Thermodynamics
Chapter 7
POWER AND REFRIGERATION CYCLES

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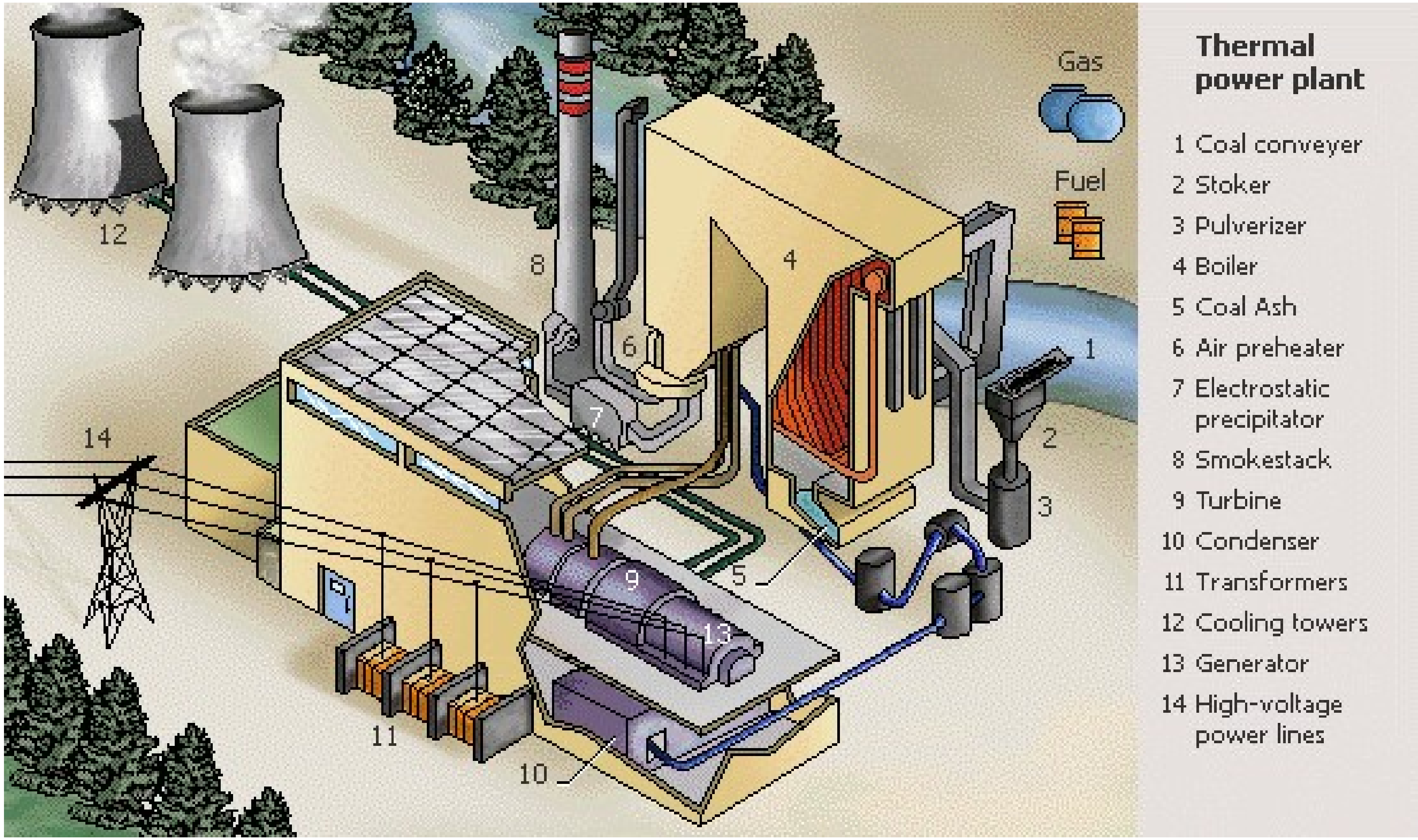
Vapor Power Cycles

Coverage

1. Analyze **vapor power cycles** in which the working fluid is alternately vaporized and condensed.
2. Investigate ways to modify the basic **Rankine** vapor power cycle to increase the cycle **thermal efficiency**.

