa} \\ \text{Sat. Liquid} \end{array} \right\} \begin{array}{l} h_1 = h_f \text{ at } 10 \text{ kPa} = 191.81 \text{ kJ/kg} \\ v_1 = v_f \text{ at } 10 \text{ kPa} = 0.00101 \text{ m}^3 / \text{kg} \end{array}$$

$$w_{\text{pump}} = h_2 - h_1 = v(P_2 - P_1) = 0.00101(15000 - 10) = 15.14 \text{ kJ/kg}$$

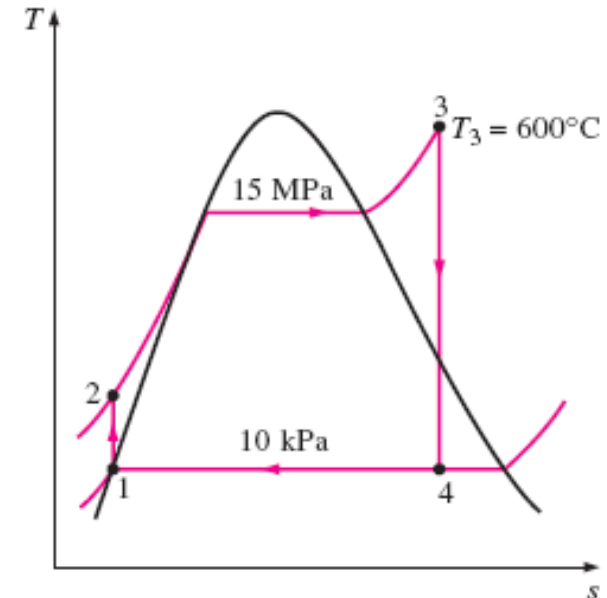
$$h_2 = 15.14 + 191.81 \text{ kJ/kg} = 206.95 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 15 \text{ MPa} \\ T_3 = 600^\circ\text{C} \end{array} \right\} \begin{array}{l} h_3 = 3583.1 \text{ kJ/kg} \\ s_3 = s_4 \end{array}$$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = 0.804$$

$$\begin{aligned} h_4 &= h_f + x_4 h_{fg} = 191.81 + 0.804(2391.1) \\ &= 2115.3 \text{ kJ/kg} \end{aligned}$$

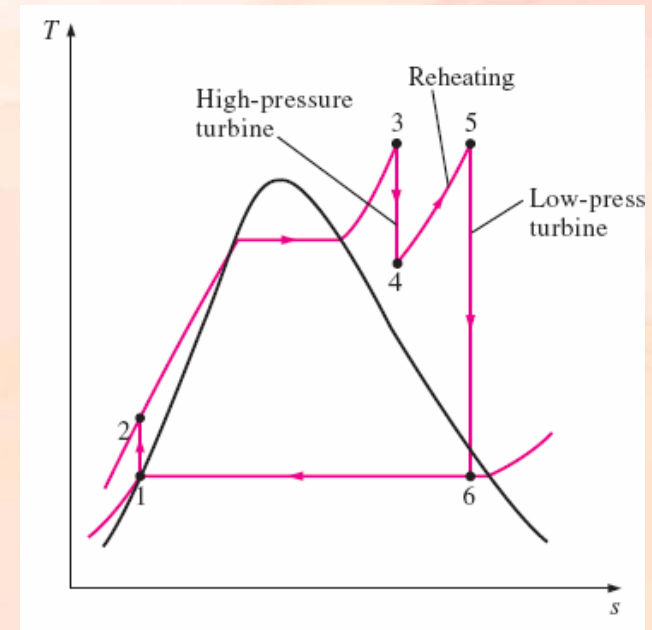
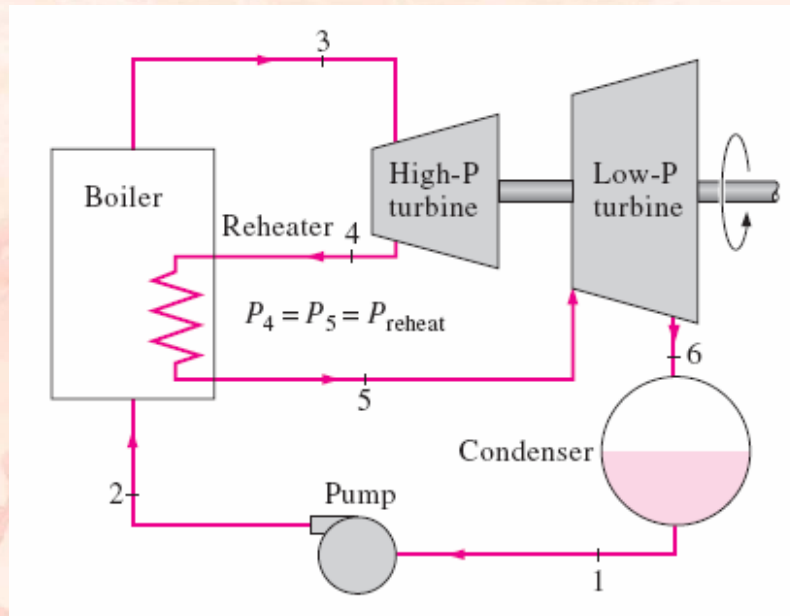
$$\eta_{\text{th}} = \frac{(3583.1 - 2115.3) - 15.14}{3583.1 - 191.81} = 0.430 \text{ or } 43.0\%$$



(c)

IDEAL REHEAT RANKINE CYCLE

Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants. This is done by expanding the steam in two-stage turbine, and reheat the steam in between the stages.



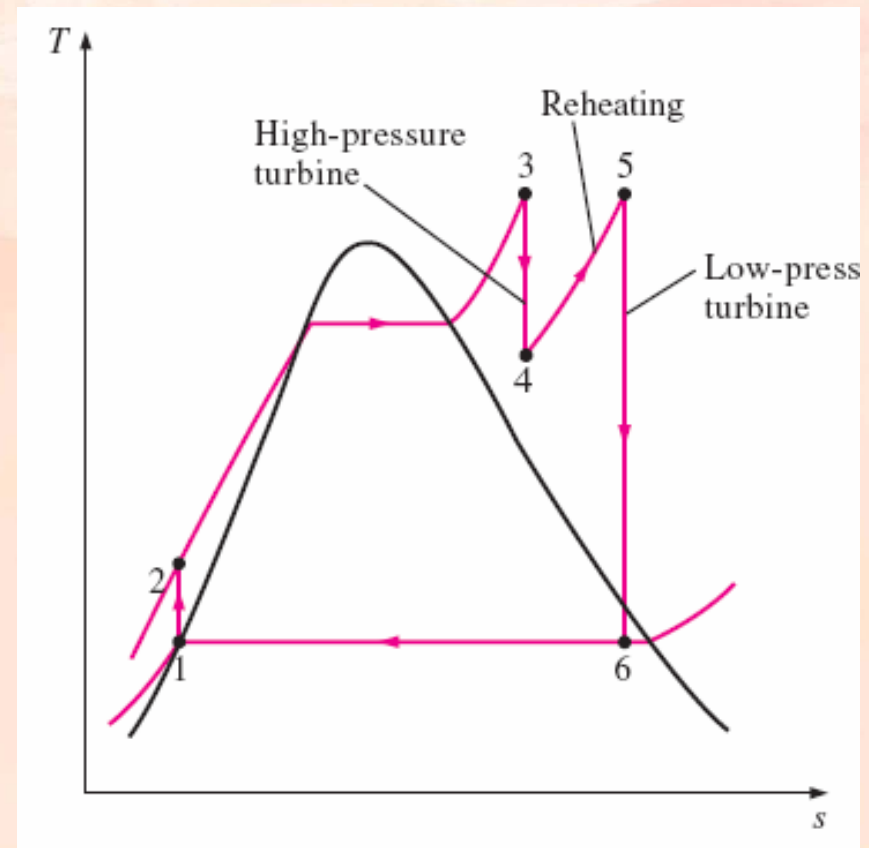
Note: Incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 ~ 5 percent.

