MEAN TEMPERATURE OF HEAT ADDITION

- In the Rankine cycle heat is added at a constant pressure but at infinite temperatures.

- If Tm1 is the mean temperature of heat addition as shown in Fig. 2.9 so that area under 4 and 1 is equal to area under 5 and 6, then heat added is

$$Q_1 = h_1 - h_4 = T_{m1}(s_1 - s_4)$$

$$T_{m1} = \text{mean temperature of heat addition} = \frac{h_1 - h_4}{s_1 - s_4} \qquad (2.17)$$

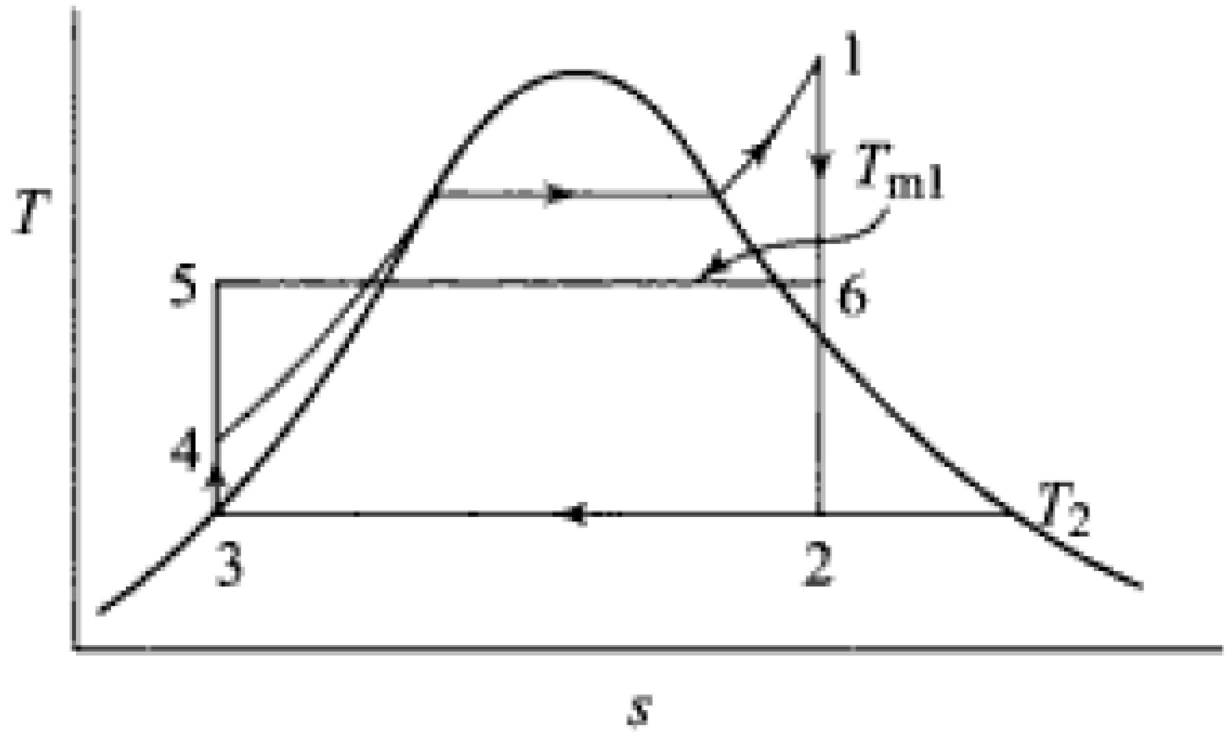


Fig. 2.9 *Mean temperature of heat addition*

Since Q_2 = heat rejected = $h_2 - h_3 = T_2(s_1 - s_4)$,

$$\eta_{\text{Rankine}} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2\,(s_1 - s_4)}{T_{m_1}\,(s_1 - s_4)} = 1 - \frac{T_2}{T_{m_1}} \qquad (2.18)$$

Where **T**2 is the temperature of heat rejection.

The lower is the **T**2 for a given **T**m1, i.e. lower is the condenser pressure, **the higher will be the efficiency of the Rankine cycle**.

- But, the lowest practicable temperature of heat rejection is the temperature of the surroundings, ***To***.

- The saturation pressure corresponding to this temperature ***To*** is the minimum pressure to which steam can be expanded in the turbine.

- This being fixed by the ambient conditions,

$$\eta_{\text{Rankine}} = f(T_{\text{m1}}) \quad \text{only} \tag{2.19}$$

- The higher the mean temperature of heat addition, the higher will be the cycle efficiency.

THE IDEAL REHEAT RANKINE CYCLE

- We noted that increasing the **boiler pressure** increases the thermal efficiency of the Rankine cycle, **but it also increases the moisture content** of the steam to unacceptable levels.

- Then it is natural to ask the following question:

How can we take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine?

Two possibilities come to mind:

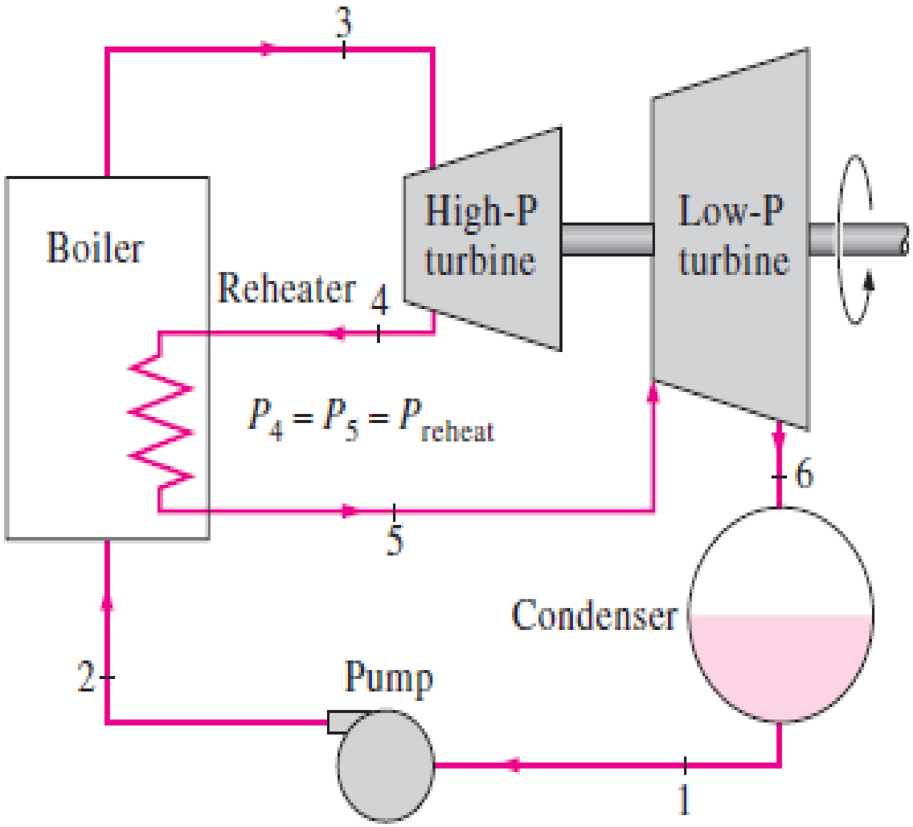
1. Superheat the steam to very high temperatures before it enters the turbine.

- This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency.

- This is not a viable solution, however, since it requires raising the steam temperature to metallurgically unsafe levels.

2. Expand the steam in the turbine in two stages, and reheat it in between.

- In other words, modify the simple ideal Rankine cycle with a **reheat process.**
- **Reheating is a practical solution to the excessive moisture** problem in turbines, and it is commonly used in modern steam power plants.
- The *T-s diagram of the ideal reheat Rankine cycle and the schematic of* the power plant operating on this cycle are shown in Fig. 10–11.
- The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle, in that the expansion process takes place in two stages.



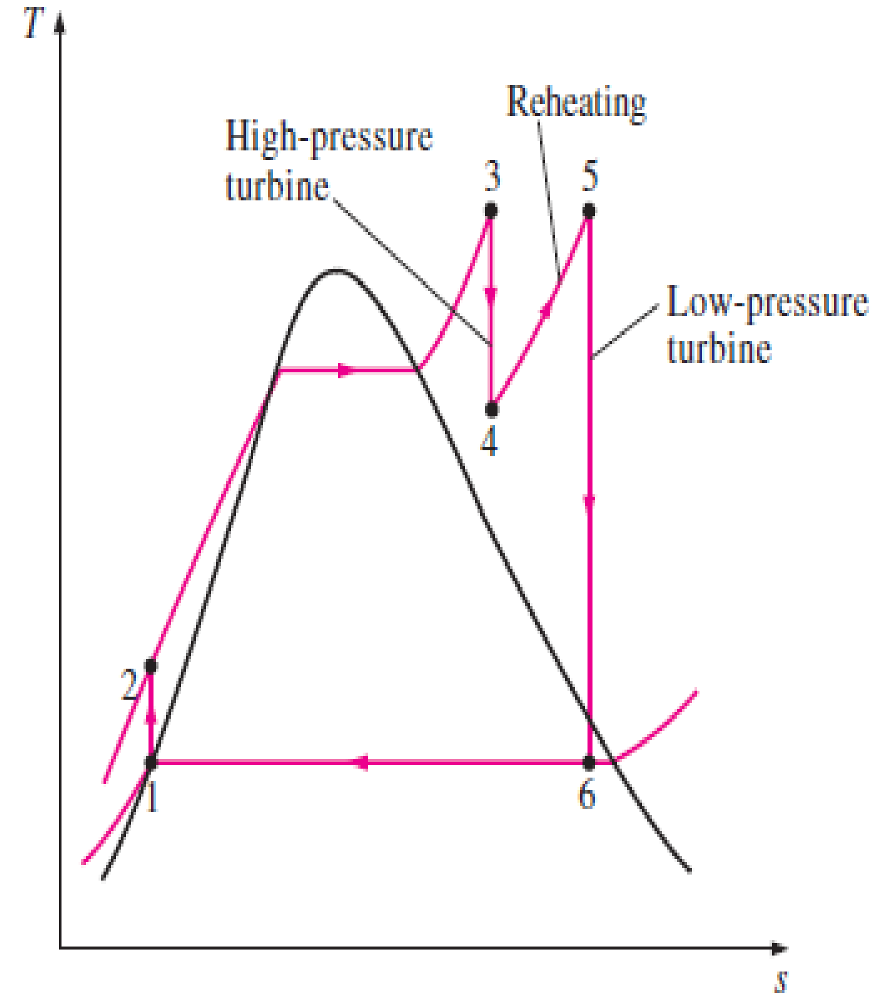


FIGURE 10–11

The ideal reheat Rankine cycle.