Thermal Power Plant



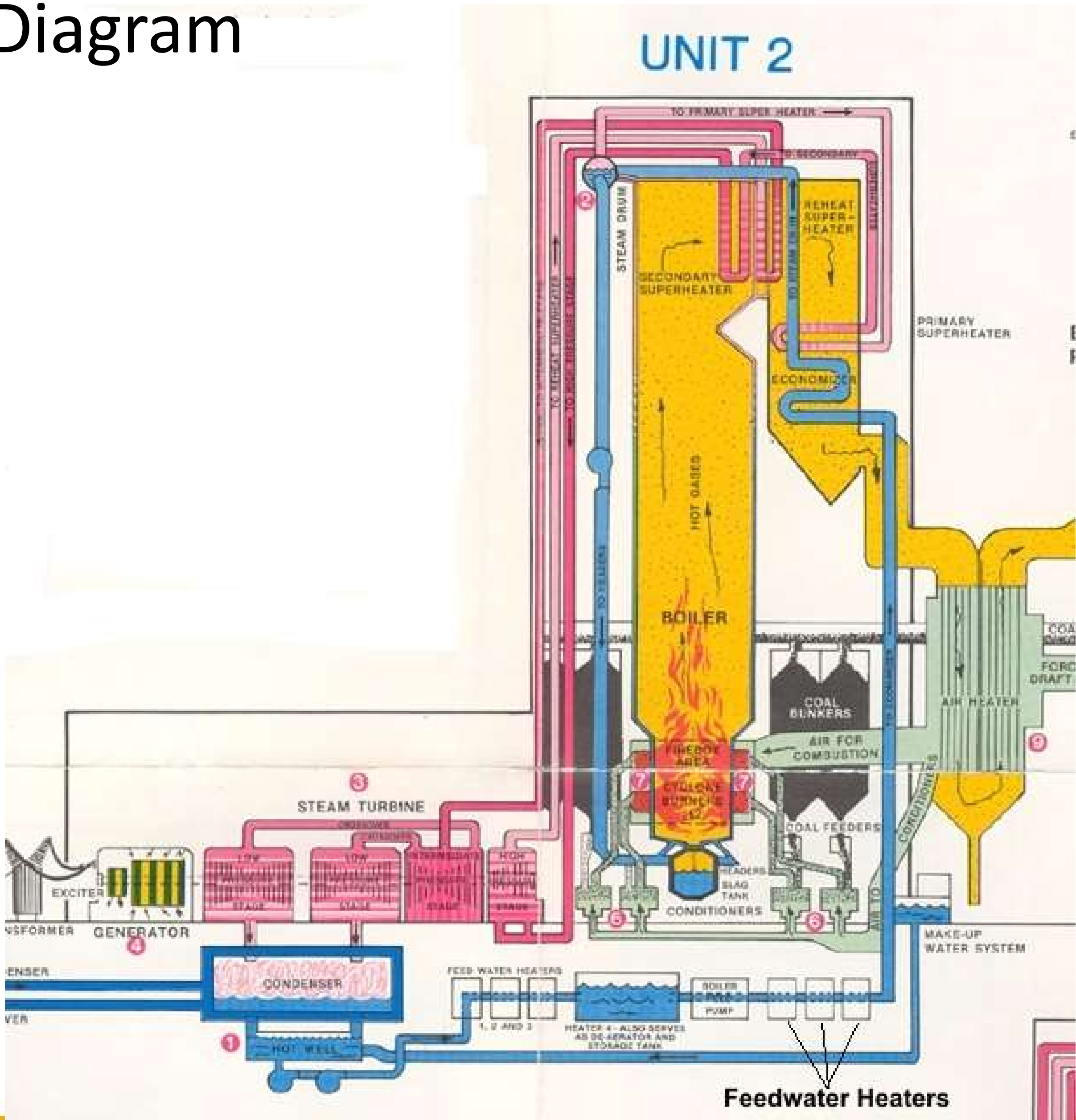
Kapar Power Station

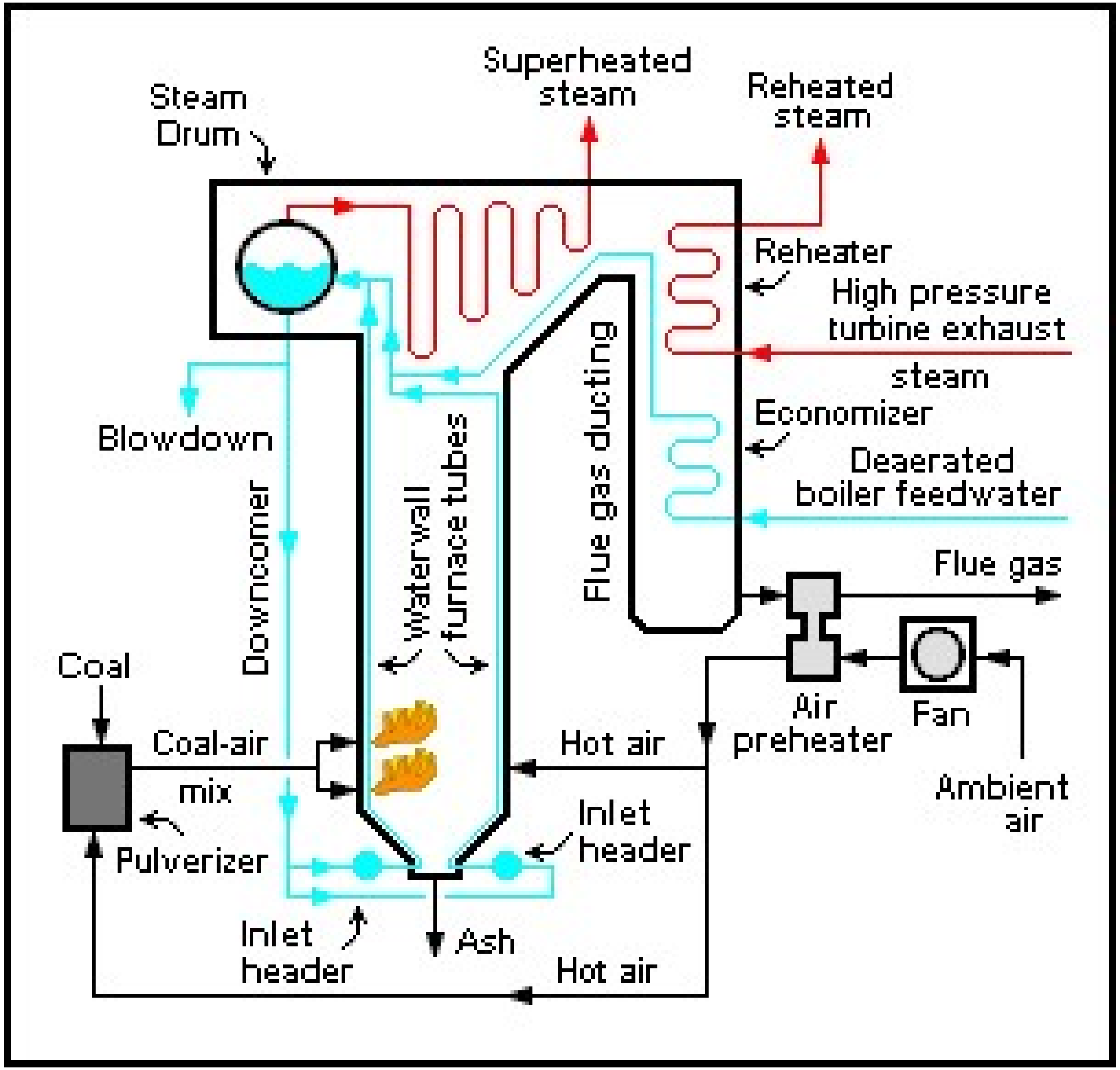
Kapar Power Station

Tanjung Bin Power Station

Tanjung Bin Power Station

Schematic Diagram

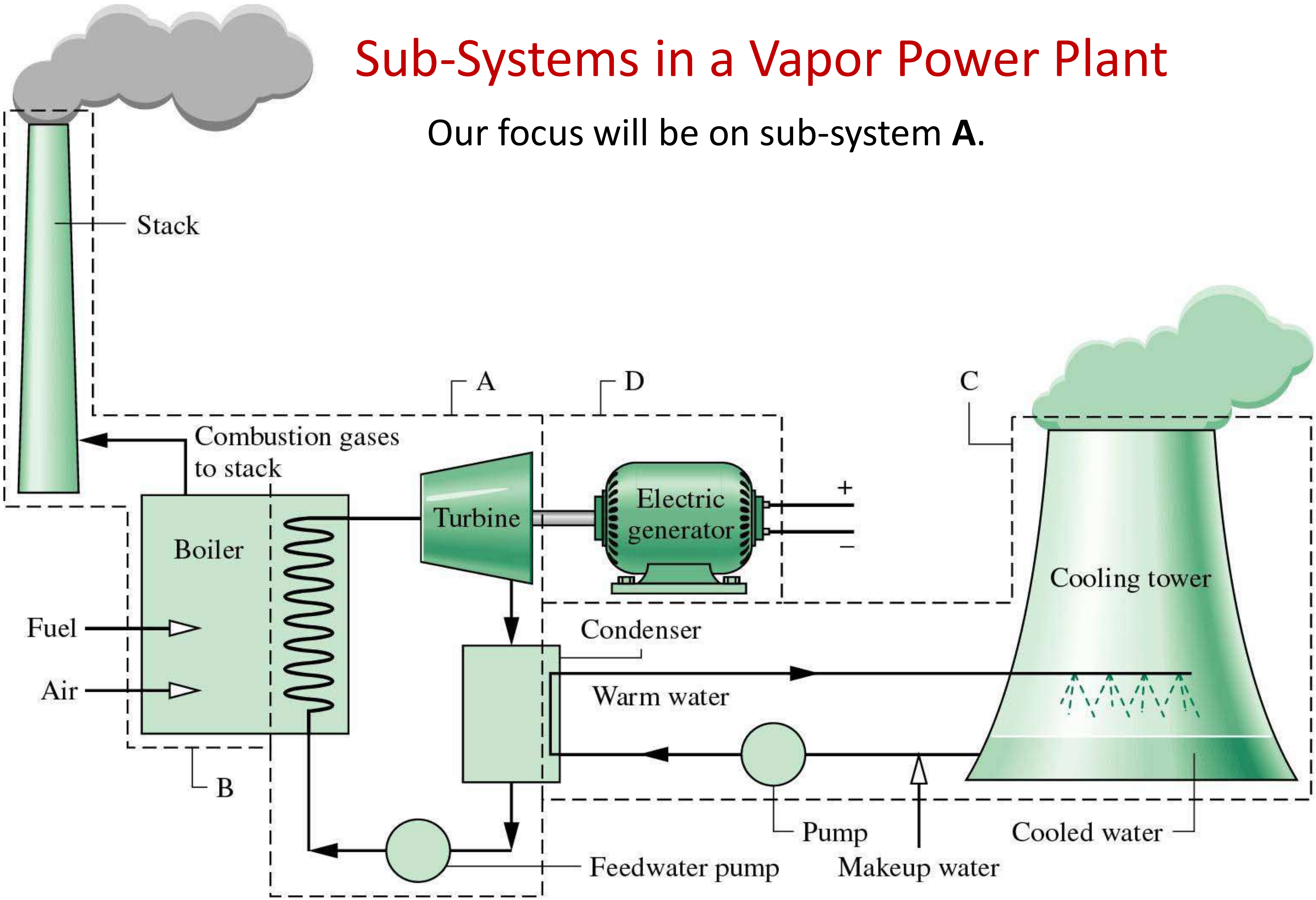




Steam Drum
Superheated steam
Reheated steam
Reheater
High pressure turbine exhaust steam
Economizer
Deaerated boiler feedwater
Flue gas
Blowdown
Downcomer
Waterwall furnace tubes
Flue gas ducting
Coal
Coal-air mix
Pulverizer
Hot air
Air preheater
Fan
Ambient air
Inlet header
Inlet header
Ash
Hot air

Sub-Systems in a Vapor Power Plant

Our focus will be on sub-system **A**.



Introduction

Steam (Water Vapor)

Steam is the most common working fluid used in vapor power cycles because of its many desirable characteristics, such as: (a) low cost, (b) availability, and (c) high enthalpy of vaporization#.

Steam power plants are commonly referred to as: (a) coal plants, (b) nuclear plants, or (c) natural gas plants, depending on the **type of fuel** used to supply heat to the steam.

The steam goes through the same **basic cycle** in all of them. Therefore, all can be analyzed in the same manner.

The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure, h_{fg}.

Carnot Vapor Cycle

Carnot cycle is the **most efficient** power cycle operating between two specified temperature limits (Fig. 10-1).

We can adopt the Carnot cycle first as a prospective **ideal cycle** for vapor power plants.

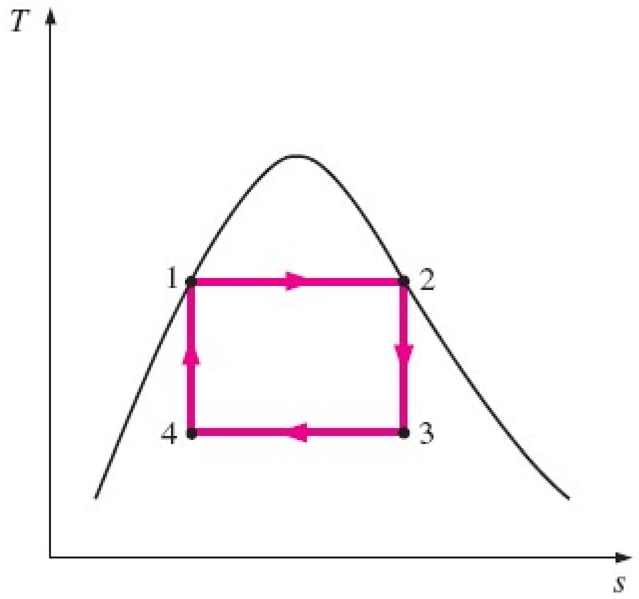


FIGURE 10–1

T-s diagram of two Carnot vapor cycles.