IDEAL REHEAT REAKINE CYCLE

With a single reheating process, the total heat input and the total turbine work output for the ideal cycle become,

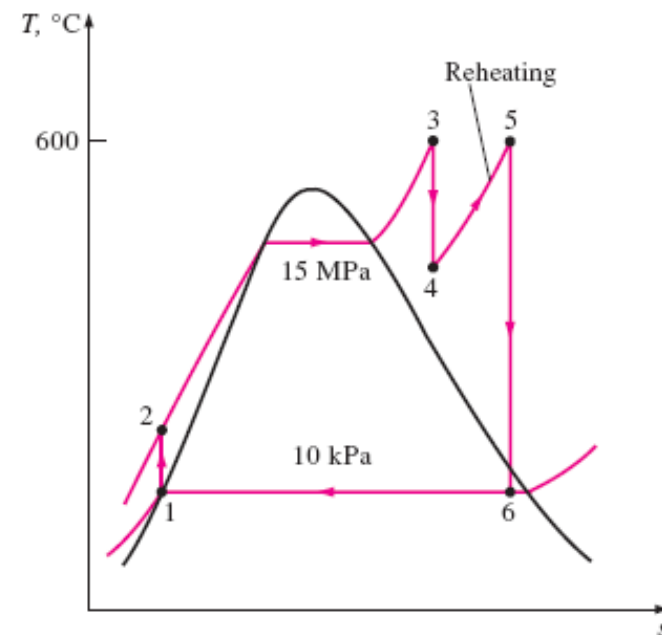
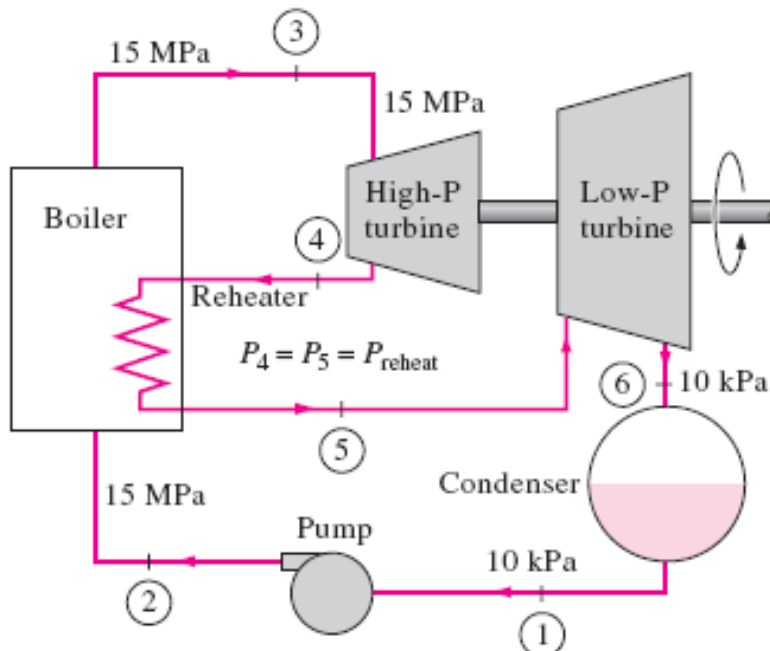
$$\begin{aligned} W_{turb} &= W_{turb,I} + W_{turb,II} \\ &= (h_3 - h_4) + (h_5 - h_6) \end{aligned}$$

$$\begin{aligned} q_{in} &= q_{primary} + q_{reheat} \\ &= (h_3 - h_2) + (h_5 - h_4) \end{aligned}$$



EXAMPLE 10-3 Pg 562

Consider a steam power plant operating on the ideal Rankine cycle. Steam enters the turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. If the moisture contents of the steam at the exit of the low pressure turbine is not 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.



EXAMPLE 10-3 Pg 562

- a) The moisture contents at state 6 should be less than 10.4, so the quality of steam at state 6 is 0.896

$$s_6 = s_f + x_6 s_{fg} = 0.6492 + 0.896(7.4996) = 7.3688 \text{ kJ/kg} = s_5$$

$$h_6 = h_f + x_6 h_{fg} = 191.81 + 0.896(2392.1) = 2335.1 \text{ kJ/kg}$$

$$\left. \begin{array}{l} T_5 = 600^\circ\text{C} \\ s_5 = s_6 \end{array} \right\} \begin{array}{l} P_5 = 4.0 \text{ MPa} \\ h_5 = 3674.9 \text{ kJ/kg} \end{array}$$

$$s_5 = s_6 \quad \int h_5 = 3674.9 \text{ kJ/kg}$$

- $$\text{b) } \left. \begin{array}{l} P_1 = 10 \text{ kPa} \\ \text{Sat. Liquid} \end{array} \right\} \begin{array}{l} h_1 = h_f \text{ at } 10 \text{ kPa} = 191.81 \text{ kJ/kg} \\ v_1 = v_f \text{ at } 10 \text{ kPa} = 0.00101 \text{ m}^3 / \text{kg} \end{array}$$

$$w_{pump} = h_2 - h_1 = v(P_2 - P_1) = 0.00101(15000 - 10) = 15.14 \text{ kJ/kg}$$

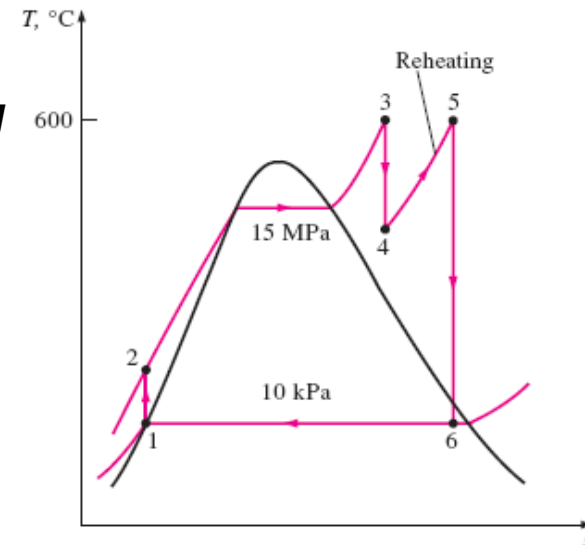
$$h_2 = 15.14 + 191.81 \text{ kJ/kg} = 206.95 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 15 \text{ MPa} \\ T_3 = 600^\circ\text{C} \end{array} \right\} \begin{array}{l} h_3 = 3583.1 \text{ kJ/kg} \\ s_3 = 6.6796 \text{ kJ/kgK} \end{array}$$

$$T_3 = 600^\circ\text{C} \quad \int s_3 = 6.6796 \text{ kJ/kgK}$$

$$\left. \begin{array}{l} P_4 = 4 \text{ MPa} \\ s_4 = s_3 \end{array} \right\} \begin{array}{l} h_4 = 3155.0 \text{ kJ/kg} \\ T_4 = 375.5^\circ\text{C} \end{array}$$

$$s_4 = s_3 \quad \int T_4 = 375.5^\circ\text{C}$$

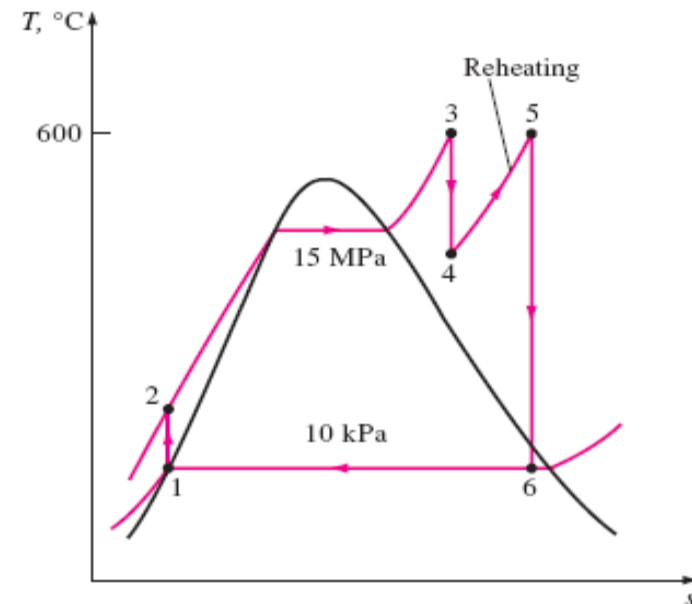


EXAMPLE 10-3 Pg 562

$$\begin{aligned} q_{in} &= (h_3 - h_2) + (h_5 - h_4) \\ &= (3583.1 - 206.95) + (3674.9 - 3155.0) \\ &= 3896.1 \text{ kJ/kg} \end{aligned}$$

$$q_{out} = h_6 - h_1 = 2335.1 - 191.81 = 2143.3 \text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2143.3}{3896.1} = 0.450 \text{ or } 45.0\%$$





THE RANKINE CYCLE

Problem 3

Consider a steam power plant that operates on a reheat Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 500°C and the low-pressure turbine at 1 MPa and 500°C. Steam leaves the condenser as a saturated liquid at a pressure of 10 kPa. The isentropic efficiency of the turbine is 80 percent, and that of the pump is 95 percent. Show the cycle on a *T-s diagram* with respect to saturation lines, and determine:

- (a) the quality (or temperature, if superheated) of the steam at the turbine exit,
- (b) the thermal efficiency of the cycle, and
- (c) the mass flow rate of the steam.