- In the first stage (the high pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the first turbine stage.

- Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure.

$$q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4) \quad (10\text{–}12)$$

$$w_{turb,out} = w_{turb,I} + w_{turb,II} = (h_3 - h_4) + (h_5 - h_6) \quad (10\text{–}13)$$

- The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent by increasing the average temperature at which heat is transferred to the steam.

- The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages.

- As the number of stages is increased, the expansion and reheat processes approach an isothermal process at the maximum temperature, as shown in Fig. 10–12.

- The use of more than two reheat stages, however, is not practical.

- The theoretical improvement in efficiency from the second reheat is about half of that which results from a single reheat.

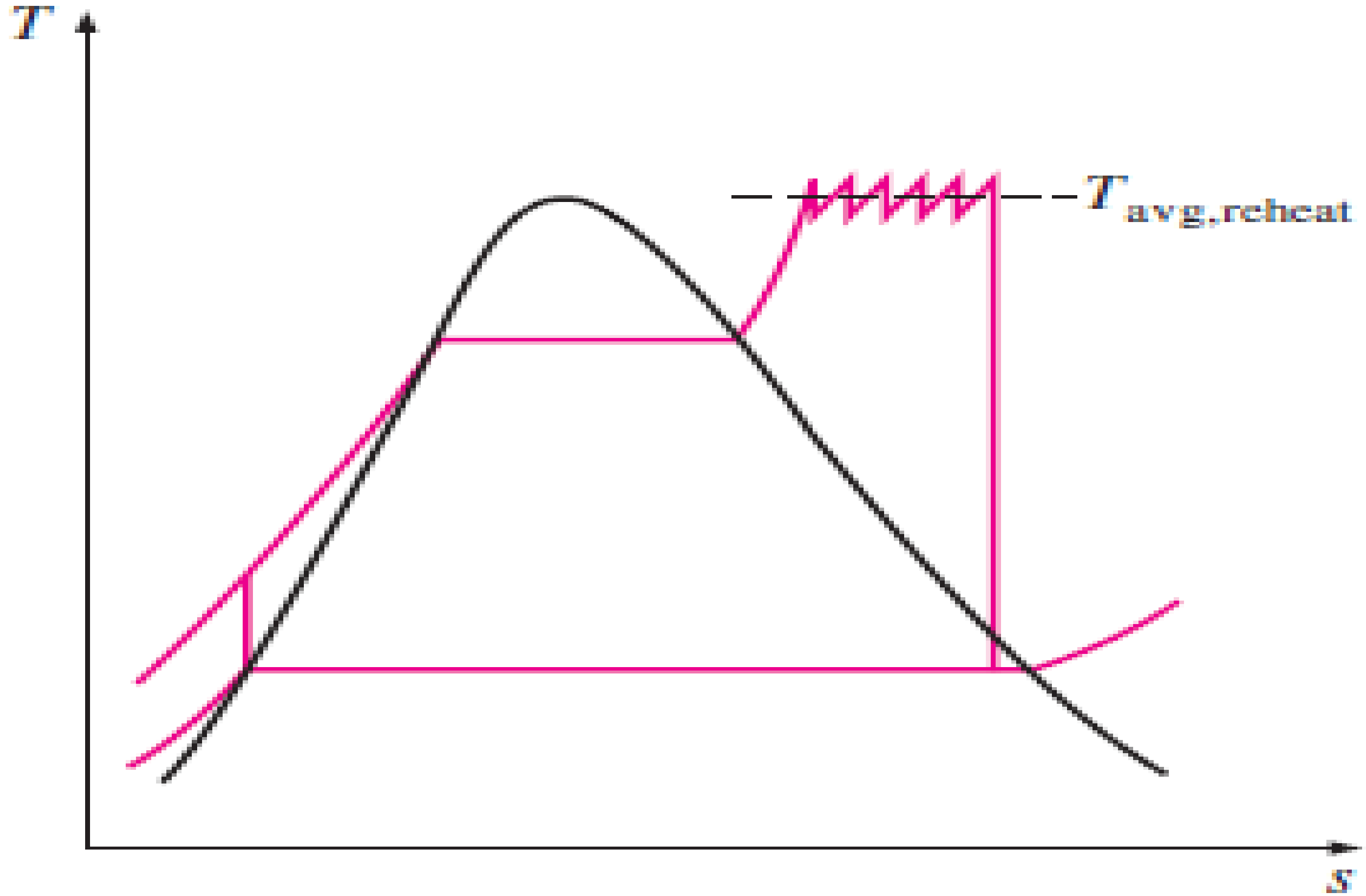


FIGURE 10–12

The average temperature at which heat is transferred during reheating increases as the number of reheat stages is increased.

- If the turbine inlet pressure is not high enough, double reheat would result in superheated exhaust.

- This is undesirable as it would cause the average temperature for heat rejection to increase and thus the cycle efficiency to decrease.

- **Therefore, double reheat is used only on supercritical-pressure (*P 22.06 MPa) power plants.***

- *A third reheat* stage would increase the cycle efficiency by about half of the improvement attained by the second reheat.

- This gain is too small to justify the added cost and complexity.

- The reheat cycle was introduced in the mid-1920s, but it was abandoned in the 1930s because of the operational difficulties.

- The steady increase in boiler pressures over the years made it necessary to reintroduce single reheat in the late 1940s and double reheat in the early 1950s.

- **The reheat temperatures are very close or equal to the turbine inlet temperature.**

- The **optimum reheat pressure is about one-fourth** of the maximum cycle pressure.

- For example, the optimum reheat pressure for a cycle with a boiler pressure of 12 MPa is about 3 MPa.

- Remember that the sole purpose of the reheat cycle is to reduce the moisture content of the steam at the final stages of the expansion process.

- If we had materials that could withstand sufficiently high temperatures, there would be no need for the reheat cycle.

THE IDEAL REGENERATIVE RANKINE CYCLE

- A careful examination of the *T-s diagram of the Rankine cycle redrawn in* Fig. 10–14 reveals that 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, we look for ways to raise the temperature of the liquid leaving the pump (called the *feedwater) before it enters the boiler.*

- One such possibility is to transfer heat to the feedwater from the expanding steam in a counter flow heat exchanger built into the turbine, that is, to use **regeneration.**

- **This solution is also impractical because it is difficult to** design such a heat exchanger and because it would increase the moisture content of the steam at the final stages of the turbine.

- 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 feed water instead.

- The device where the feedwater is heated by regeneration is called a **regenerator, or a feedwater heater (FWH).**

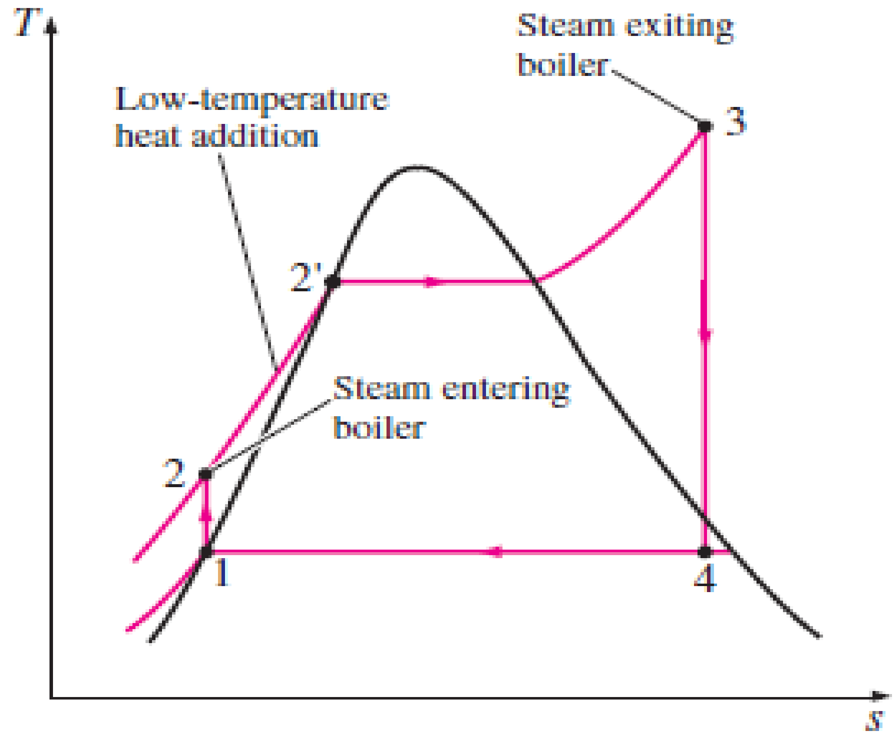


FIGURE 10–14

The first part of the heat-addition process in the boiler takes place at relatively low temperatures.

- Regeneration not only improves cycle efficiency, but also provides a convenient means of **deaerating** the feedwater (removing the air that leaks in at the condenser) to prevent corrosion in the boiler.

- Therefore, regeneration has been used in all modern steam power plants since its introduction in the early 1920s.

- A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters).

Open Feedwater Heaters

- 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.