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).

$$\eta_{Carnot} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$

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.

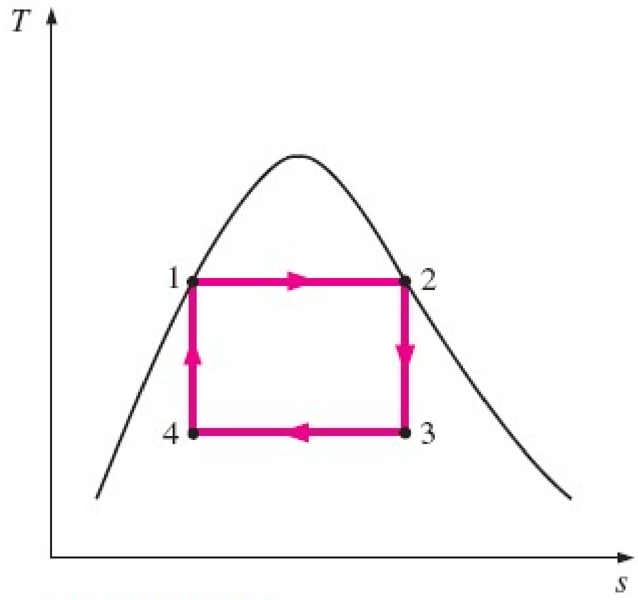


FIGURE 10–1

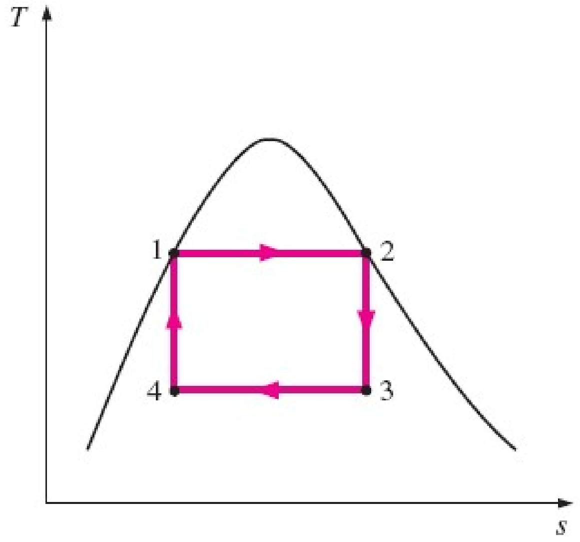
T-s diagram of two Carnot vapor cycles.

The Rankine Cycle

Many of the impracticalities associated with the Carnot cycle can be eliminated by: (a) **superheating** the steam in the boiler, and (b) condensing the steam **completely** in the condenser.

The modified Carnot cycle is called the **Rankine cycle**, where the **isothermal processes are replaced with constant pressure processes** to facilitate doing (a) and (b) above. This is the ideal and practical cycle for vapor power plants (Figure 10-2).

This ideal cycle does not involve any internal irreversibilities.



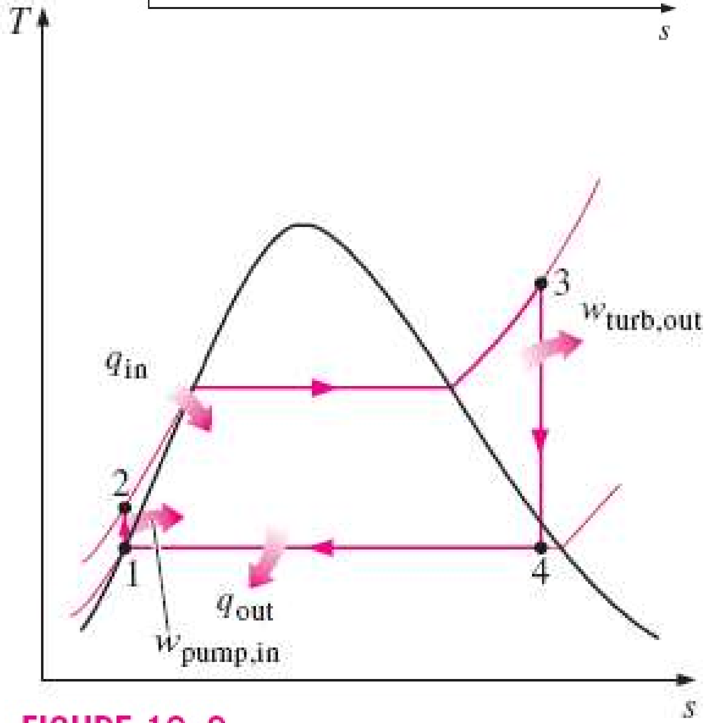


FIGURE 10–2

The simple 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.