Answers: (a) 88.1 °C, (b) 34.1 percent, (c) 62.7 kg/s



Problem 10-39

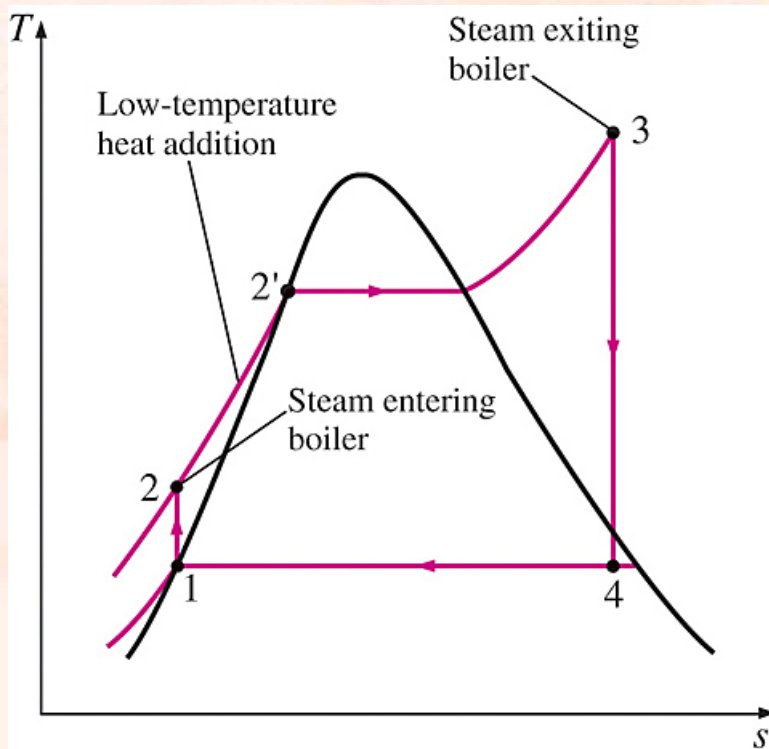
A steam power plant operates on the reheat Rankine cycle. Steam enters the high-pressure turbine at 12.5 MPa and 550°C at a rate of 7.7 kg/s and leaves at 2 MPa. Steam is then reheated at constant pressure to 450°C before it expands in the low-pressure turbine. The isentropic efficiencies of the turbine and the pump are 85 percent and 90 percent, respectively. Steam leaves the condenser as a saturated liquid. If the moisture content of the steam at the exit of the turbine is not to exceed 5 percent, determine:

- (a) the condenser pressure,
- (b) the net power output, and
- (c) the thermal efficiency.

Answers: (a) 9.73 kPa, (b) 10.2 MW, (c) 36.9 percent.

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.



Regeneration Process

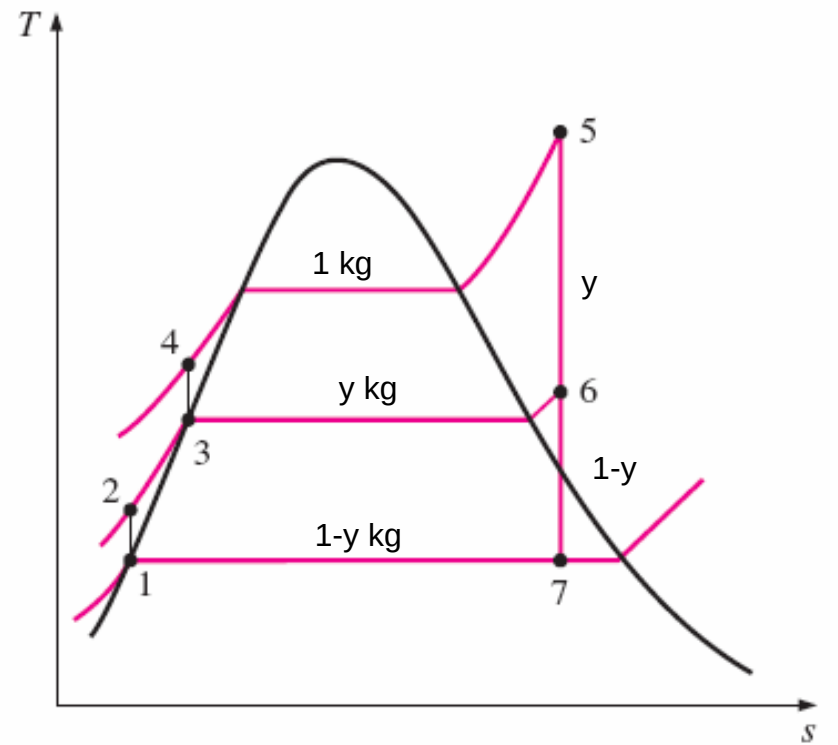
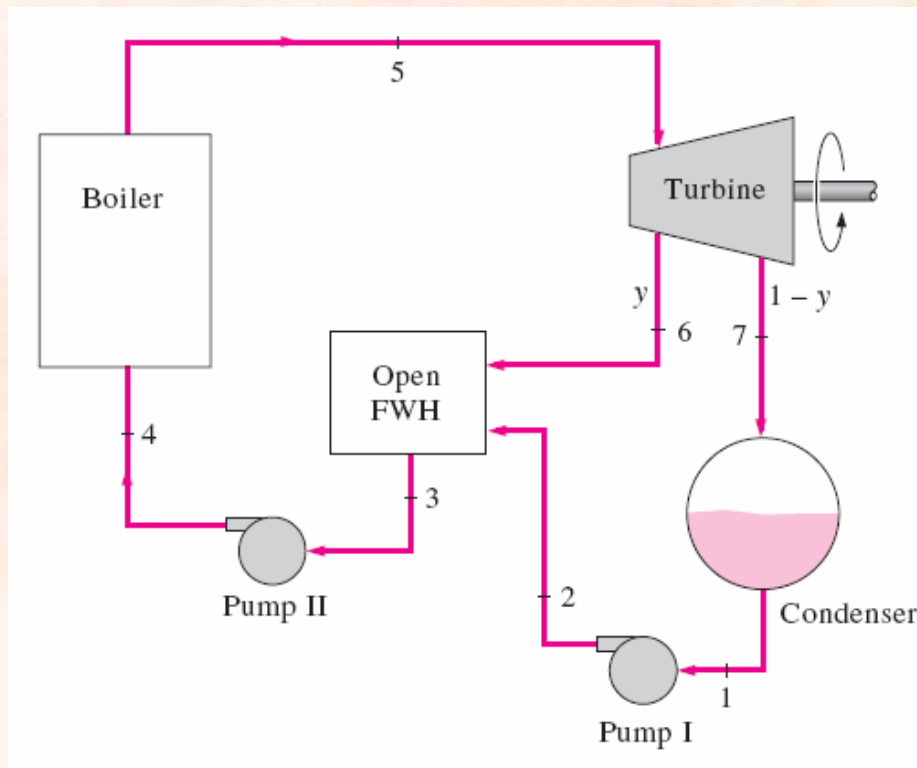
Steam is extracted from the turbine at various points, and is used to heat the feedwater, before it enters the boiler. The device where the feedwater is heated using the steam is called a regenerator, or a feedwater heater (FWH).

A feedwater heater is a heat exchanger where heat is transferred from the extracted steam to the feedwater either by: (a) mixing the two fluid streams (open FWH) or (b) without mixing them (closed FWH) – heat transfer from steam to feedwater.

IDEAL REGENERATIVE RANKINE CYCLE

Open Feedwater Heaters

An open FWH is a mixing chamber, where the steam extracted from the turbine (state 6) mixes with the feedwater exiting the pump (state 2). Ideally, the mixture leaves the heater as a saturated liquid (state 3) at the FWH's pressure.



IDEAL REGENERATIVE RANKINE CYCLE

Energy Analyses

The heat and work interactions in a regenerative Rankine cycle with one feedwater heater can be expressed (per unit mass of steam flowing through the boiler), as follows:

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

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

$$w_{turb} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

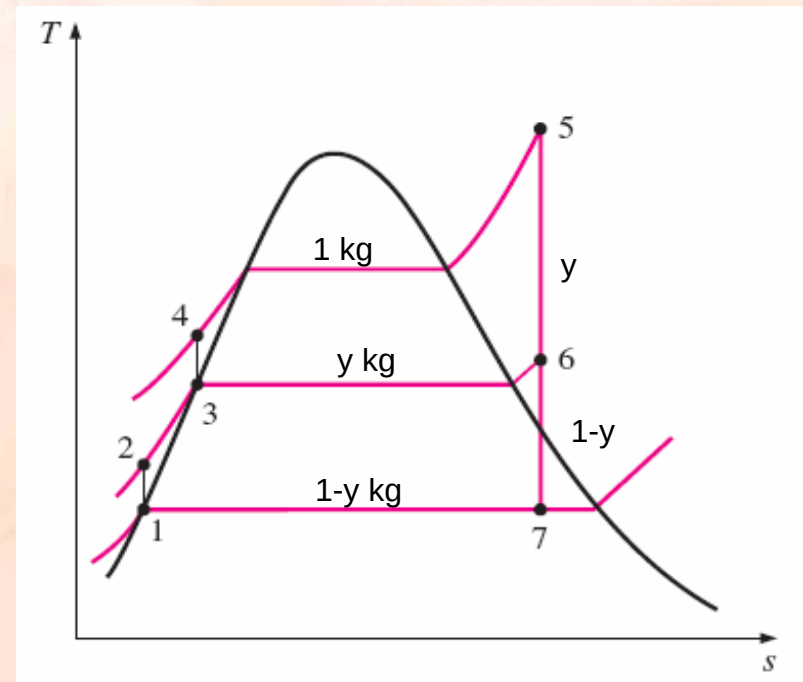
$$w_{pump} = (1 - y)w_{pump,I} + w_{pump,II}$$

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

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

Mass fraction of steam extracted from the turbine,

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



Note: The cycle efficiency increases further as the number of feedwater heaters is increased.