- The schematic of a steam power plant with one open feedwater heater (also called *single-stage regenerative cycle) and the T-s* diagram of the cycle are shown in Fig. 10–15.

- In an ideal regenerative Rankine cycle, steam enters the turbine at the boiler pressure (state 5) and expands isentropically to an intermediate pres sure (state 6).

- **Some steam is extracted at this state and routed to the feedwater heater, while the remaining steam continues to expand isentropically to the condenser pressure (state 7).**

- **This steam leaves the condenser as a saturated liquid at the condenser pressure (state 1).**

- **The condensed water, which is also called the *feedwater, then enters an isentropic pump, where it* is compressed to the feedwater heater pressure (state 2) and is routed to the feedwater heater, where it mixes with the steam extracted from the turbine.**

- **The fraction of the steam extracted is such that the mixture leaves the heater as a saturated liquid at the heater pressure (state 3).**

- **A second pump raises the pressure of the water to the boiler pressure (state 4).**

- **The cycle is completed by heating the water in the boiler to the turbine inlet state (state 5).**

- In the analysis of steam power plants, it is more convenient to work with quantities expressed per unit mass of the steam flowing through the boiler.

- For each 1 kg of steam leaving the boiler, *1 kg expands partially in the turbine* and y kg is extracted at state 6.

- The remaining (1 - *y) kg expands completely to* the condenser pressure.

- Therefore, the mass flow rates are different in different components.

- If the mass flow rate through the boiler is *m' , for example,* it is (1-*y)m' through the condenser.*

- *In light of Fig. 10–15, the* heat and work interactions of a regenerative Rankine cycle with one feedwater heater can be expressed per unit mass of steam flowing through the boiler as follows:

$$q_{in} = h_5 - h_4 \tag{10–14}$$

$$q_{out} = (1 - y)(h_7 - h_1) \tag{10–15}$$

$$w_{turb,out} = (h_5 - h_6) + (1 - y)(h_6 - h_7) \tag{10–16}$$

$$w_{pump,in} = (1 - y)w_{pump\ I,in} + w_{pump\ II,in} \tag{10–17}$$

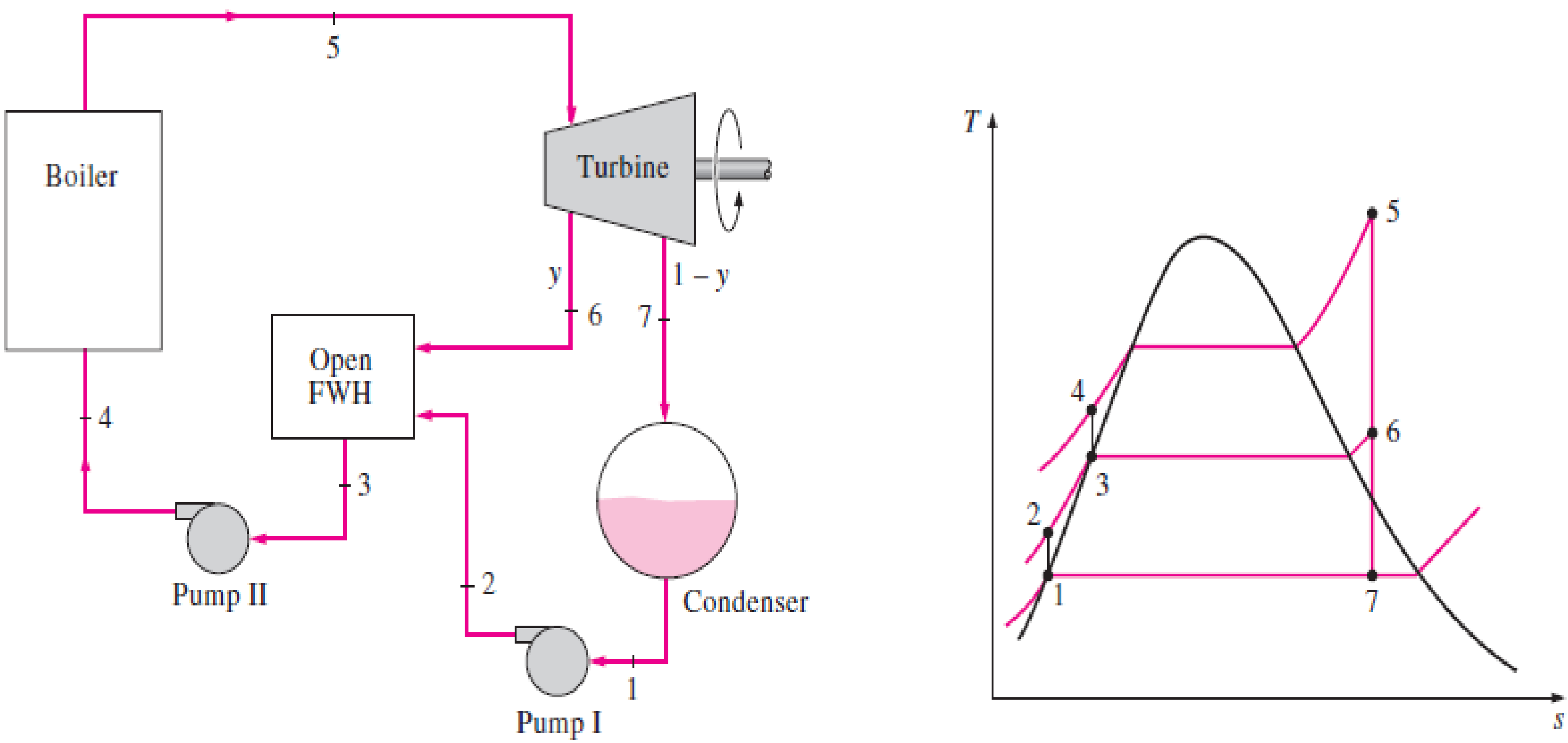


FIGURE 10–15

The ideal regenerative Rankine cycle with an open feedwater heater.

where

$$y = \dot{m}_6/\dot{m}_5 \qquad \text{(fraction of steam extracted)}$$

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

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

- The thermal efficiency of the Rankine cycle increases as a result of regeneration.
- This is because regeneration raises the average temperature at which heat is transferred to the steam in the boiler by raising the temperature of the water before it enters the boiler.
- The cycle efficiency increases further as the number of feedwater heaters is increased.
- Many large plants in operation today use as many as **eight feedwater heaters.**
- The optimum number of feedwater heaters is determined from economical considerations.
- The use of an additional feedwater heater cannot be justified unless it saves more from the fuel costs than its own cost.

Closed Feedwater Heaters

- Another type of feedwater heater frequently used in steam power plants is the **closed feedwater heater.**

- **In CFH 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.

- The schematic of a steam power plant with one closed feedwater heater and the *T-s diagram of* the cycle are shown in Fig. 10–16.

- In an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.

- In actual power plants, the feedwater leaves the heater below the exit temperature of the extracted steam because a temperature difference of at least a few degrees is required for any effective heat transfer to take place.

- The condensed steam is then either pumped to the feedwater line or routed to another heater or to the condenser through a device called a **trap.**

- **A trap** allows the liquid to be throttled to a lower pressure region but *traps the* vapor.

- The enthalpy of steam remains constant during this throttling process.

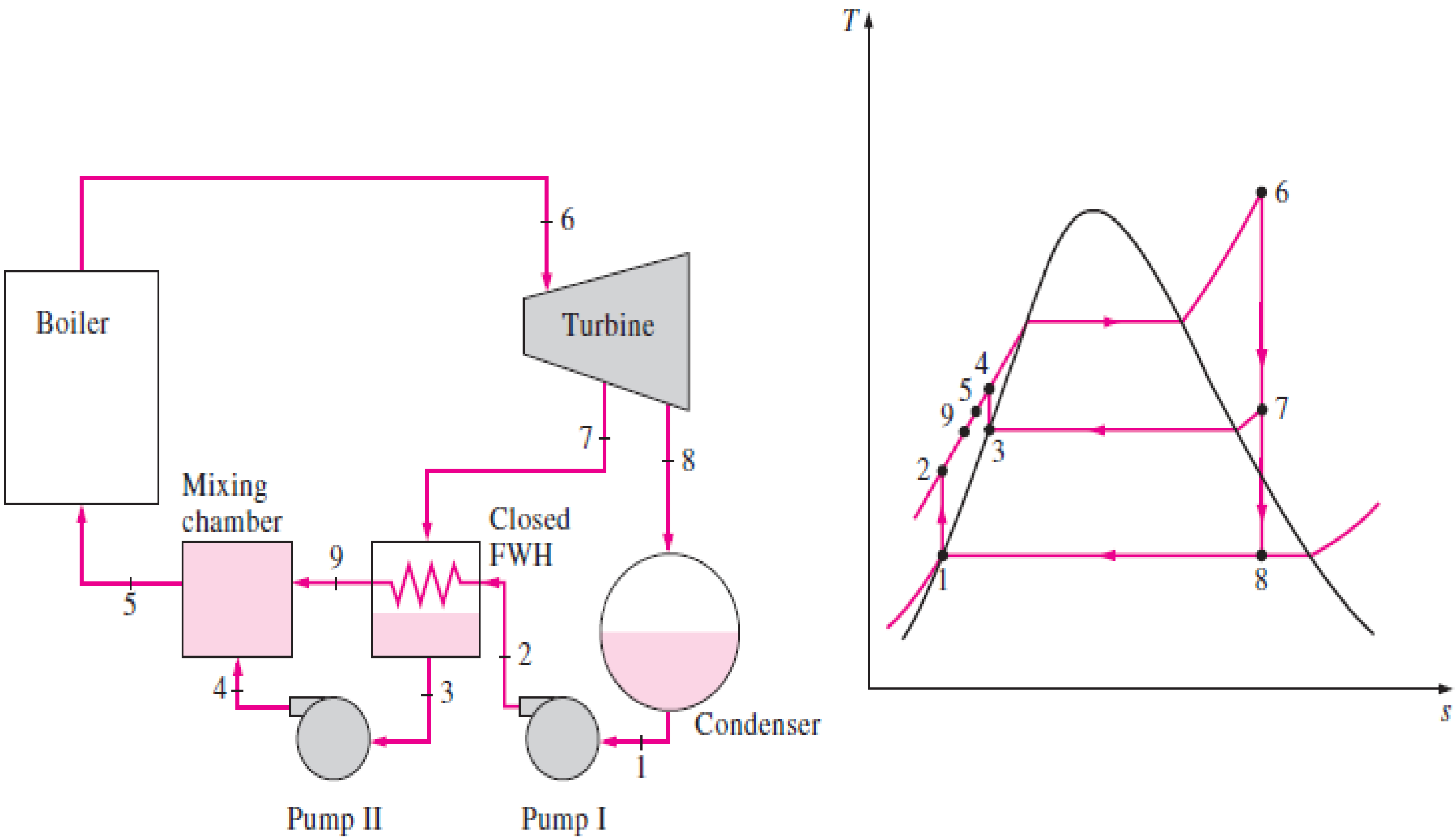


FIGURE 10–16

The ideal regenerative Rankine cycle with a closed feedwater heater.