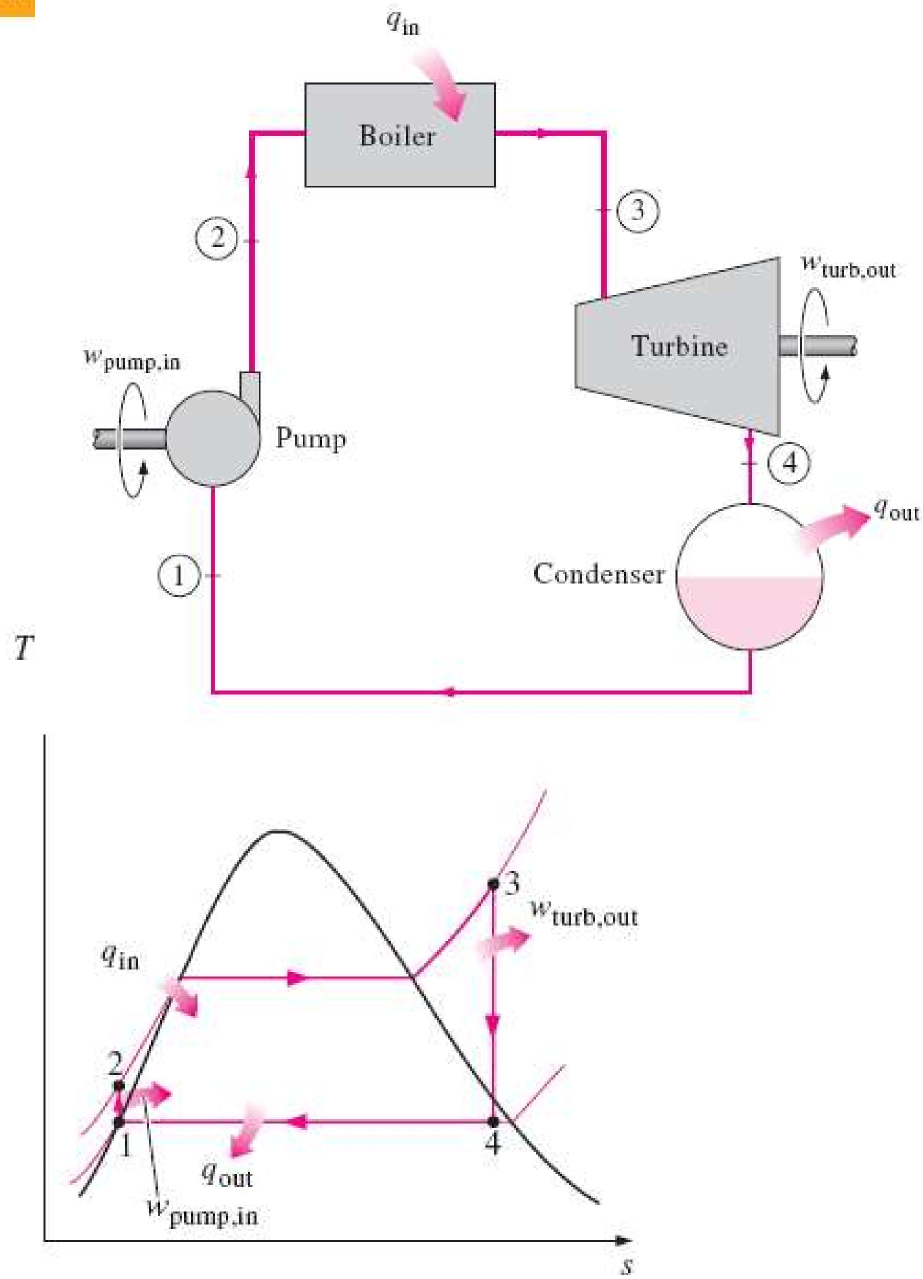


FIGURE 10–2

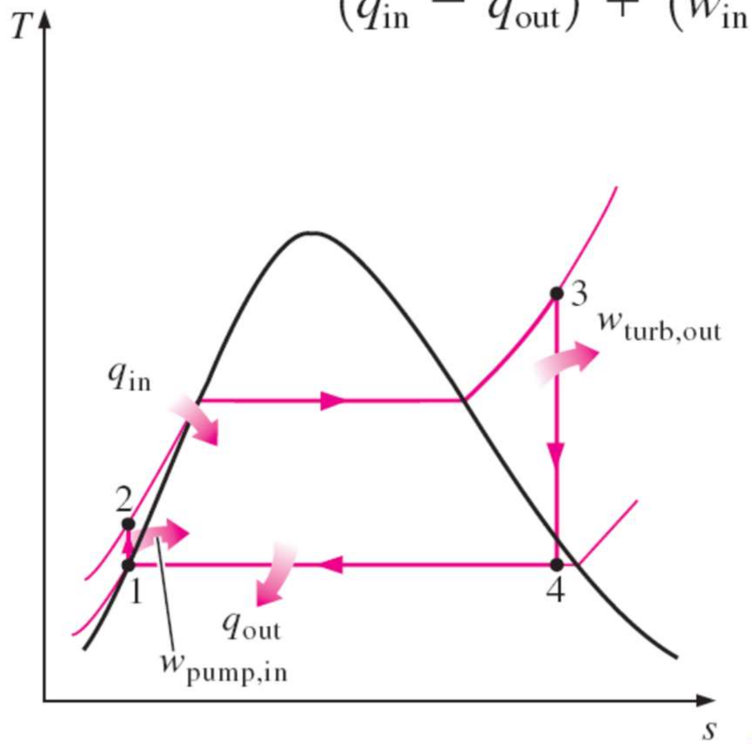
The simple ideal Rankine cycle.

Energy Analysis of Ideal Rankine Cycle

The pump, boiler, turbine, and condenser are **steady-flow** devices. Thus all four processes that make up 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:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \qquad (kJ/kg)$$



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.

Energy Interactions in Each Device

Pump: The work needed to operate the water pump,

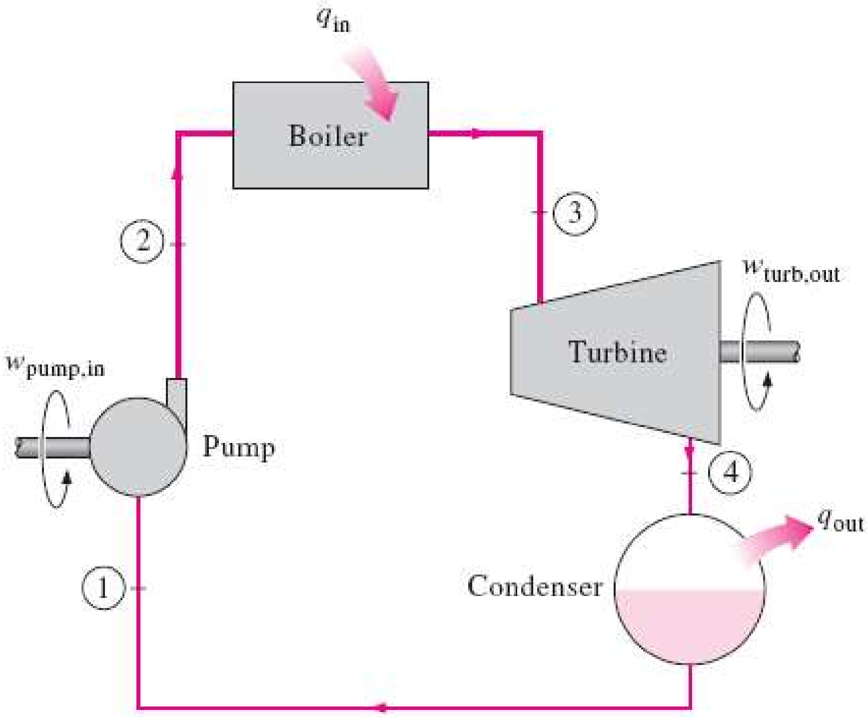
$$w_{\text{pump,in}} = h_2 - h_1$$

where,

$$w_{\text{pump,in}} = v(P_2 - P_1) \qquad h_1 = h_{f\,@\,P_1} \quad \text{and} \quad v \cong v_1 = v_{f\,@\,P_1}$$

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

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



Turbine: The amount of work produced by the turbine,

$$w_{\text{turb,out}} = h_3 - h_4$$

Condenser: The amount of heat rejected to cooling medium in the condenser,

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

Performance of Ideal Rankine Cycle

Thermal Efficiency

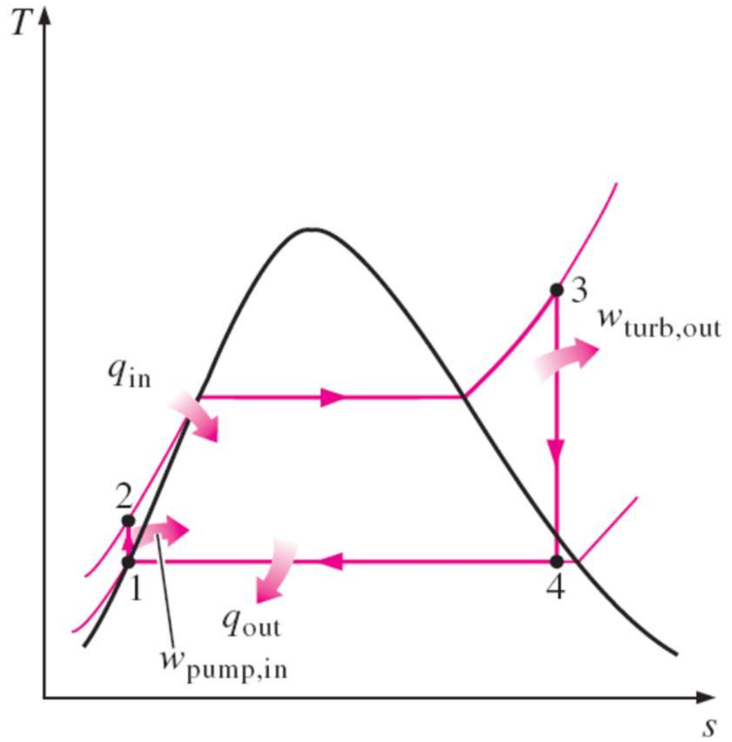
The thermal efficiency of the Rankine cycle is determined from,

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

where the **net work** output,

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

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.

Problem

The Simple Rankine Cycle

10–16

Consider a 210-MW steam power plant that operates on a simple **ideal Rankine cycle**. Steam enters the turbine at 10 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa. Show the cycle on a *T-s diagram* with respect to saturation lines, and determine:

(a) the quality 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) 0.793, (b) 40.2 percent, (c) 165 kg/s

Problem

The Simple Rankine Cycle

10-16

Solve Prob. 10-16.