IDEAL REGENERATIVE RANKINE CYCLE

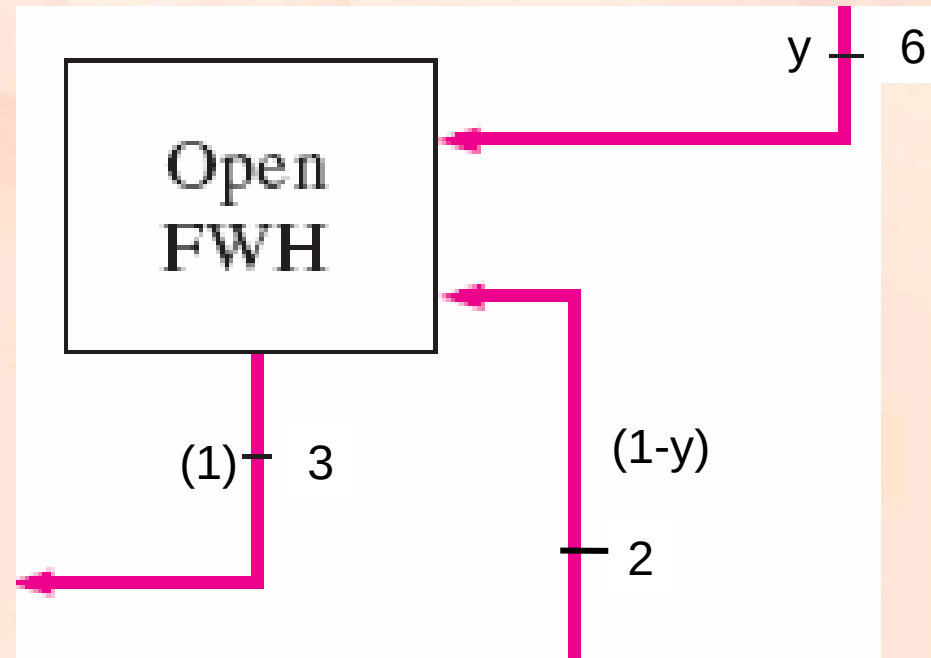
The mass of the steam extracted from the turbine, y , is determined by doing an energy balance on the feed-water heater.

$$\sum (m.h)_{in} = \sum (m.h)_{out}$$

$$(y) \cdot h_6 + (1 - y) \cdot h_2 = (1) \cdot h_3$$

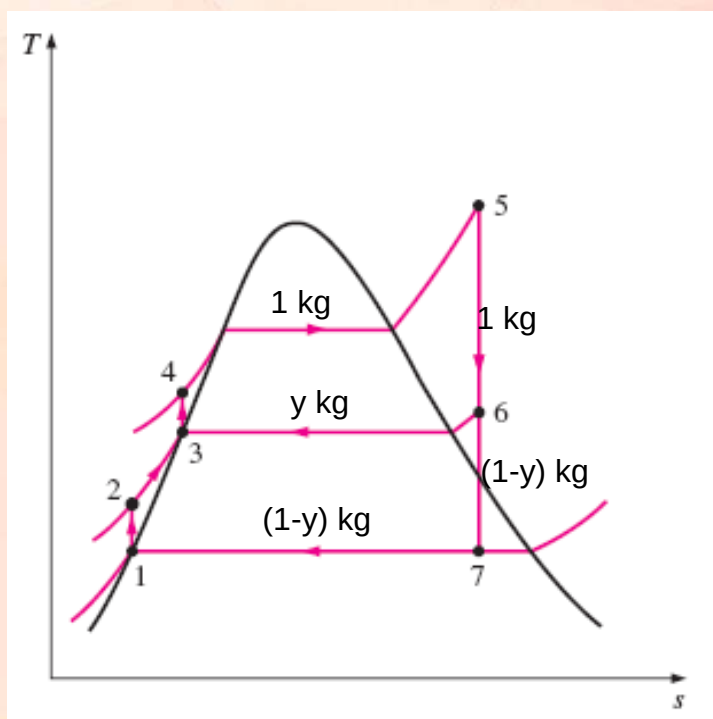
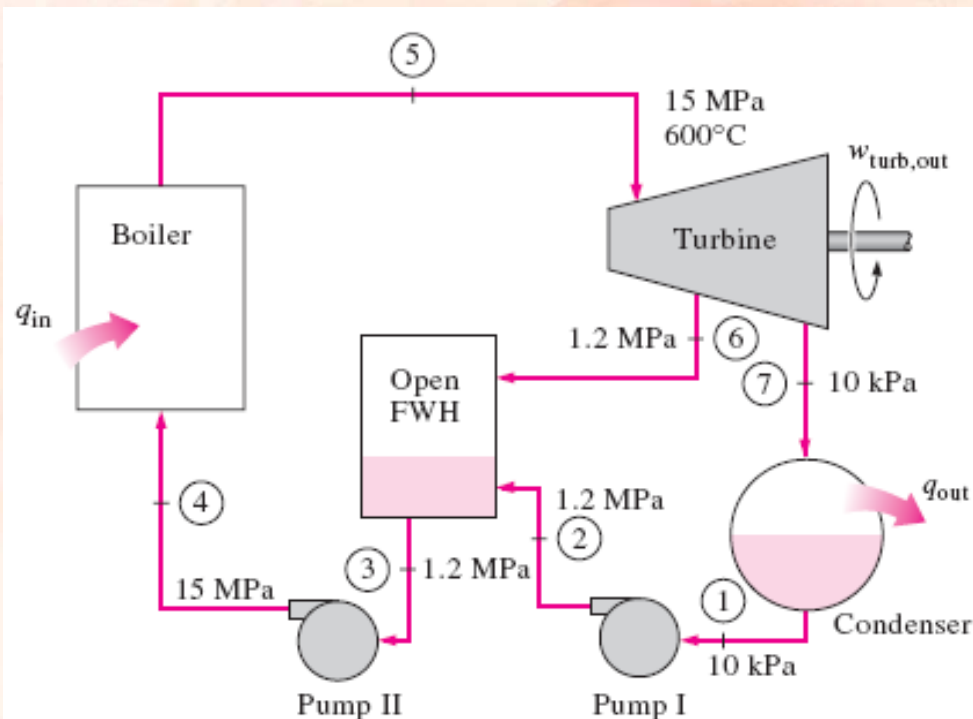
Solve to give,

$$y = \frac{(h_3 - h_2)}{(h_6 - h_2)}$$



EXAMPLE 10-5 Pg 585

Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feed water 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 feed water heater. Determine the fraction of steam extracted from the turbine and the thermal efficiency of the cycle.



EXAMPLE 10-5 Pg 585

$$\left. \begin{array}{l} P_1 = 10 \text{ kPa} \\ \text{Sat. Liquid} \end{array} \right\} \begin{array}{l} h_1 = h_f \text{ at } 10 \text{ kPa} = 191.81 \text{ kJ/kg} \\ v_1 = v_f \text{ at } 10 \text{ kPa} = 0.00101 \text{ m}^3 / \text{kg} \end{array}$$

$$w_{\text{pump.I}} = h_2 - h_1 = v(P_2 - P_1) = 0.00101(1200 - 10) = 1.20 \text{ kJ/kg}$$

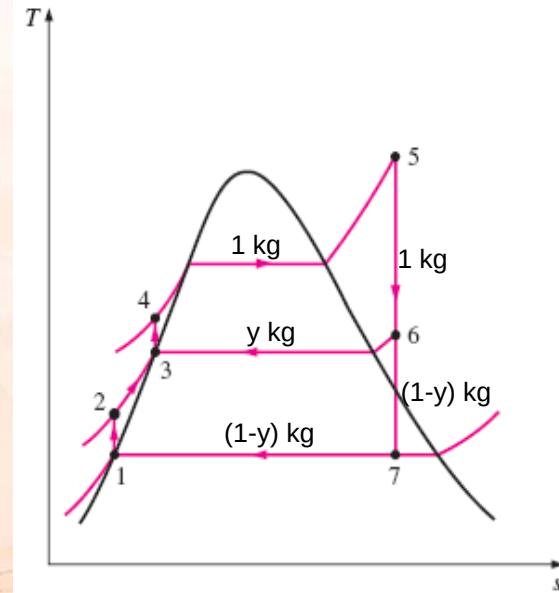
$$h_2 = 1.20 + 191.81 \text{ kJ/kg} = 193.01 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 1.2 \text{ MPa} \\ \text{Sat. Liquid} \end{array} \right\} \begin{array}{l} h_3 = h_f \text{ at } 1.2 \text{ MPa} = 798.33 \text{ kJ/kg} \\ v_3 = v_f \text{ at } 1.2 \text{ MPa} = 0.001138 \text{ m}^3 / \text{kg} \end{array}$$

$$w_{\text{pump.II}} = h_4 - h_3 = v_3(P_4 - P_3) = 0.001138(15000 - 1200) = 15.70 \text{ kJ/kg}$$

$$h_4 = 15.70 + 798.33 \text{ kJ/kg} = 814.03 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_5 = 15 \text{ MPa} \\ T_5 = 600^\circ\text{C} \end{array} \right\} \begin{array}{l} h_5 = 3583.1 \text{ kJ/kg} \\ s_5 = 6.6796 \text{ kJ/kgK} \end{array}$$