- The open and closed feedwater heaters can be compared as follows:
- **Open feedwater heaters** are simple and inexpensive and have good heat transfer characteristics.
- They also bring the feedwater to the saturation state.
- For each heater, however, a pump is required to handle the feedwater.
- **The closed feedwater heaters** are more complex because of the internal tubing network, and thus they are more expensive.
- Heat transfer in closed feedwater heaters is also less effective since the two streams are not allowed to be in direct contact.
- However, closed feedwater heaters do not require a separate pump for each heater since the extracted steam and the feedwater can be at different pressures.
- Most steam power plants use a combination of open and closed feedwater heaters, as shown in Fig. 10–17.

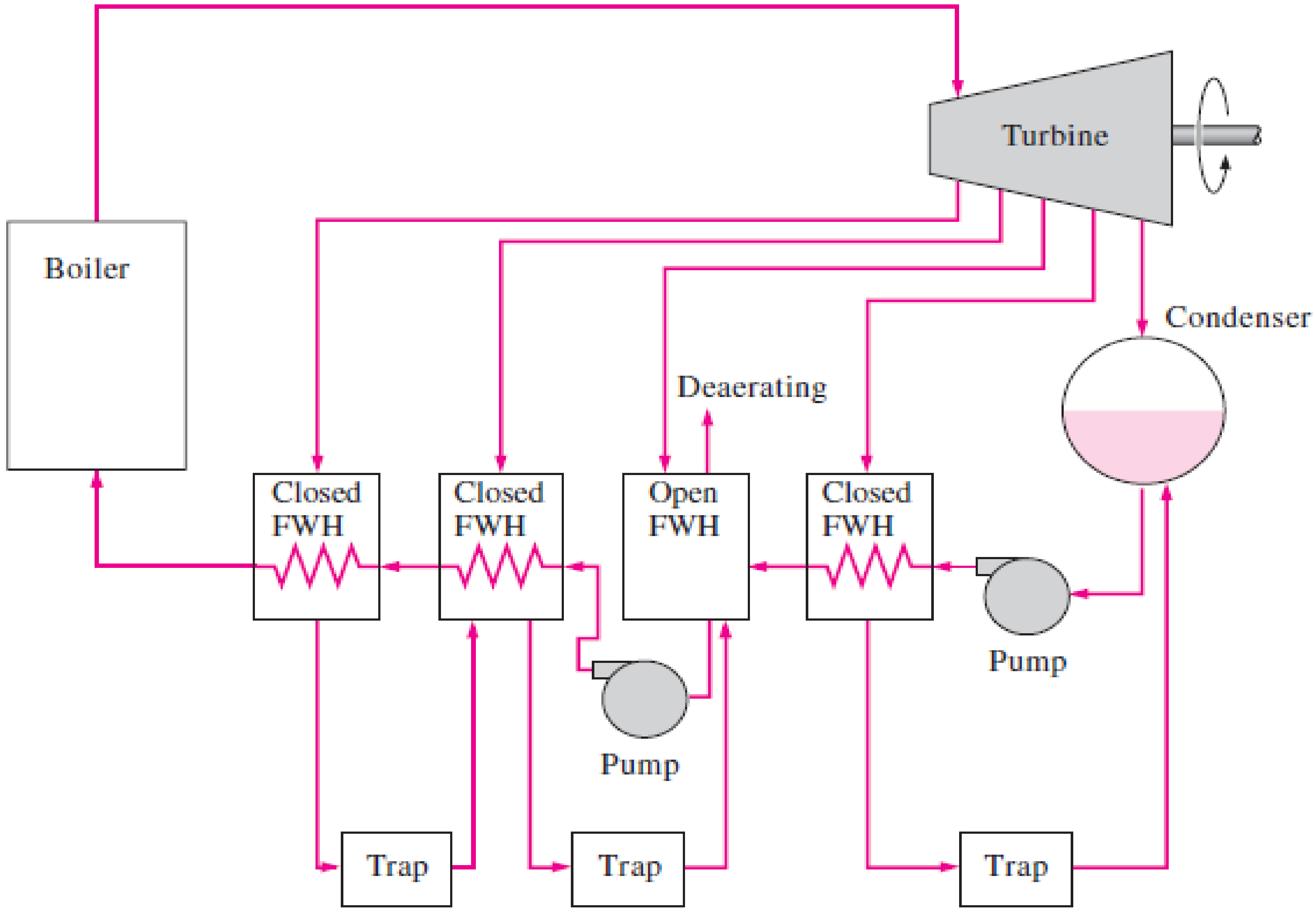


FIGURE 10–17

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

DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES

- **The actual vapor power cycle differs from the ideal Rankine cycle, as illustrated in Fig. 10–4*a, as a result of irreversibilities in various components.***

- **Fluid friction and heat loss to the surroundings are the two common sources of irreversibilities.**

- ***Fluid friction causes pressure drops in the boiler, the condenser, and the*** **piping between various components.**

- **As a result, steam leaves the boiler at a somewhat lower pressure.**

- **Also, the pressure at the turbine inlet is somewhat lower than that at the boiler exit due to the pressure drop in the connecting pipes.**

- The pressure drop in the condenser is usually very small.

- To compensate for these pressure drops, the water must be pumped to a sufficiently higher pressure than the ideal cycle calls for.

- This requires a larger pump and larger work input to the pump.

- The other major source of irreversibility is the *heat loss from the steam to* the surroundings as the steam flows through various components.

- To maintain the same level of net work output, more heat needs to be transferred to the steam in the boiler to compensate for these undesired heat losses.

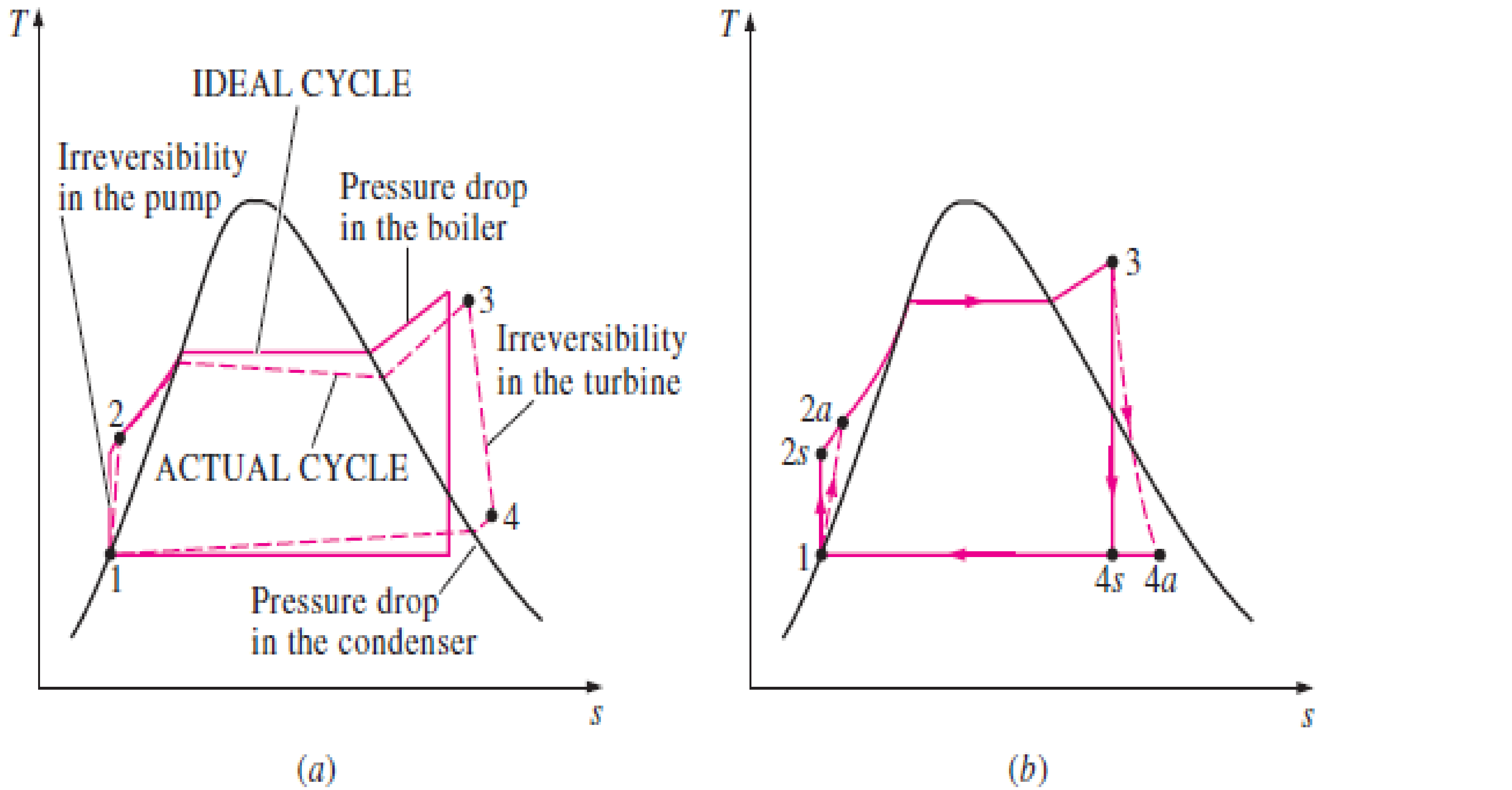


FIGURE 10–4

(*a*) Deviation of actual vapor power cycle from the ideal Rankine cycle. (*b*) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