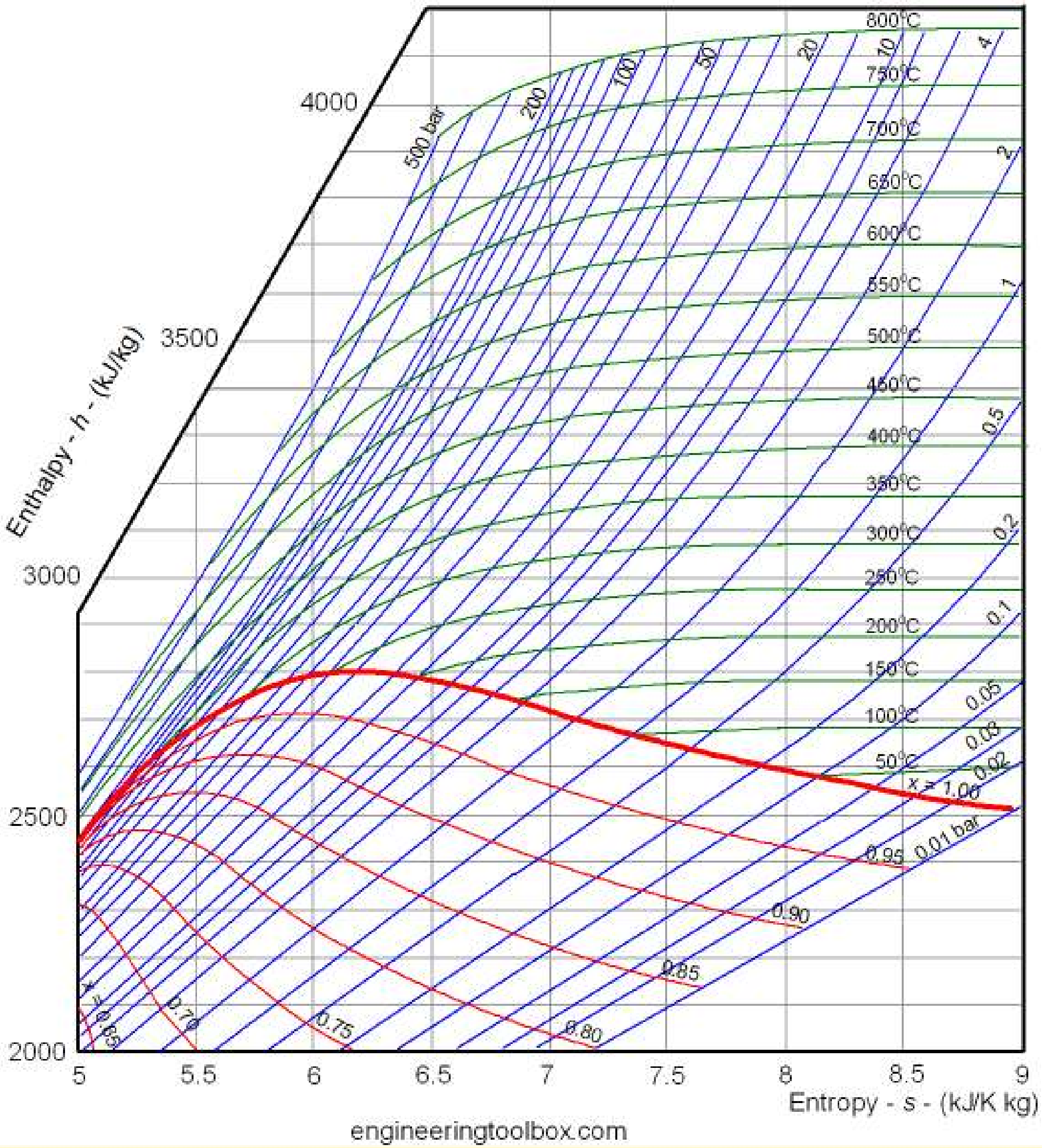
Answers: (a) 0.793, (b) 40.2 percent, (c) 165 kg/s

10–17

Repeat Prob. 10–16 assuming an **isentropic efficiency** of 85 percent for both the turbine and the pump.

Answers: (a) 0.874, (b) 34.1 percent, (c) 194 kg/s

Mollier Diagram (h-s diagram)



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.

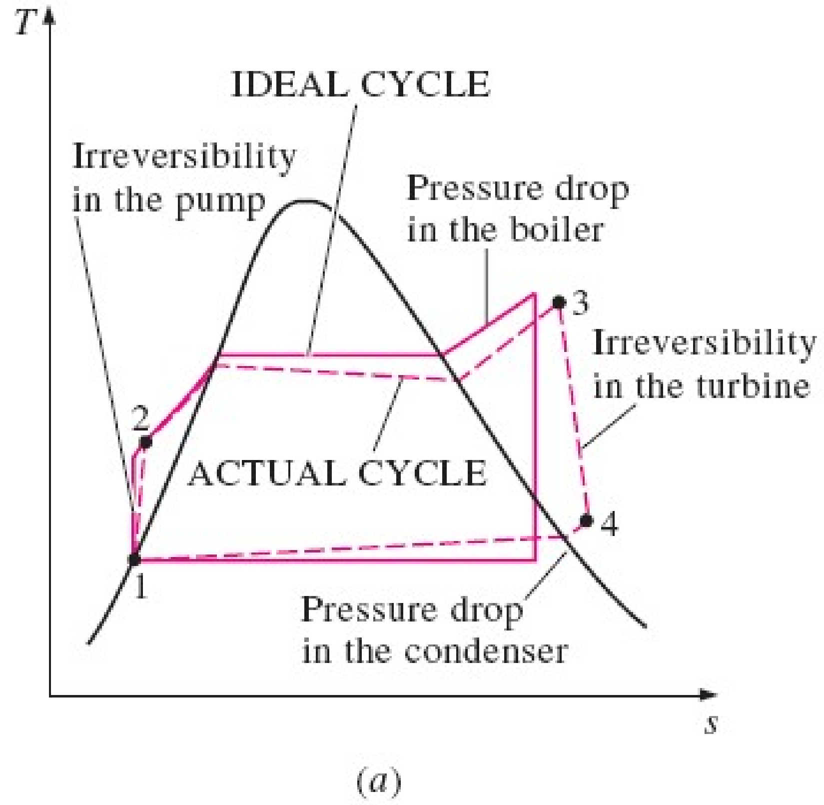


FIGURE 10–4

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

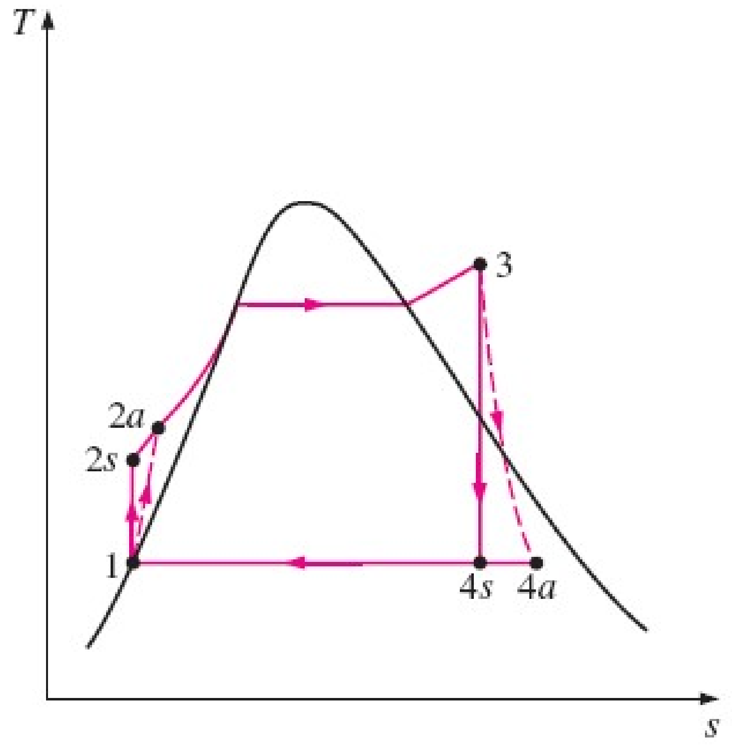
Isentropic Efficiencies

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,

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

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



In actual condensers, the liquid is usually **sub-cooled** to prevent the onset of cavitation, which may damage the water pump. Additional losses occur at the bearings between the moving parts as a result of **friction**. Two other factors are the steam that **leaks** out during the cycle and air that leaks into the condenser.

Problem

The Simple Rankine Cycle

Homework Exercise

10–22

Consider a steam power plant that operates on a simple **ideal Rankine cycle** and has a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa by running cooling water from a lake through the tubes of the condenser at a rate of 2000 kg/s. Show the cycle on a *T-s diagram* with respect to saturation lines, and determine:

(a) the thermal efficiency of the cycle,
(b) the mass flow rate of the steam, and
(c) the temperature rise of the cooling water.

Answers: (a) 38.9 percent, (b) 36 kg/s, (c) 8.4°C

Increasing Efficiency of Rankine Cycle

Thermal efficiency of the ideal Rankine cycle can be increased by: (a) Increasing the average temperature at which heat is transferred to the working fluid in the boiler, or (b) decreasing the average temperature at which heat is rejected from the working fluid in the condenser.

Lowering the Condenser Pressure

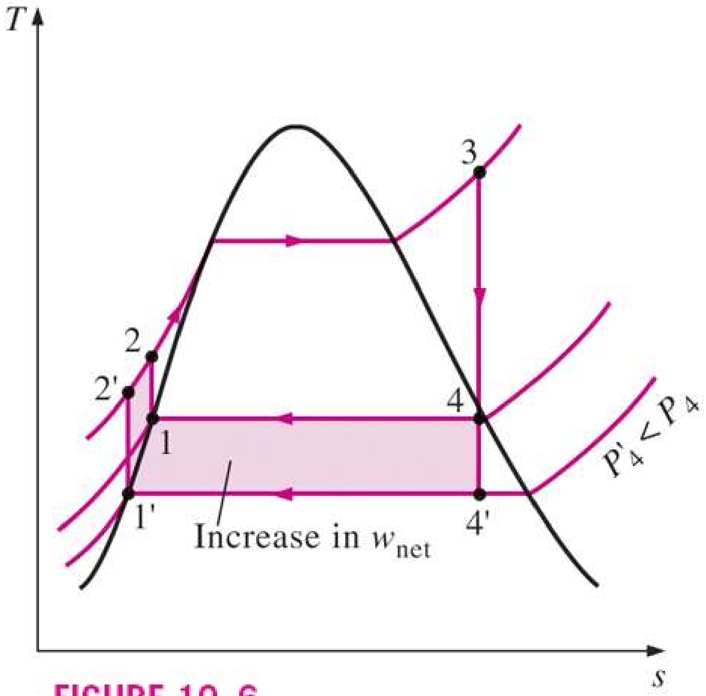


FIGURE 10–6

The effect of lowering the condenser pressure on the ideal Rankine cycle.