EXAMPLE 10-5 Pg 585

$$\left. \begin{aligned} P_6 &= 1.2 \text{ MPa} \\ s_6 &= s_5 = 6.6796 \text{ kJ/kgK} \end{aligned} \right\} \begin{aligned} h_6 &= 2860.2 \text{ kJ/kg} \\ (T_6 &= 218.4^\circ \text{C}) \end{aligned}$$

$$s_7 = s_6 = s_5 \rightarrow x_7 = \frac{s_7 - s_f}{s_{fg}} = \frac{6.6796 - 0.6492}{7.4996} = 0.8041$$

$$h_7 = h_f + x_7 h_{fg} = 191.81 + 0.8041(2392.1) = 2115.3 \text{ kJ/kg}$$

Energy balance,

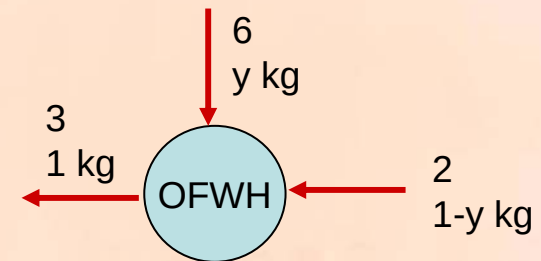
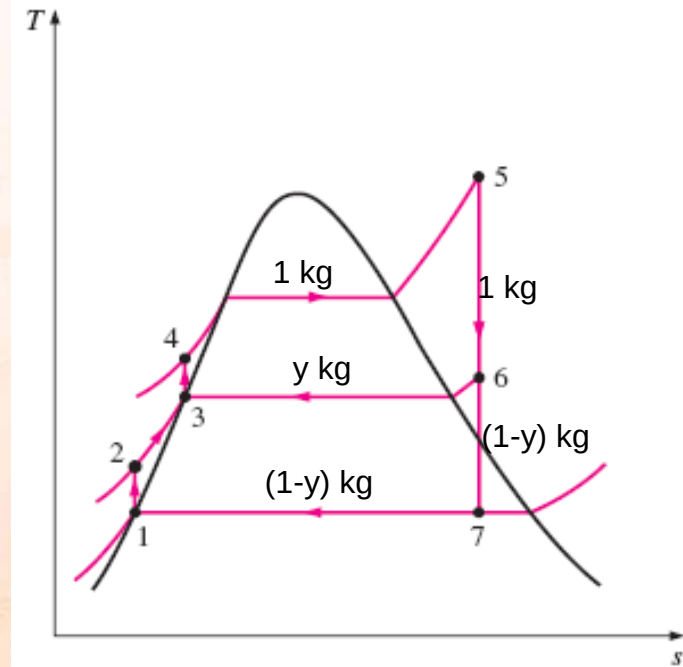
$$y h_6 + (1 - y) h_2 = 1(h_3)$$

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{798.33 - 193.01}{2860.2 - 193.01} = 0.227$$

$$q_{in} = h_5 - h_4 = (3583.1 - 814.03) = 2769.1 \text{ kJ/kg}$$

$$q_{out} = (1 - y)(h_7 - h_1) = (1 - 0.227)(2115.3 - 191.81)$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1486.9}{2769.1} = 0.463 \text{ or } 46.3\%$$





IDEAL REGENERATIVE RANKINE CYCLE

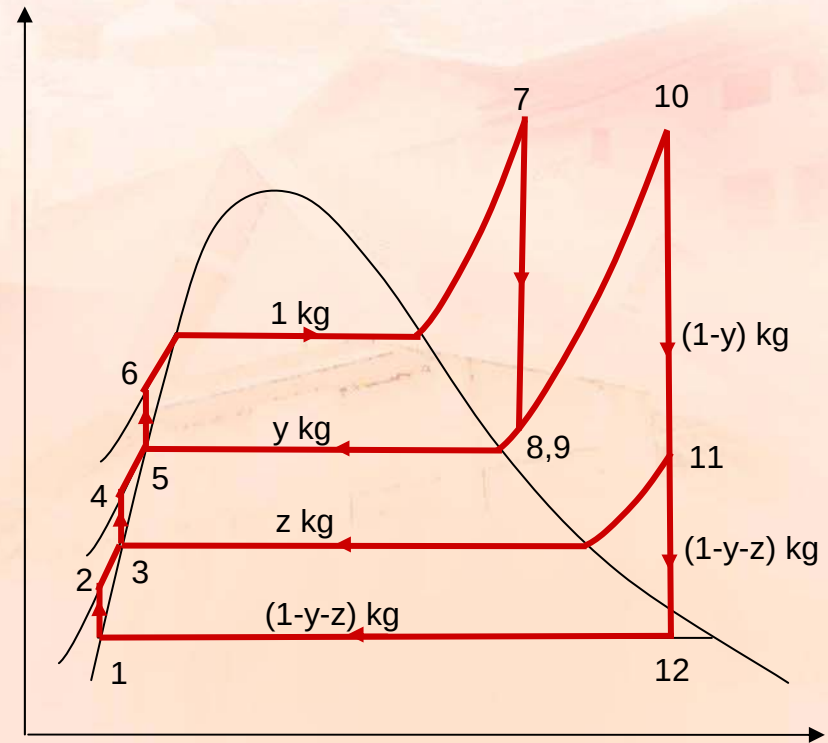
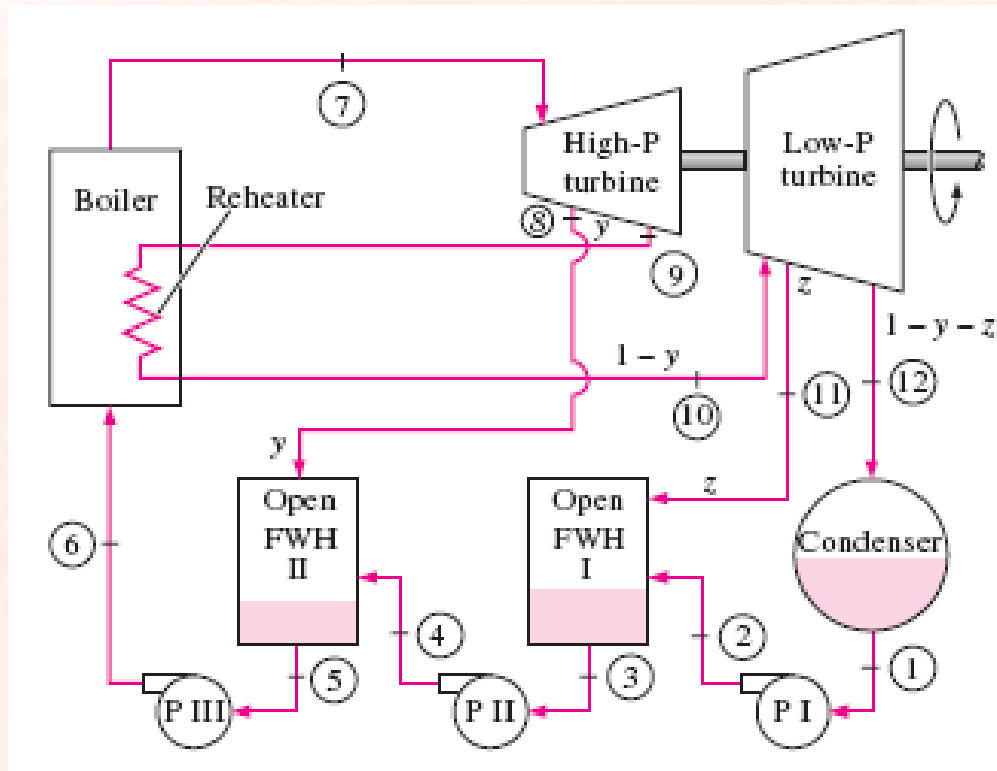
Problem 4

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 kg of steam flowing through the boiler, and
- (b) the thermal efficiency of the cycle.