- As a result, cycle efficiency decreases.
- A pump requires a greater work input, and a turbine produces a smaller work output as a result of irreversibilities.
- Under ideal conditions, the flow through these devices is isentropic.
- The deviation of actual pumps and turbines from the isentropic ones can be accounted for by utilizing *isentropic efficiencies*, *defined as*

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad (10\text{–}10)$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \qquad (10\text{–}11)$$

- **where states 2*a and 4a are the actual exit states of the pump and the turbine*, respectively, and 2*s and 4s are the corresponding states for the isentropic* case (Fig. 10–4*b)*.**

- **Other factors also need to be considered in the analysis of actual vapor power cycles.**

- **Additional losses occur at the bearings between the moving parts as a result of friction.**

- **Steam that leaks out during the cycle and air that leaks into the condenser represent two other sources of loss.**

- **Finally, the power consumed by the auxiliary equipment such as fans that supply air to the furnace should also be considered in evaluating the overall performance of power plants.**

COGENERATION

INTRODUCTION

- **In all the cycles discussed so far, the sole purpose was to convert a portion of the heat transferred to the working fluid to work, which is the most valuable form of energy.**

- **The remaining portion of the heat is rejected to rivers, lakes, oceans, or the atmosphere as waste heat, because its quality (or grade) is too low to be of any practical use.**

- **Wasting a large amount of heat is a price we have to pay to produce work, because electrical or mechanical work is the only form of energy on which many engineering devices (such as a fan) can operate.**

- **Many systems or devices, however, require energy input in the form of heat, called *process heat.***

APPLICATIONS OF PROCESS HEAT

- ***Industries that rely heavily on process heat*** **are chemical, pulp and paper, oil production and refining, steel making, food processing, and textile industries.**

- **Process heat in these industries is usually supplied by steam at 5 to 7 atm and 150 to 200°C .**

- **Energy is usually transferred to the steam by burning coal, oil, natural gas, or another fuel in a furnace.**

- **Now let us examine the operation of a process-heating plant closely.**

PROCESS HEATING PLANT

- **Disregarding any heat losses in the piping, all the heat transferred to the water in the boiler is used in the process-heating units, as shown in Fig. 10–20.**

- **Therefore, process heating seems like a perfect operation with practically no waste of energy.**

- **From the second-law point of view, however, things do not look so perfect.**

- **The temperature in furnaces is typically very high (around 1400°C), and thus the energy in the furnace is of very high quality.**

- **This high-quality energy is transferred to water to produce steam at about 200°C or below (a highly irreversible process).**

- **Associated with this irreversibility is, of course, a loss in exergy or work potential.**

- **It is simply not wise to use high-quality energy to accomplish a task that could be accomplished with low-quality energy**

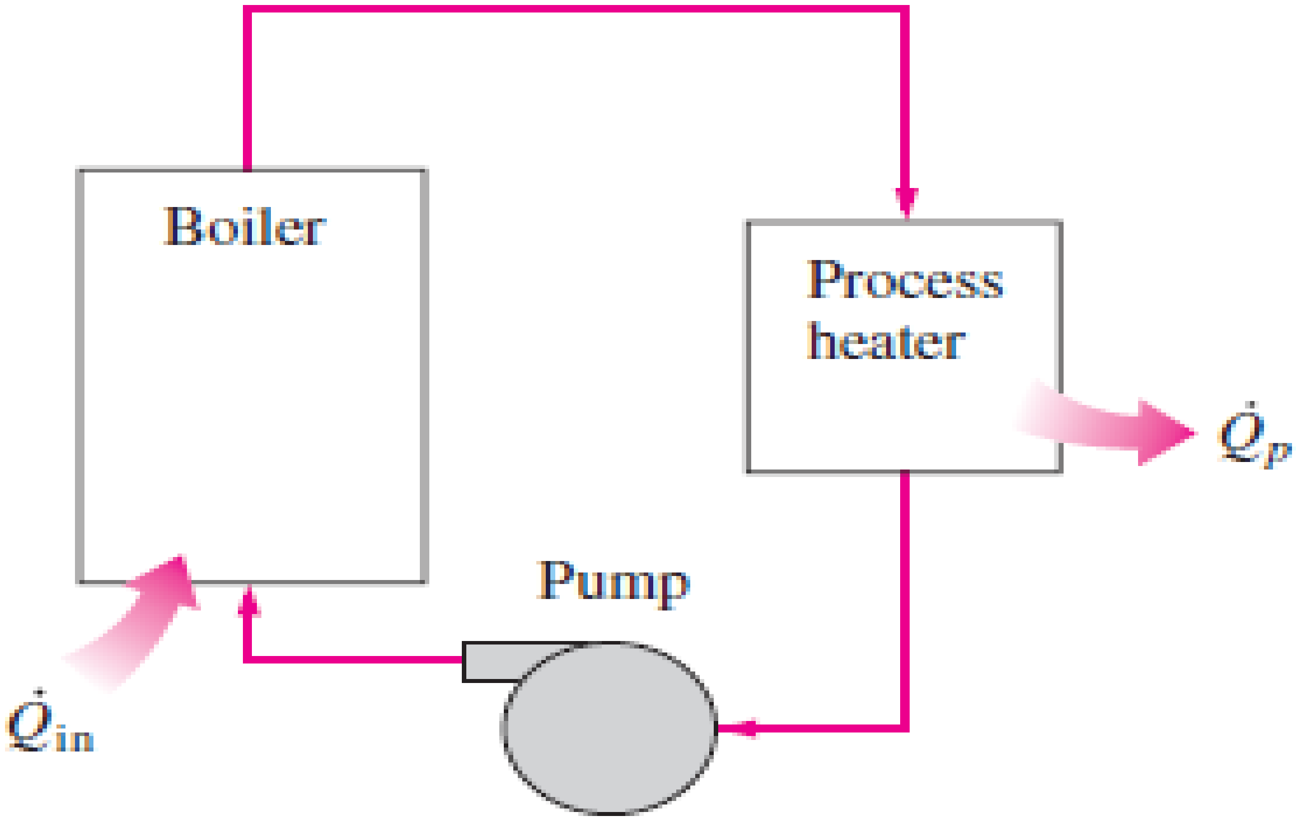


FIGURE 10–20

A simple process-heating plant.

- **Industries that use large amounts of process heat also consume a large amount of electric power.**

- **Therefore, it makes economical as well as engineering sense to use the already-existing work potential to produce power instead of letting it go to waste.**

- **The result is a plant that produces electricity while meeting the process-heat requirements of certain industrial processes.**

- **Such a plant is called a *cogeneration plant.***

- ***In general, cogeneration* is *the production of more than one useful form of energy (such as process heat and electric power) from the same energy source.***

COGENERATION PLANT

- **Either a steam-turbine (Rankine) cycle or a gas-turbine (Brayton) cycle or even a combined cycle (discussed later) can be used as the power cycle in a cogeneration plant.**

- **The schematic of an ideal steam-turbine cogeneration plant is shown in Fig. 10–21.**

- **Let us say this plant is to supply process heat *Q* , *at pressure P*, at 500 kPa at a rate of 100 kW.**

- **To meet this demand, steam is expanded in the turbine to a pressure of 500 kPa, producing power at a rate of, say, 20 kW.**

- **The flow rate of the steam can be adjusted such that steam leaves the process heating section as a saturated liquid at 500 kPa.**

(1 bar = 100 kPa = 0.1 MPa)

- **Condensate is then pumped to the boiler pressure and is heated in the boiler to state 3.**
- **The pump work is usually very small and can be neglected.**

- **Disregarding any heat losses, the rate of heat input in the boiler is determined from an energy balance to be 120 kW.**

- **Probably the most striking feature of the ideal steam-turbine cogeneration plant shown in Fig. 10–21 is the absence of a condenser.**

- **Thus no heat is rejected from this plant as waste heat.**

- **In other words, 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 E*u for a cogeneration* plant as:**

$$\epsilon_u = \frac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{net} + \dot{Q}_p}{\dot{Q}_{in}} \tag{10–23}$$

or

$$\epsilon_u = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} \tag{10–24}$$

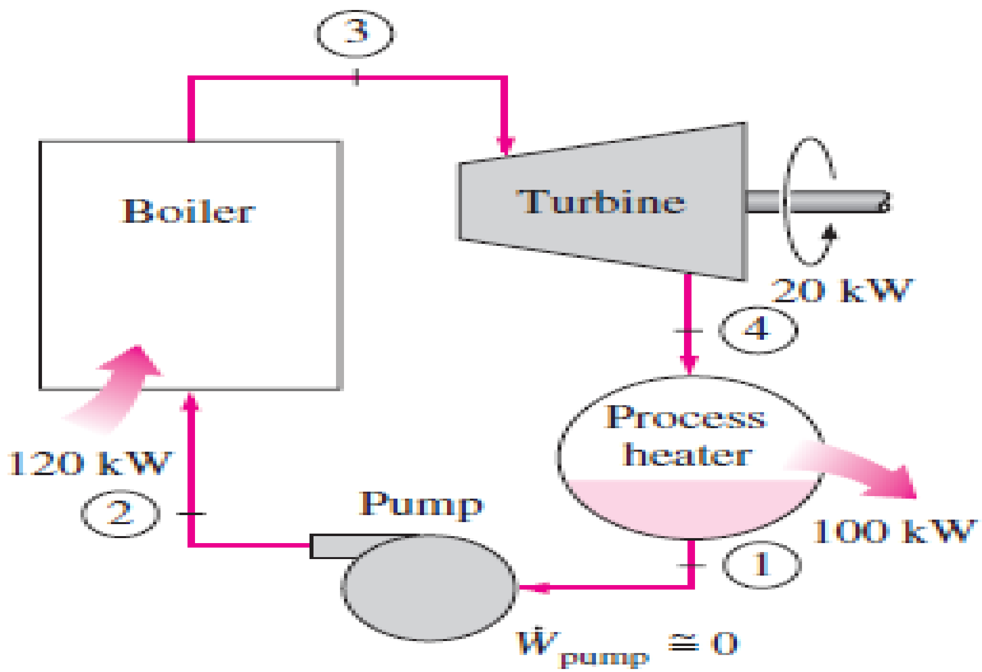


FIGURE 10–21
An ideal cogeneration plant.

where Q'_{out} represents the heat rejected in the condenser.