The condensers of steam power plants usually operate well **below** the atmospheric pressure. There is a lower limit to this pressure depending on the temperature of the cooling medium.

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.

Superheating the Steam to High Temperatures

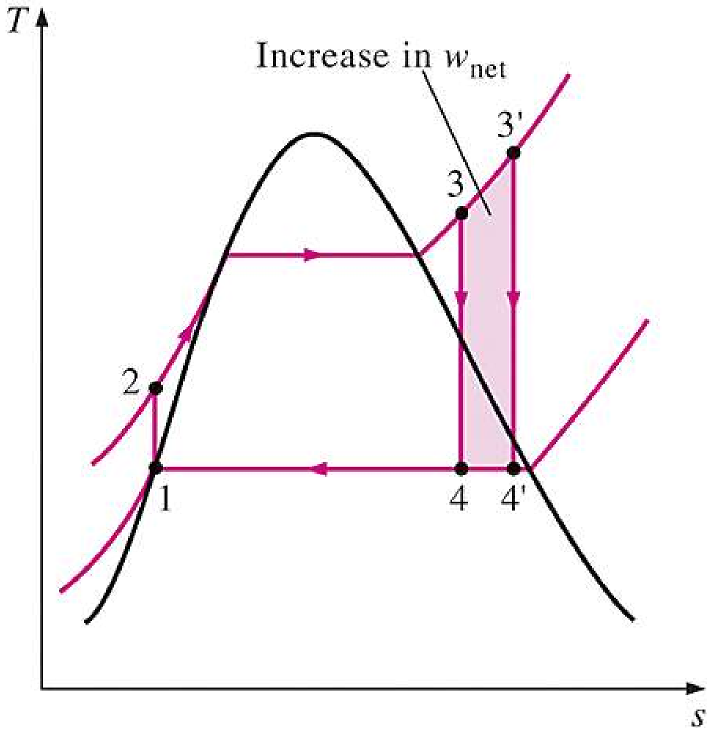


FIGURE 10–7

The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.

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**.

Increasing the Boiler Pressure

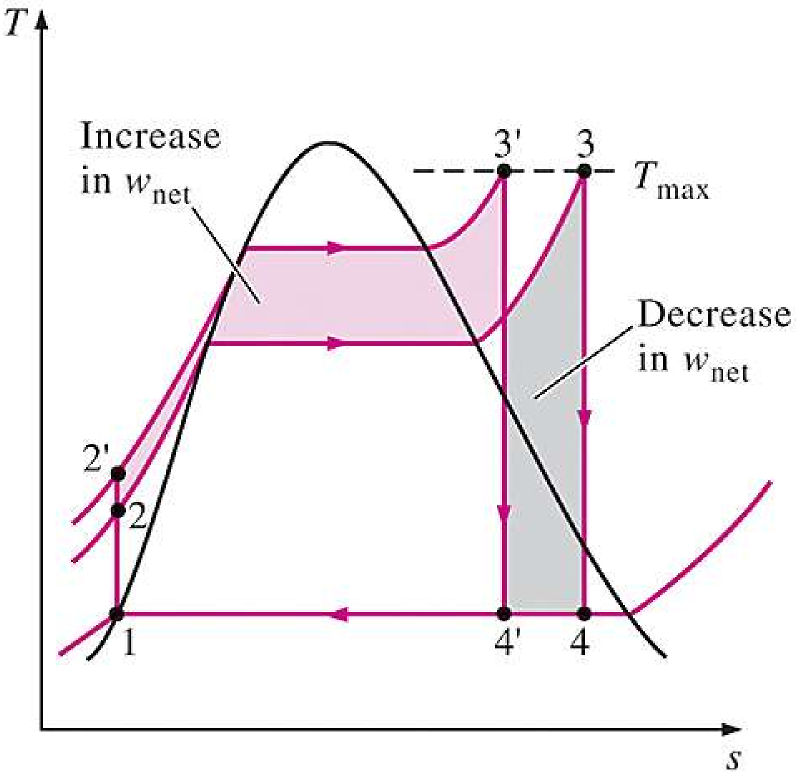


FIGURE 10–8

The effect of increasing the boiler pressure on the ideal Rankine cycle.

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.

The 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.

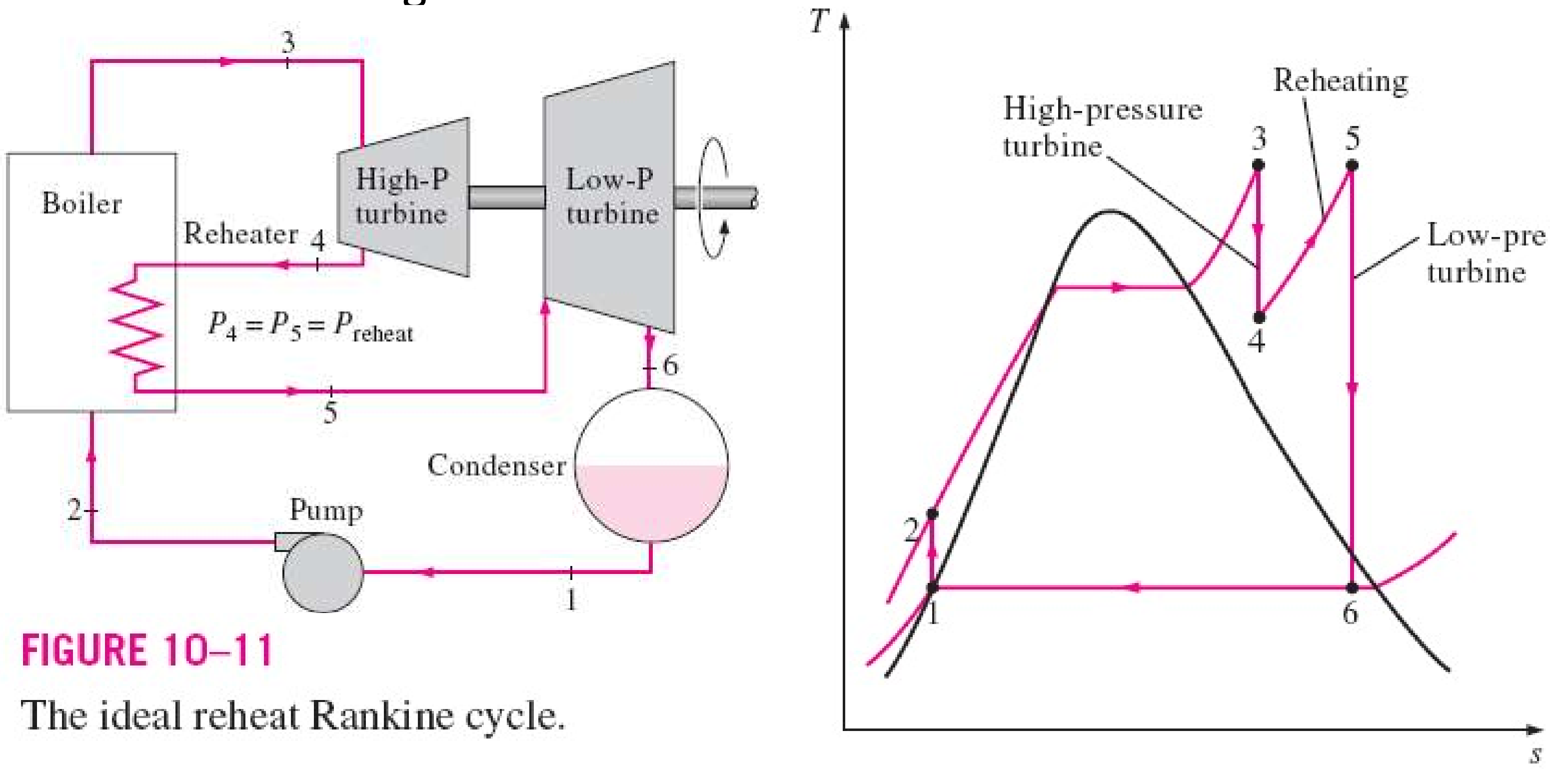


FIGURE 10–11

The ideal reheat Rankine cycle.