Answers: (a) 1017 kJ/kg, (b) 37.8 percent

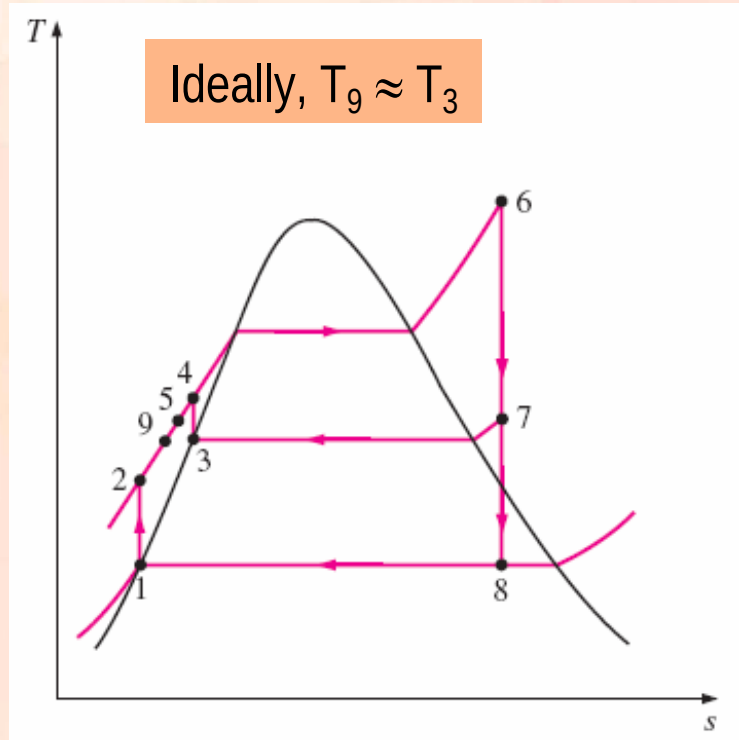
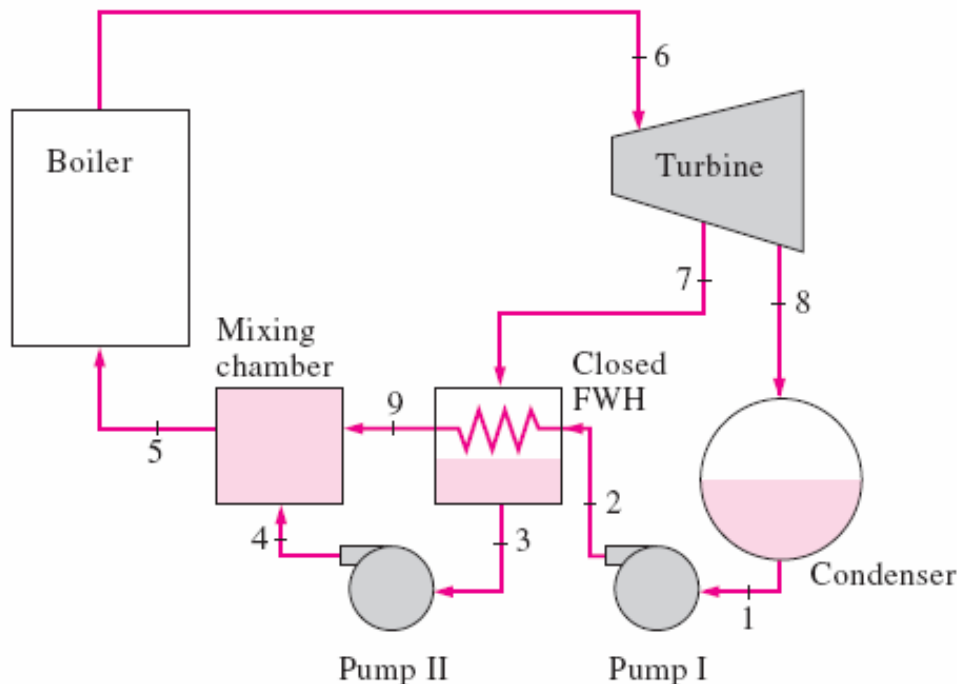
MULTIPLE OPEN FEED WATER HEATERS WITH REHEATER



IDEAL REGENERATIVE RANKINE CYCLE

Closed Feedwater Heater

In a closed feedwater heater, heat is transferred from the extracted steam (state 7) to the feedwater leaving the pump (state 2) without mixing. The two streams can be at different pressures ($P_7 \neq P_2$). The condensate (state 3) is pumped into a mixing chamber to mixed with the heated feedwater (state 9).





IDEAL REGENERATIVE RANKINE CYCLE

Problem 6

A steam power plant operates on an ideal reheat-regenerative Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 550°C and leaves at 0.8 MPa. Some steam is extracted at this pressure to heat the feedwater in a closed feed water heater. The rest of the steam is reheated to 500°C and is expanded in the low-pressure turbine to the condenser pressure of 10 kPa.

Show the cycle on a T-s diagram and determine:

- (a) the mass flow rate of steam through the boiler, and
- (b) thermal efficiency of the cycle.

Answers: (a) 54.5 kg/s, (b) 44.4 percent



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IDEAL REGENERATIVE RANKINE CYCLE

Open vs. Closed Feedwater Heater

Open FWHs

- Simple and inexpensive
- Good heat transfer characteristics.
- For each feedwater heater used, additional feedwater pump is required.

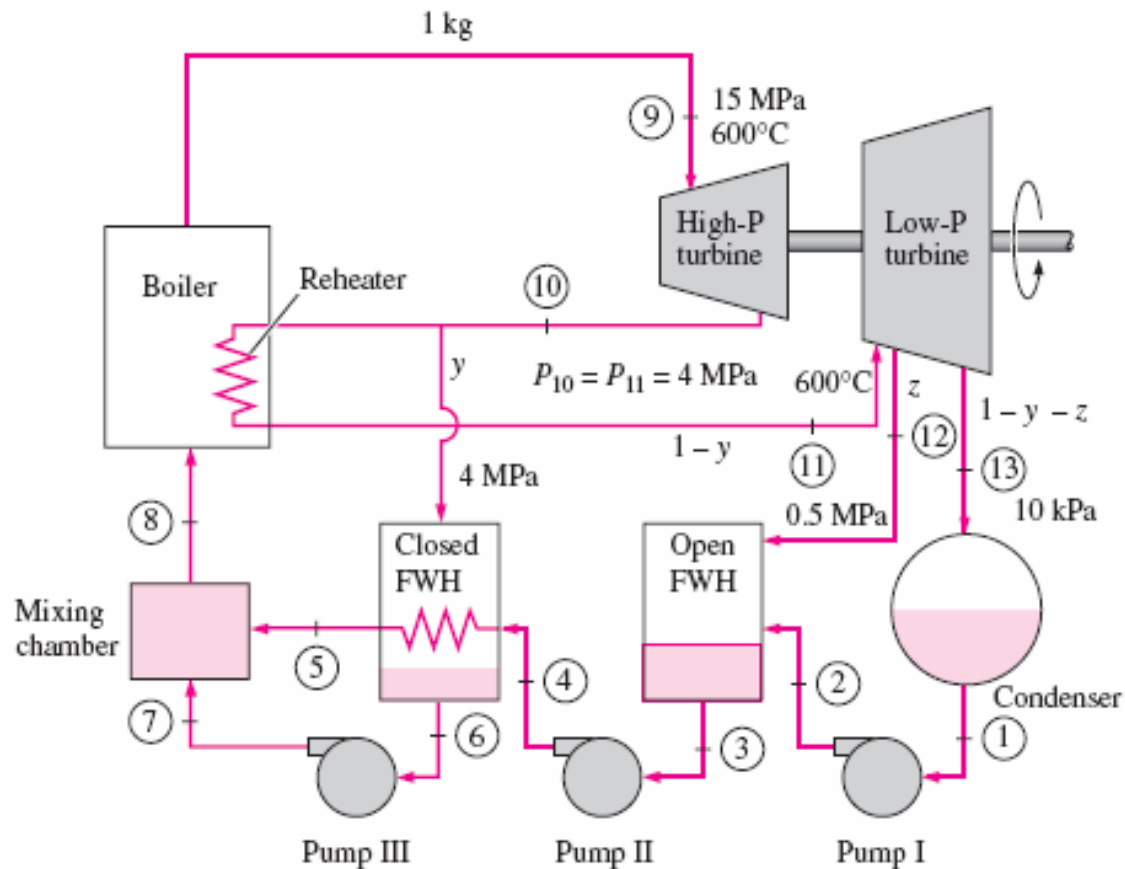
Closed FWHs

- More complex because of the internal tubing network, thus more expensive.
- Heat transfer is **less effective** since the two streams are not allowed to be in direct contact.
- Do not require a separate pump for each FWH since the extracted steam and the feedwater can be at different pressures.