- **Strictly speaking, Q'_{out} also includes all the undesirable heat losses from the piping and other components, but they are usually small and thus neglected.**

- **It also includes combustion inefficiencies such as incomplete combustion and stack losses when the utilization factor is defined on the basis of the heating value of the fuel.**

- **The utilization factor of the ideal steam-turbine cogeneration plant is obviously 100 percent.**

- **Actual cogeneration plants have utilization factors as high as 80 percent.**

- **Some recent cogeneration plants have even higher utilization factors.**

- **A cogeneration plant with adjustable loads is shown in Fig. 10 – 22.**

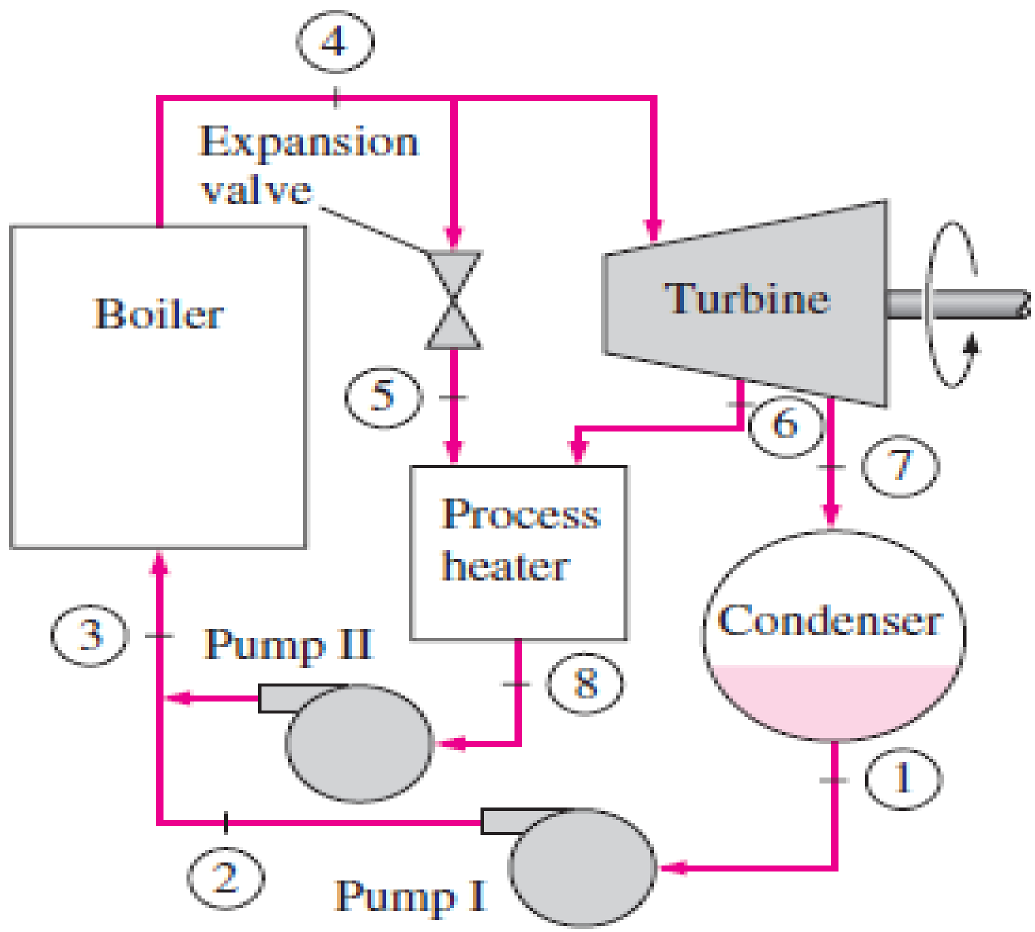


FIGURE 10–22

A cogeneration plant with adjustable loads.

DEAERATORS

- **One of the feedwater heaters is a contact-type open heater, known as deaerator, others being closed heaters.**

- **It is used for the purpose of deaerating the feedwater.**

- **The presence of dissolved gases like oxygen and carbon dioxide in water makes the water corrosive, as they react with the metal to form iron oxide.**

- **The solubility of these gases in water decreases with increase in temperature and becomes zero at the boiling or saturation temperature.**

- **These gases are removed in the deaerator, where feedwater is heated to the saturation temperature by the steam extracted from the turbine.**

- **Feedwater, after passing through a heat exchanger, called vent condenser, is sprayed from the top so as to expose large surface area, and the bled steam from the turbine is fed from the bottom (Fig. 2.30a).**

- **By contact, the steam condenses and the feedwater is heated to the saturation temperature.**

- **Dissolved oxygen and carbon dioxide gases get released from the water and leave along with some vapour, which is condensed back in the vent condenser, and the gases are vented out.**

Chemical methods

- **To neutralize the effect of residual dissolved oxygen and carbon dioxide gases in water, sodium sulphite (Na_2SO_3) or hydrazine (N_2H_4) is injected in suitable calculated doses into the feedwater at the suction of the boiler feed pump (BFP).**

- **During suction of the BFP, some of the saturated feedwater may flash into vapour due to reduction in pressure causing vapour lock and cavitation problems in the pump.**

- **To prevent this from occurring and to provide a net positive suction head (NPSH) for the pump, the deaerator is located at a sufficient height (H) from the basement where the pump is installed so that the pressure before suction is ($P_{sat} + \rho_f gH$).**

- **When this water is sucked by the pump, the pressure does not fall below Psat and there is no flashing of any water into vapour, which protects the BFP from any damage due to vapour lock and cavitation.**

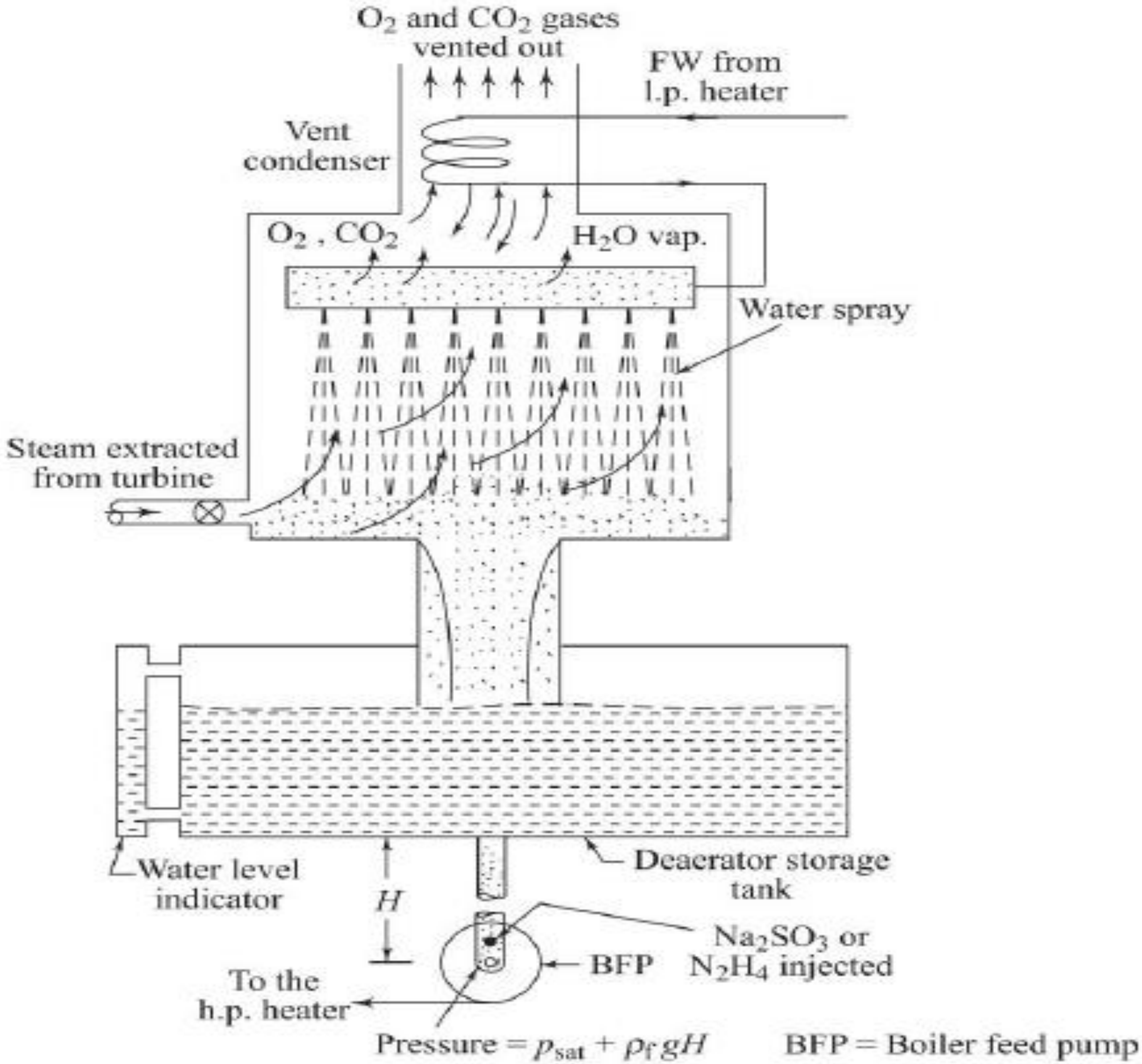
- The deaerator is usually placed near the middle of the feedwater system so that the total pressure difference between the condenser and the boiler is shared equitably between the condensate pump and boiler feed pump.