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

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

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

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

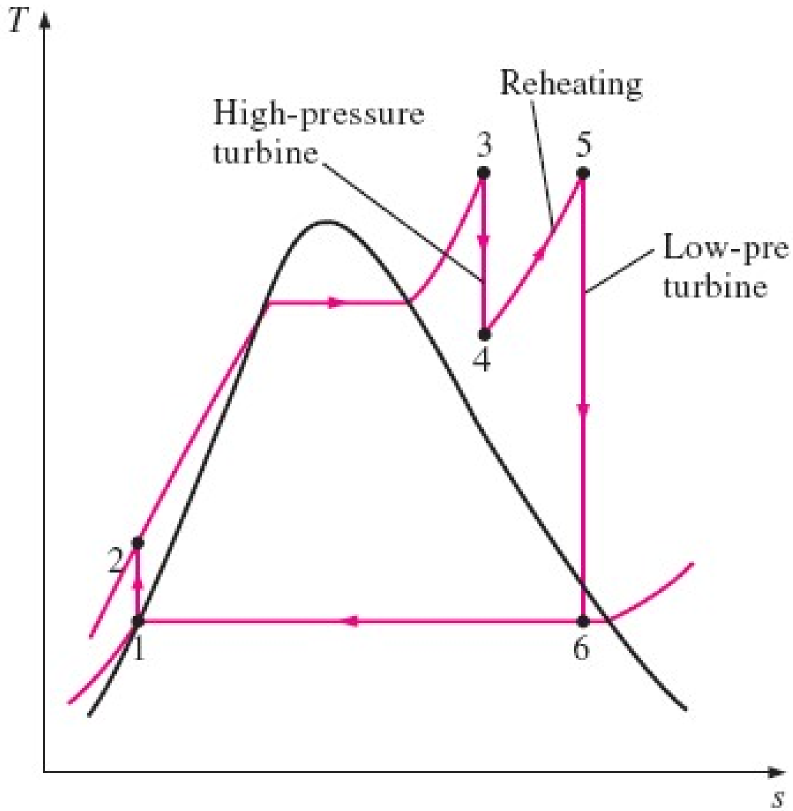


FIGURE 10–11

The ideal reheat Rankine cycle.

Problem

The Reheat Rankine Cycle

10–34

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 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

The Reheat Rankine Cycle

10–38

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.

Problem

The Regenerative Rankine Cycle

10–44

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

Refrigeration

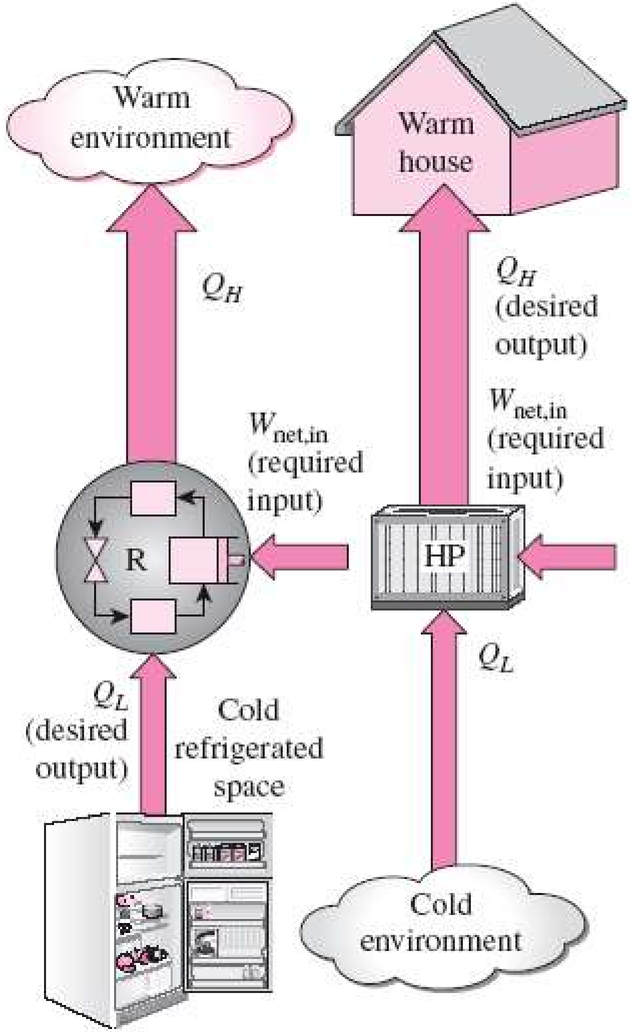
Objectives

- Introduce the concepts of refrigerators and heat pumps and the measure of their performance.
- Analyze the ideal vapor-compression refrigeration cycle.
- Analyze the actual vapor-compression refrigeration cycle.

Introduction

- Refrigeration is the process of removing heat from an enclosed space, or from a substance, and rejecting it to an environment.
- The primary purpose of refrigeration is lowering the temperature of the enclosed space or substance and then maintaining that lower temperature.
- The term cooling refers generally to any natural or artificial process by which heat is dissipated. The process of artificially producing extreme cold temperatures is referred to as cryogenics

REFRIGERATORS AND HEAT PUMPS



(*a*) Refrigerator (*b*) Heat pump

- The transfer of heat from a low-temperature region to a high-temperature one requires special devices called **refrigerators**.
- Another device that transfers heat from a low-temperature medium to a high-temperature one is the **heat pump**.
- Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only.
- The objective of a refrigerator is to remove heat (Q_L) from the cold medium
- The objective of a heat pump is to supply heat (Q_H) to a warm medium.

Methods of refrigeration

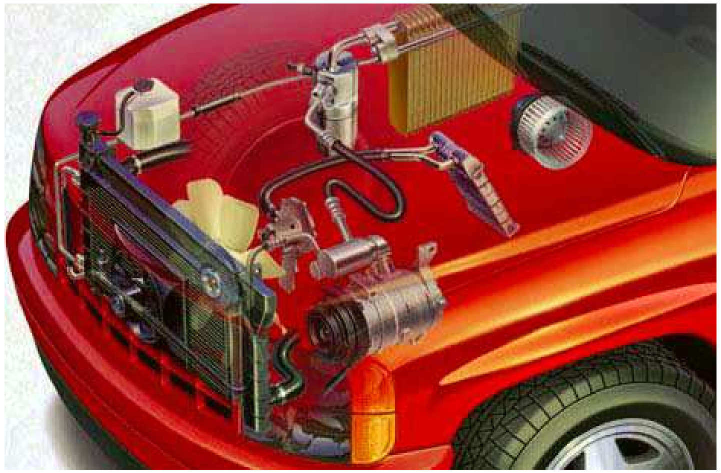
- Can be classified as ***non-cyclic*, *cyclic*** and ***thermoelectric*.**
- **Non-cyclic refrigeration -** cooling is accomplished by melting ice or by subliming dry ice (frozen carbon dioxide). Are used for small-scale refrigeration i.e. laboratories and workshops, or in portable coolers.
- **Cyclic refrigeration -** Consists of a refrigeration cycle, heat is removed from a low-temperature space/source and rejected to a high-temperature sink with the help of external work
- Cyclic refrigeration can be classified as **Vapor cycle** and Gas cycle
- Vapor cycle refrigeration can further be classified as:
  - **Vapor-compression refrigeration**
  - Vapor-absorption refrigeration

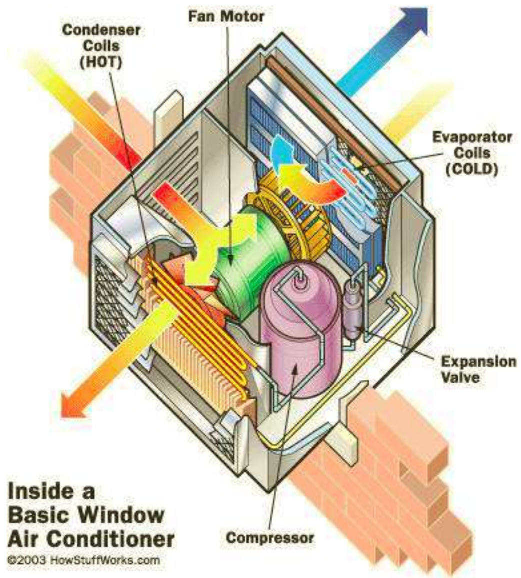
Methods of refrigeration

- **Gas cycle -** Air is most often the working fluid. The hot and cold gas-to-gas heat exchangers are used. Less efficient than the vapor compression cycle because the gas cycle works on the reverse Brayton cycle instead of the reverse Rankine cycle
- **Thermoelectric refrigeration -** Thermoelectric cooling uses the Peltier effect to create a heat flux between the junction of two different types of materials. Commonly used in camping and portable coolers
- **Thermoacoustic refrigeration** uses sound waves in place of a compressor to create cooling power.