TOPIC 4 : VAPOR POWER CYCLE

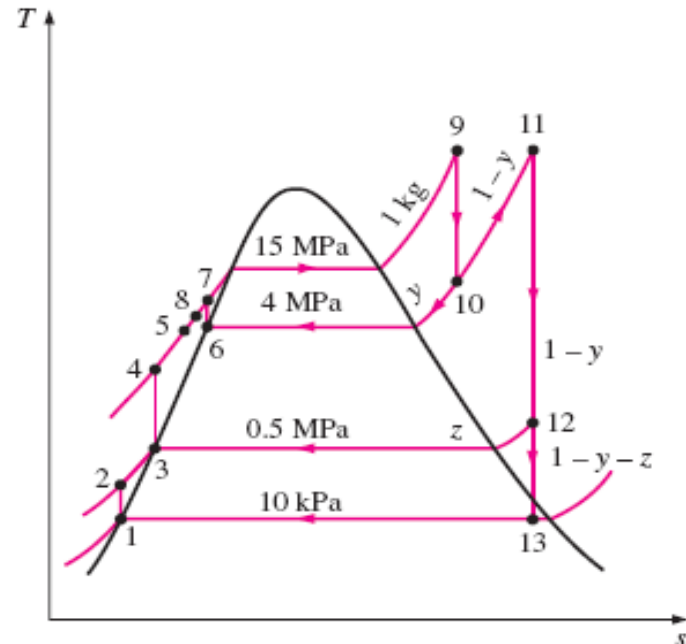
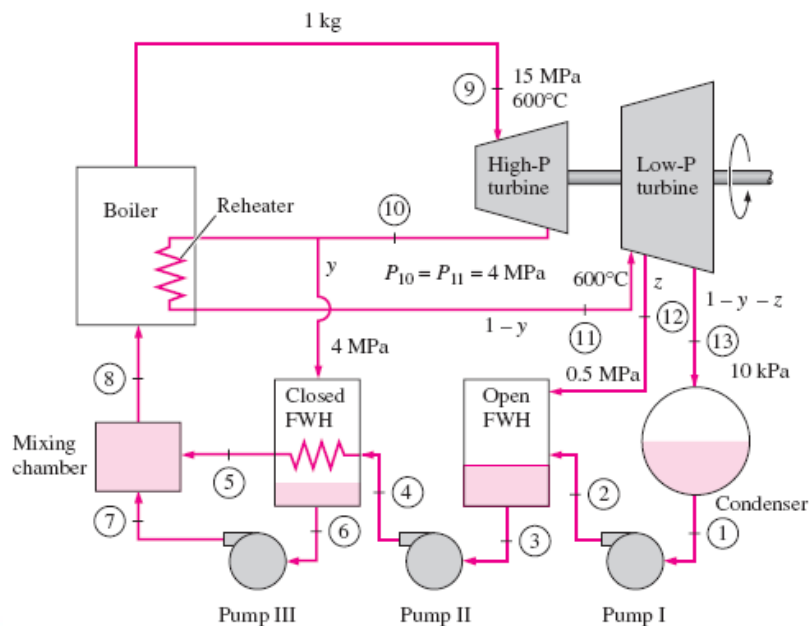
Open & Closed FWH Combined

Most steam power plants use a combination of open and closed feedwater heaters.



EXAMPLE 10-6 Pg 588

Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feed water heater, one closed feed water 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 leaves the turbine at a pressure of 4 MPa for the closed feed water 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 feed water heater at the same pressure. Steam for the open feed water heater is extracted from the low pressure turbine at a pressure 0.5 MPa. Determine the fraction of steam extracted from the turbine as well as the thermal efficiency of the cycle.



EXAMPLE 10-6 Pg 588

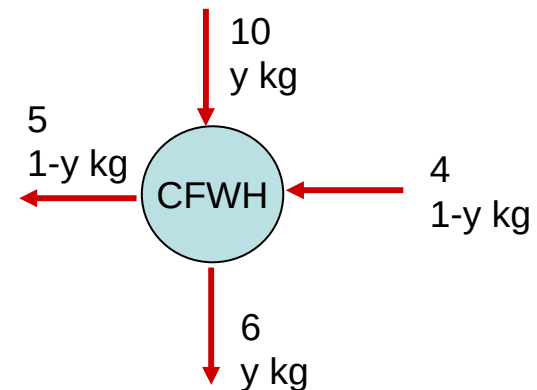
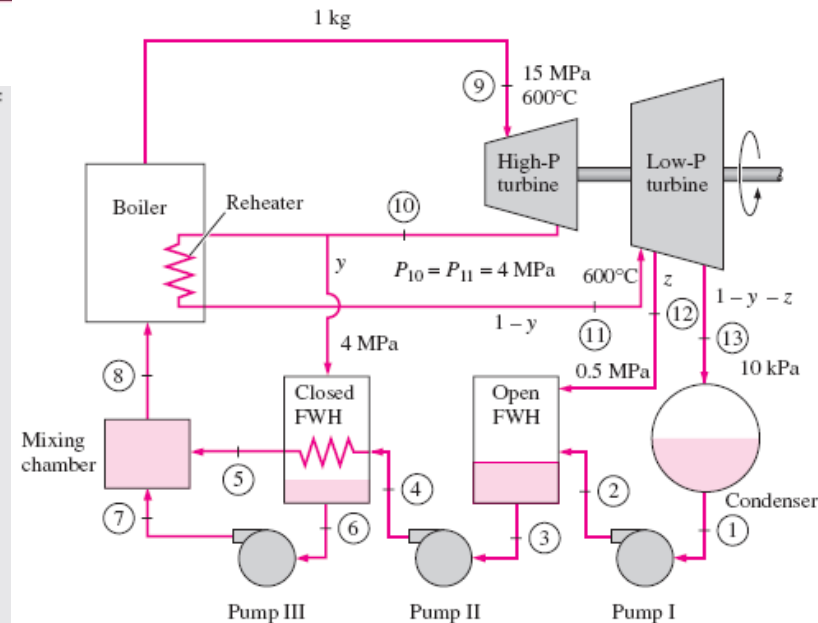
The enthalpies at the various states and the pump work per unit mass of fluid flowing through them are

$h_1 = 191.81 \text{ kJ/kg}$	$h_9 = 3155.0 \text{ kJ/kg}$
$h_2 = 192.30 \text{ kJ/kg}$	$h_{10} = 3155.0 \text{ kJ/kg}$
$h_3 = 640.09 \text{ kJ/kg}$	$h_{11} = 3674.9 \text{ kJ/kg}$
$h_4 = 643.92 \text{ kJ/kg}$	$h_{12} = 3014.8 \text{ kJ/kg}$
$h_5 = 1087.4 \text{ kJ/kg}$	$h_{13} = 2335.7 \text{ kJ/kg}$
$h_6 = 1087.4 \text{ kJ/kg}$	$w_{\text{pump I, in}} = 0.49 \text{ kJ/kg}$
$h_7 = 1101.2 \text{ kJ/kg}$	$w_{\text{pump II, in}} = 3.83 \text{ kJ/kg}$
$h_8 = 1089.8 \text{ kJ/kg}$	$w_{\text{pump III, in}} = 13.77 \text{ kJ/kg}$

For closed feed water heater,

$$yh_{10} + (1-y)h_4 = (1-y)h_5 + h_6$$

$$\begin{aligned}
 y &= \frac{h_5 - h_4}{(h_{10} - h_6) + (h_5 - h_4)} \\
 &= \frac{1087.4 - 643.92}{(3155.0 - 1087.4) + (1087.4 - 643.92)} \\
 &= 0.1766
 \end{aligned}$$