- **The feedwater heaters before the deaerator are often termed as high pressure (h.p.) heaters and those after the deaerator are termed as low pressure (L.P.) heaters.**

- The deaerator is not used in water-cooled-and-moderated nuclear power plants because of the concern regarding radioactivity release with deaeration.

- Figure 2.30(b) shows a boiler feed pump (BFP) schematic.

- Feed water from deaerator is raised to boiler pressure and fed to economizer.


O$_2$ and CO$_2$ gases vented out
FW from l.p. heater
Vent condenser
O$_2$, CO$_2$
H$_2$O vap.
Water spray
Steam extracted from turbine
Water level indicator
Deaerator storage tank
H
Na$_2$SO$_3$ or N$_2$H$_4$ injected
BFP
To the h.p. heater
Pressure = $p_{sat} + \rho_f gH$
BFP = Boiler feed pump

(a)

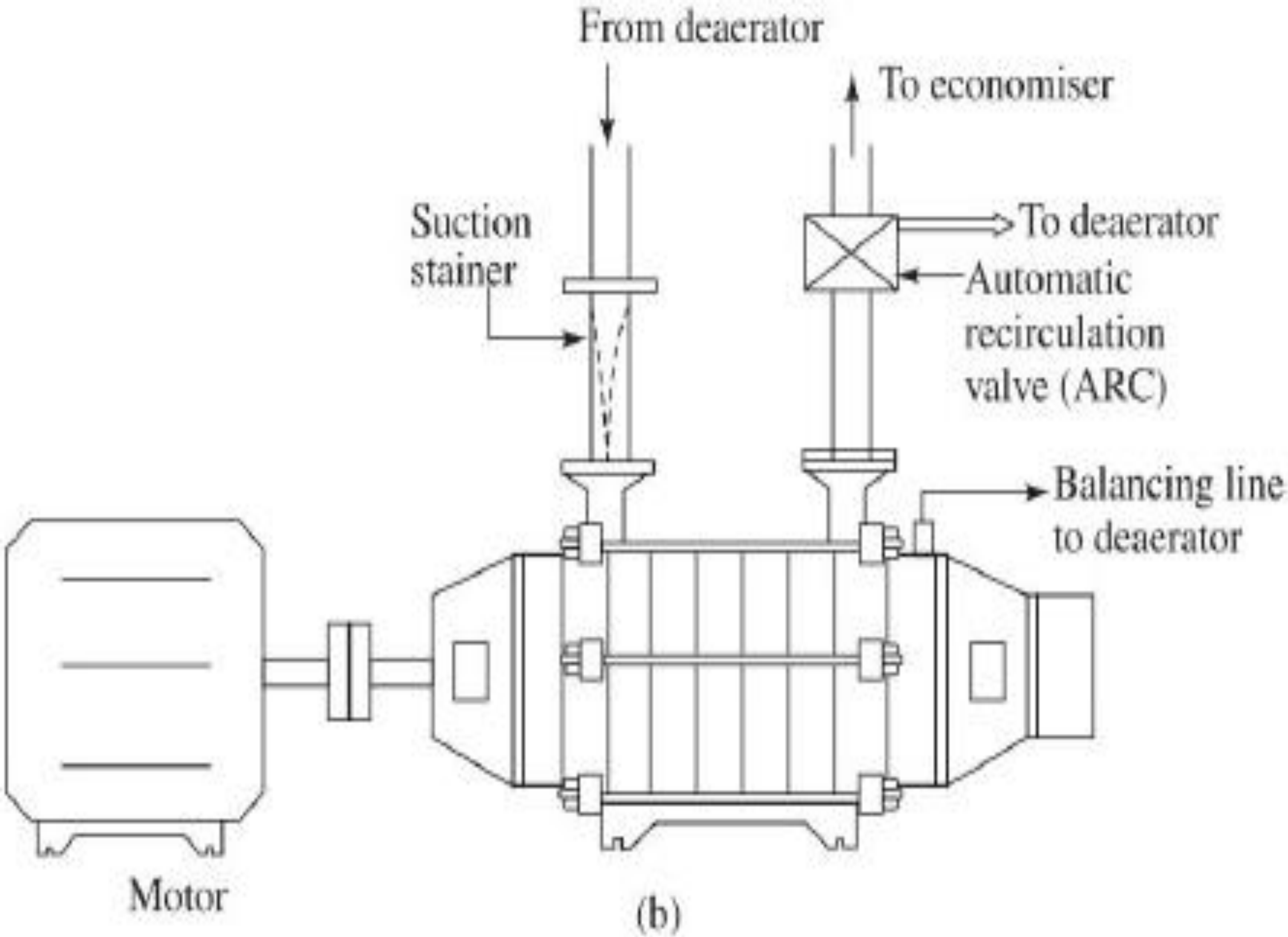


Fig. 2.30 *(a) Deaerator with storage tank (b) Boiler feed pump*

Deaerator working principle:

- Using Henry's law of partial pressures, the principle behind deaeration can be explained as follows:
- The quantity of a gas dissolved in a given quantity of liquid is directly proportional to its partial pressure surrounding the liquid.

- Therefore, by reducing the partial pressure of the unwanted gasses in the surrounding atmosphere, the gasses are diminished.

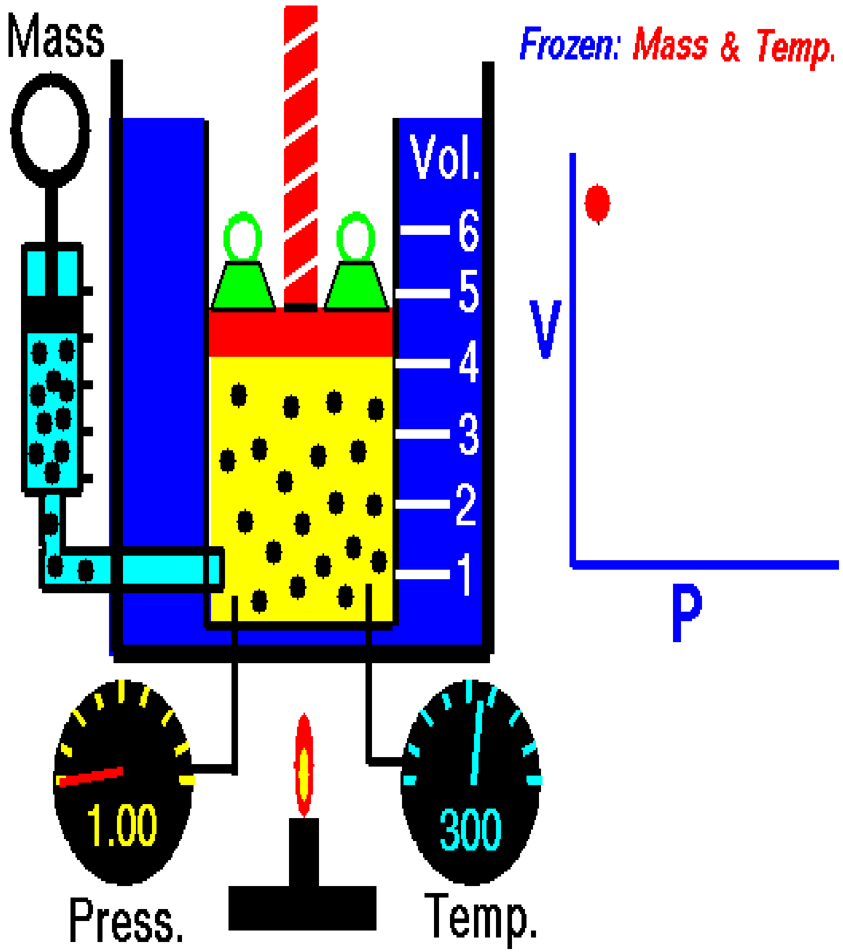
- These partial pressures are reduced by spraying the liquid into a countercurrent flow of steam.

- The steam, which is free of non-condensable gasses, is the liquid's new atmosphere and Henry's law prevails.