EXAMPLE 10-6 Pg 588

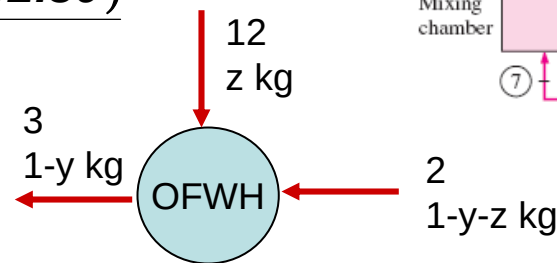
For open feed water heater,

$$zh_{12} + (1 - y - z)h_2 = (1 - y)h_3$$

$$z = \frac{(1 - y)(h_3 - h_2)}{h_{12} - h_2}$$

$$= \frac{(1 - 0.1766)(640.09 - 192.30)}{(3014.8 - 192.30)}$$

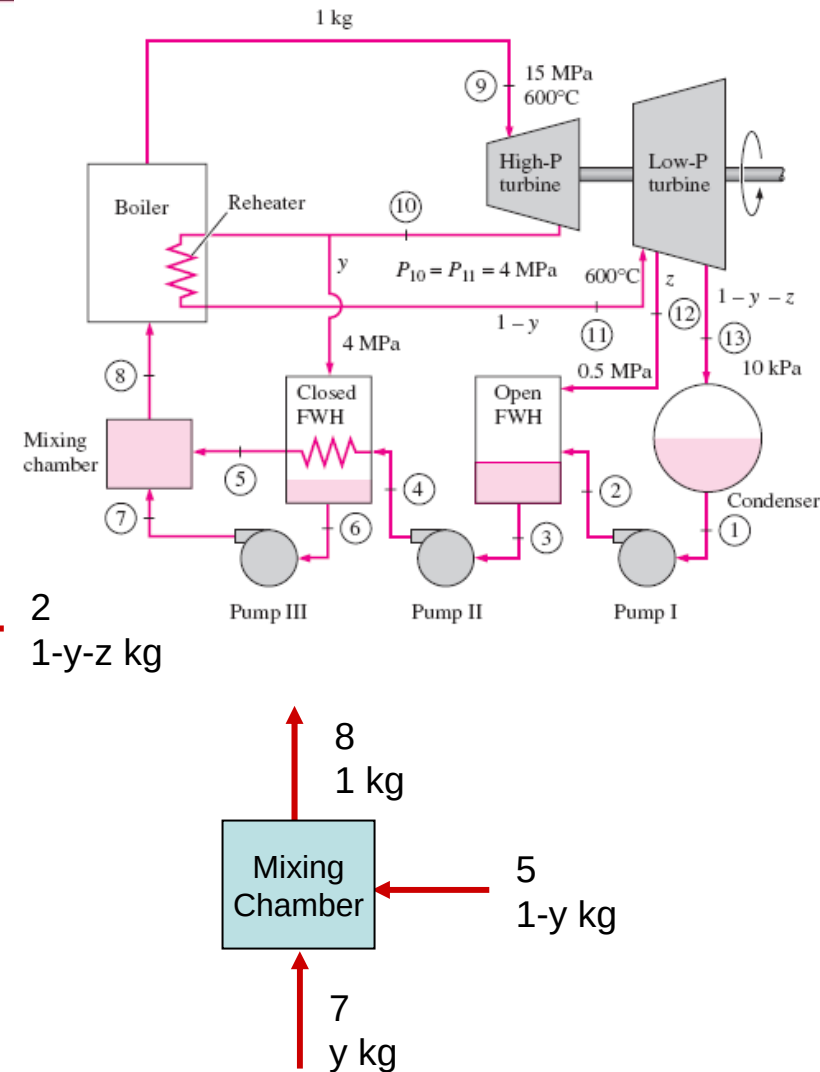
$$= 0.1306$$



$$(1)h_8 = (1 - y)h_5 + yh_7$$

$$h_8 = (1 - 0.1766)(1087.4) + 0.1766(1101.2)$$

$$= 1089.8 \text{ kJ/kg}$$

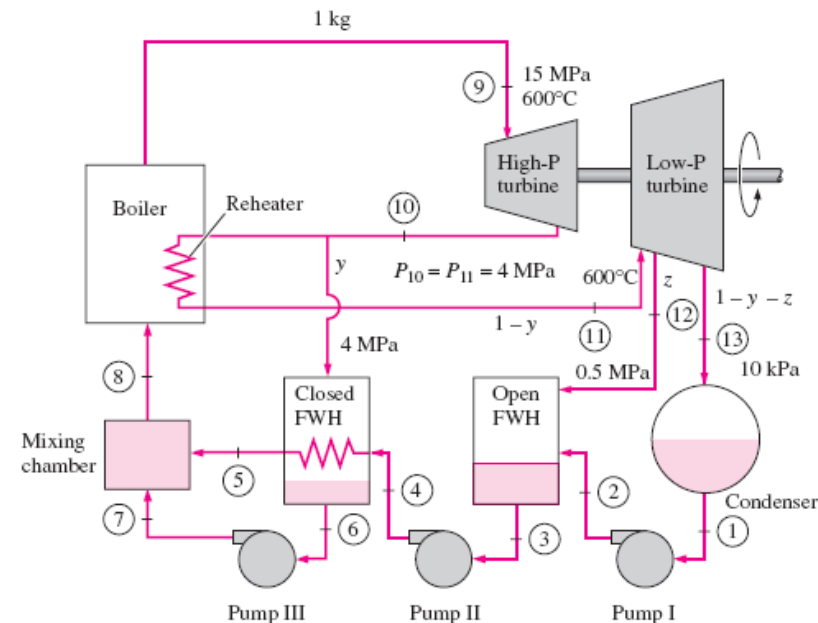


EXAMPLE 10-6 Pg 588

$$\begin{aligned} q_{in} &= (h_9 - h_8) + (1 - y)(h_{11} - h_{10}) \\ &= (3583.1 - 1089.8) + (1 - 0.1766)(3674.9 - 3155.0) \\ &= 2921.4 \text{ kJ/kg} \end{aligned}$$

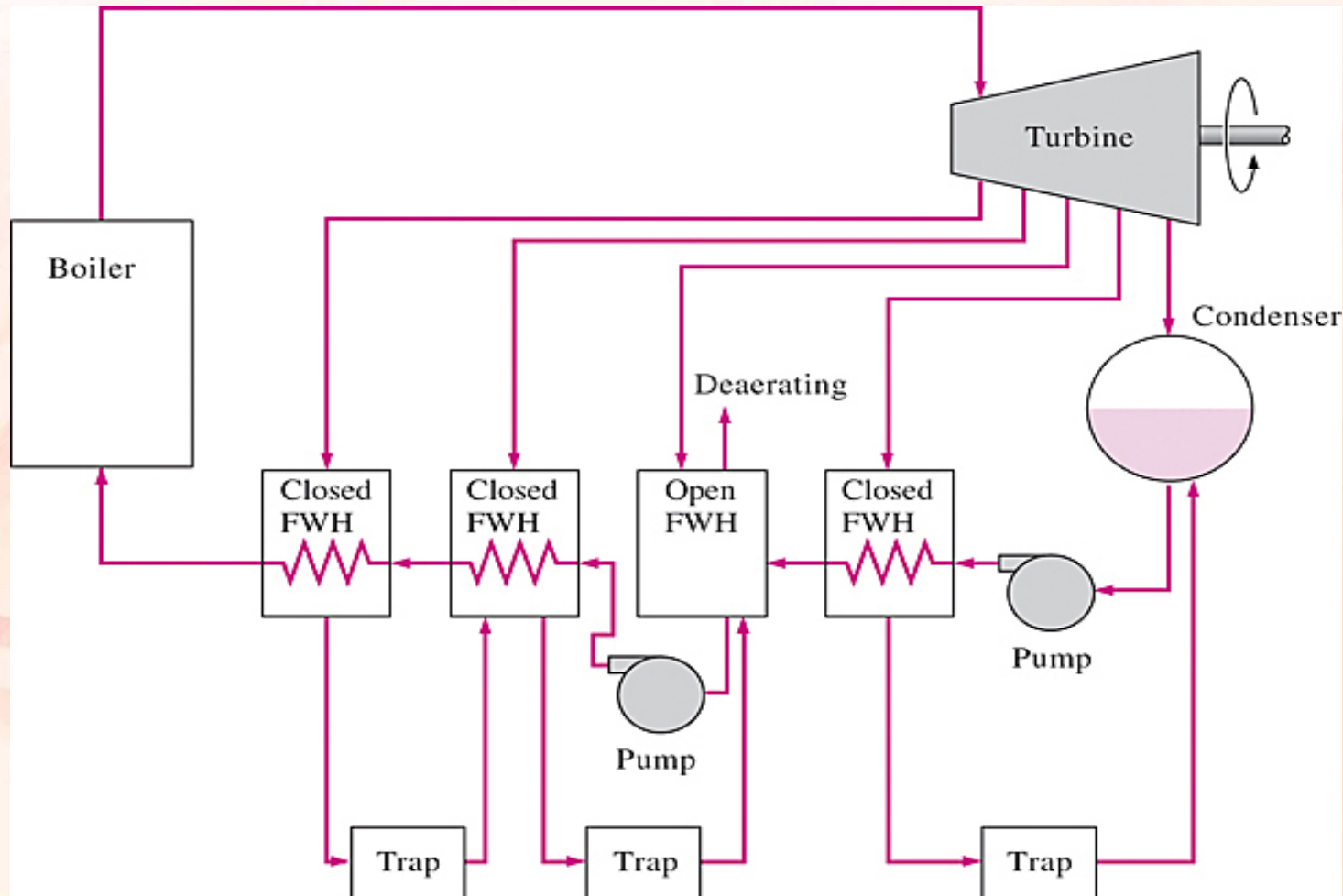
$$\begin{aligned} q_{out} &= (1 - y - z)(h_{13} - h_1) \\ &= (1 - 0.1766 - 0.1306)(2335.7 - 191.81) \\ &= 1485.3 \text{ kJ/kg} \end{aligned}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1485.3}{2921.4} = 0.492 \text{ or } 49.2\%$$



IDEAL REGENERATIVE RANKINE CYCLE

Open & Closed FWH Combined





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THE END