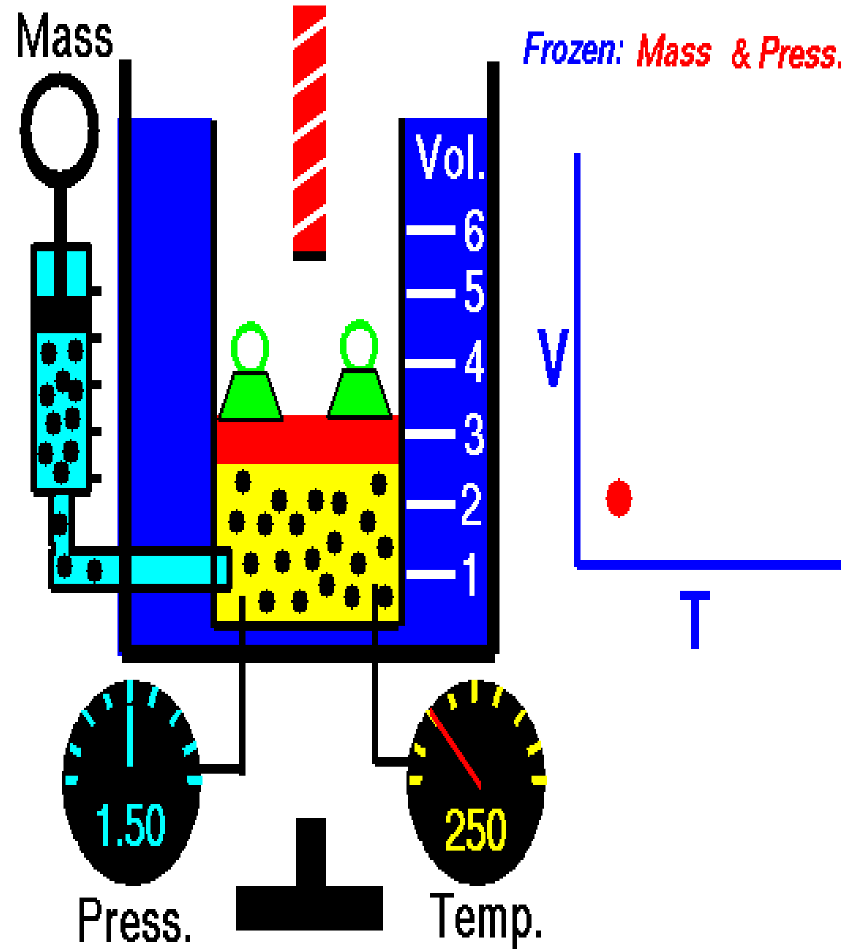
- Using steam is advantageous in that the solubility of a gas in a liquid decreases with an increase in the temperature of that liquid.

Boyles & Charles laws

Boyles law



Charles law



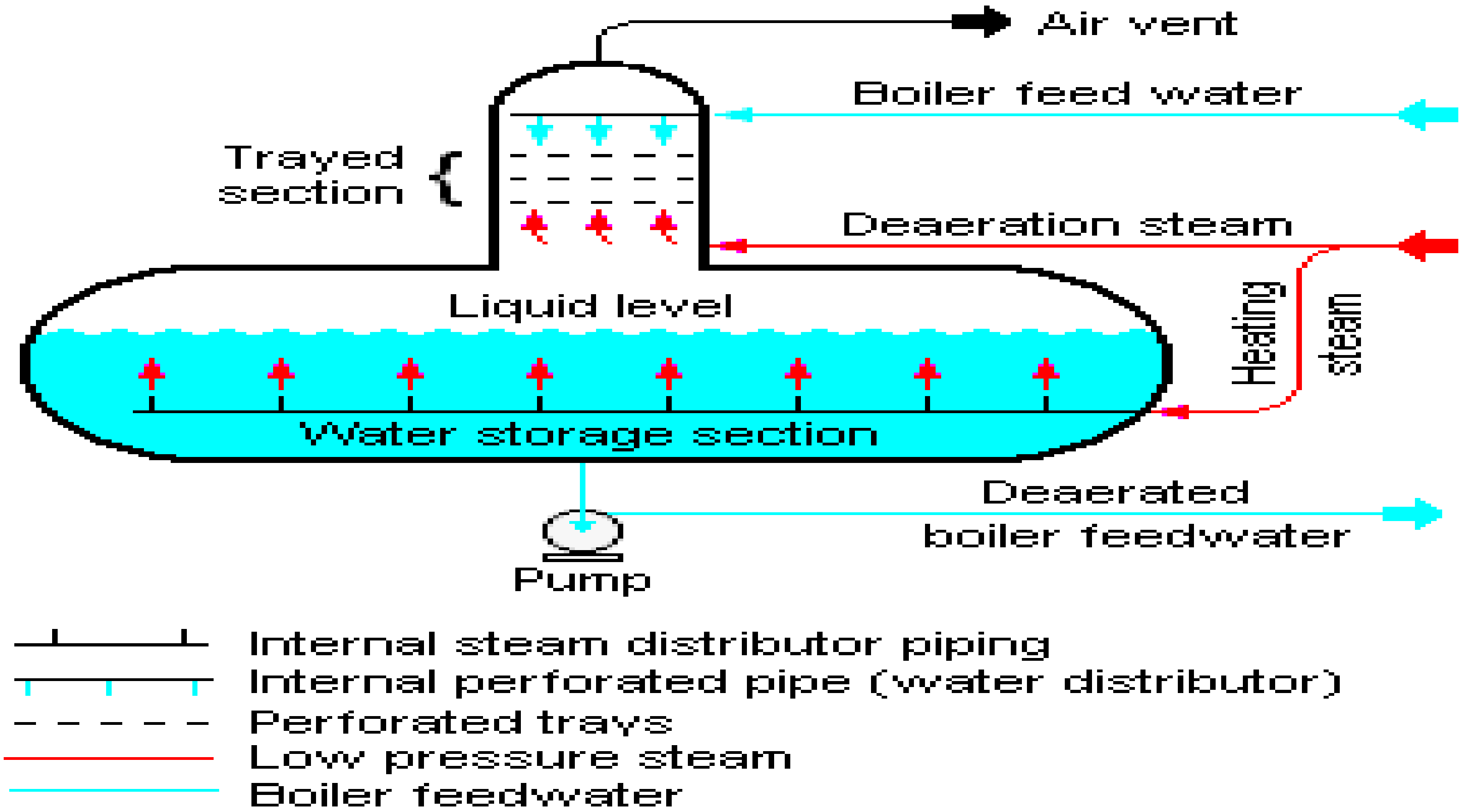
Basic types of Deaerators

The *tray-type* (also called the *cascade-type*):

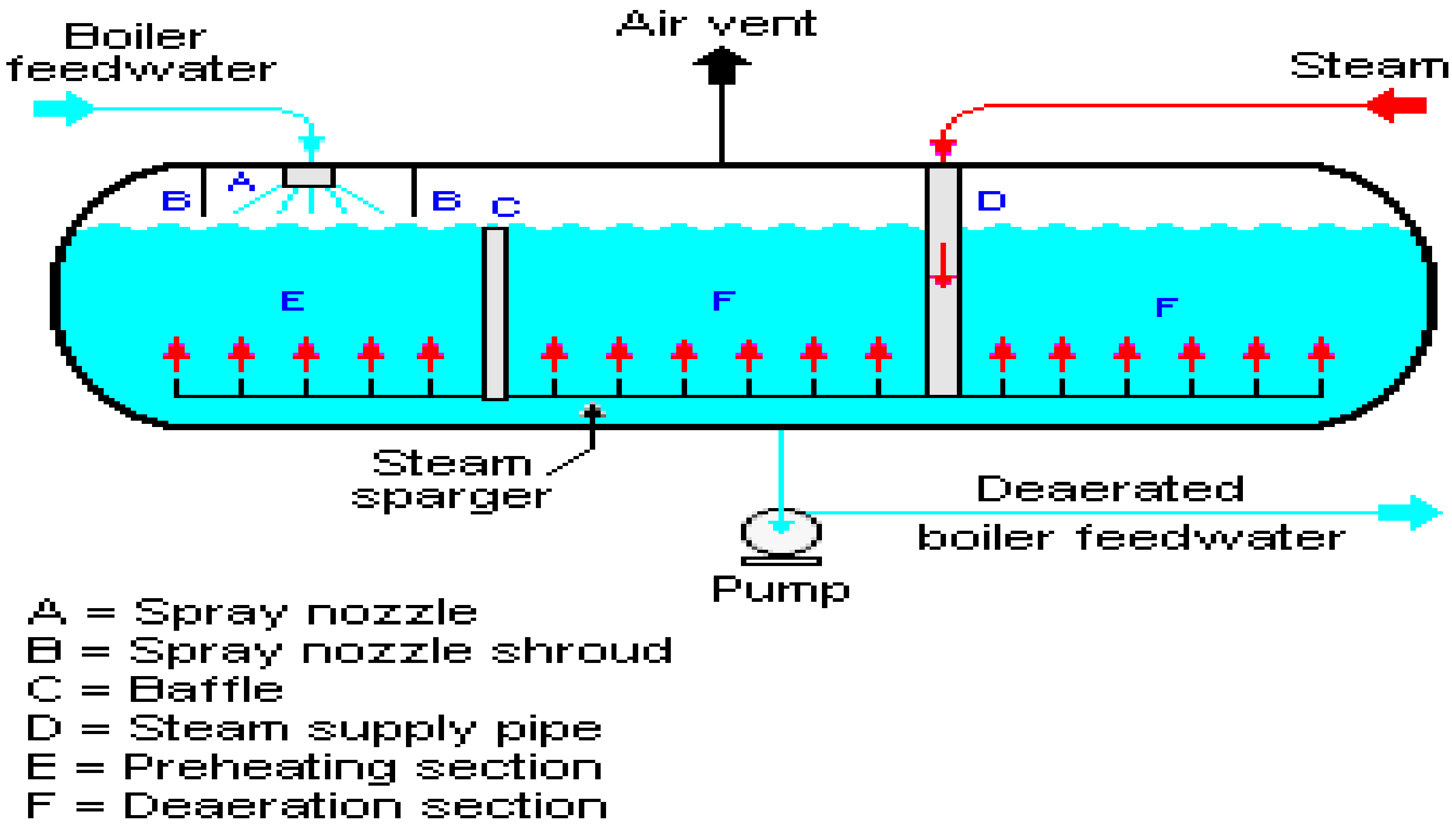
It includes a vertical domed deaeration section mounted on top of a horizontal cylindrical vessel which serves as the deaerated boiler feedwater storage tank.

The *spray-type* consists only of a horizontal (or vertical) cylindrical vessel which serves as both the deaeration section and the boiler feedwater storage tank.

Tray-type deaerator



Spray-type deaerator



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