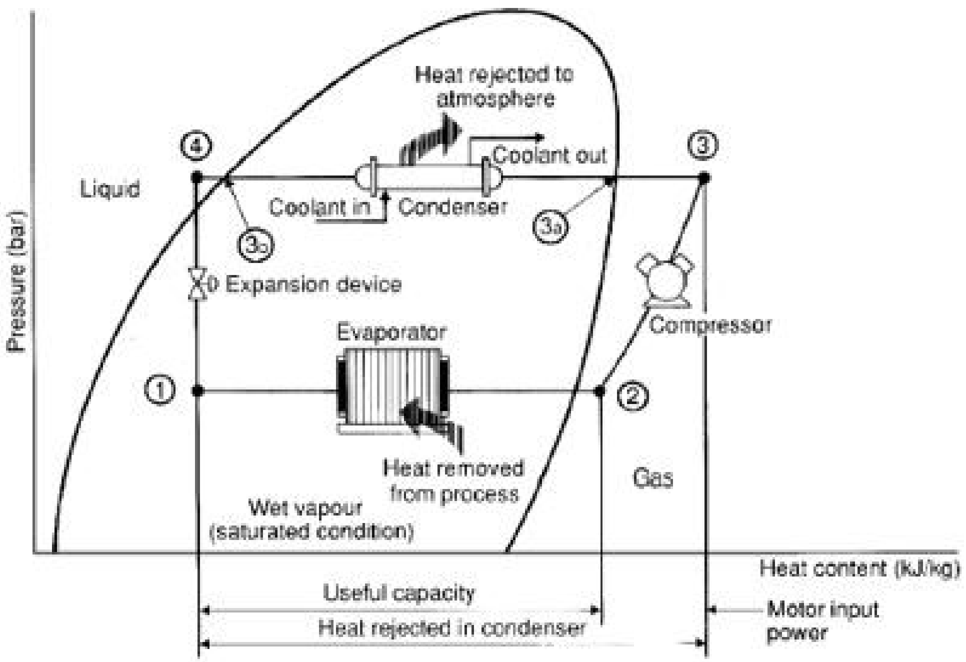
VAPOR COMPRESSION REFRIGERATION SYSTEM (VCRS)

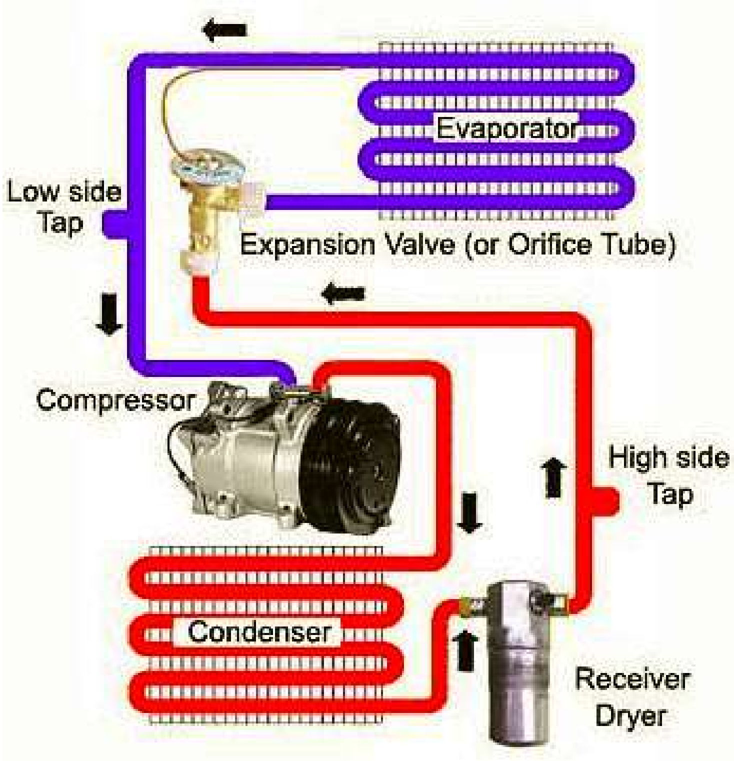
- Food Processing and storage - Refrigerator
- Building air conditioning system
- Car air conditioning system
- Water cooler
- Ice cube maker
- Low temperature drying process





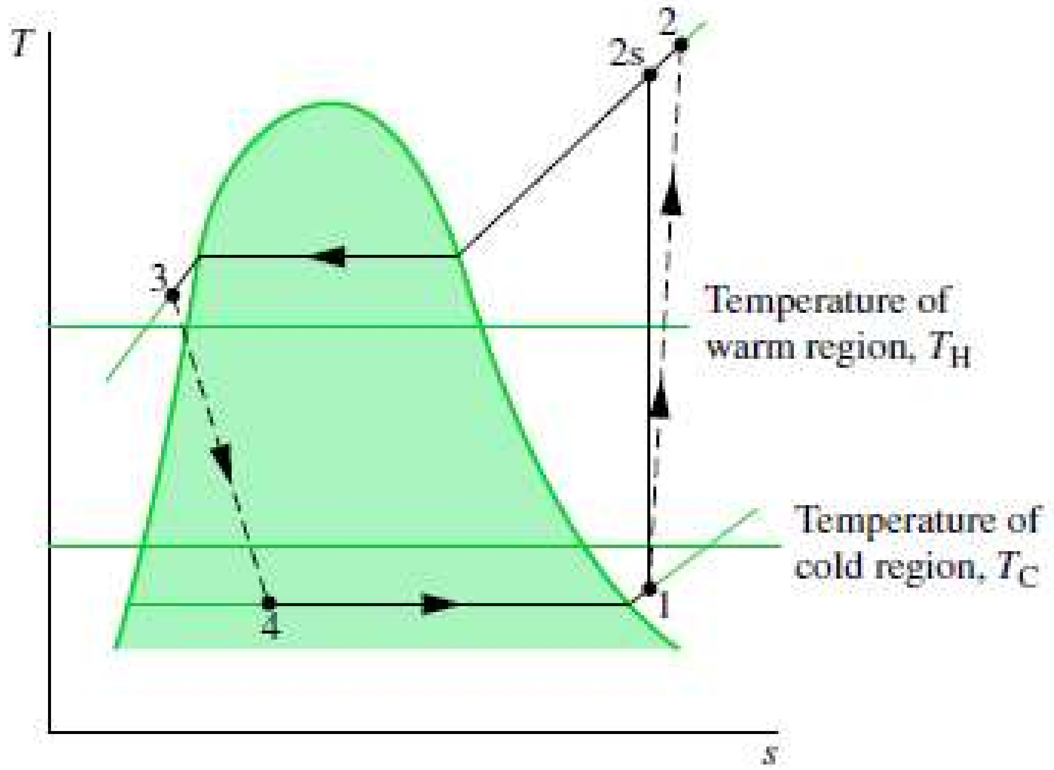
Operation of VCRS





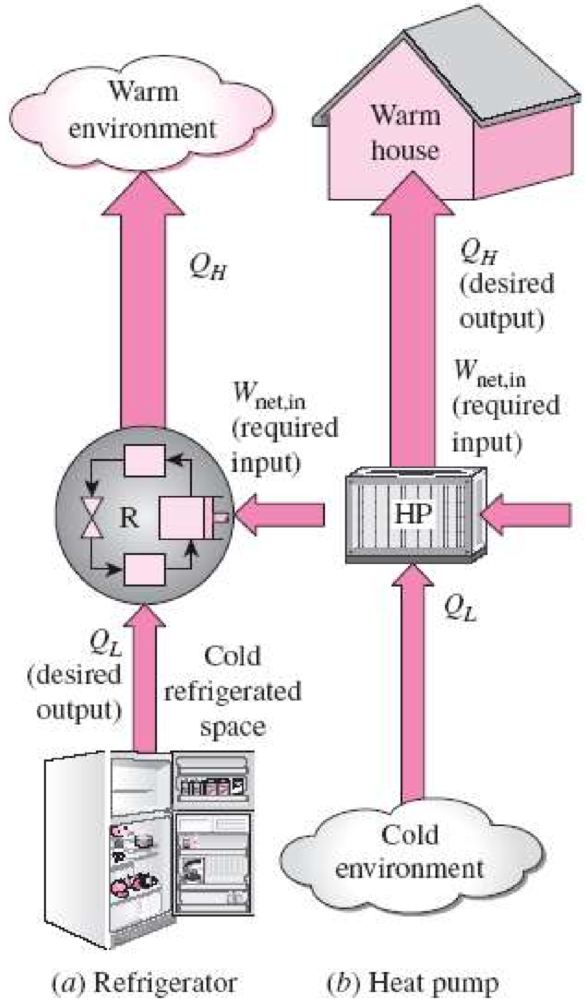
Refrigerated Space, Ambient Temperatures vs Cycle Temperatures

- Need to have delta_T to allow heat transfer
- Evaporator temperature lower than refrigerated space temperature
- Condenser temperature higher than ambient temperature



Coefficient of Performance

The performance of refrigerators and heat pumps is expressed in terms of the coefficient of performance (COP), defined as,



$$COP_R = \frac{Desired\ Output}{Required\ Input} = \frac{Cooling\ Effect}{Work\ Input} = \frac{Q_L}{W_{net,in}}$$

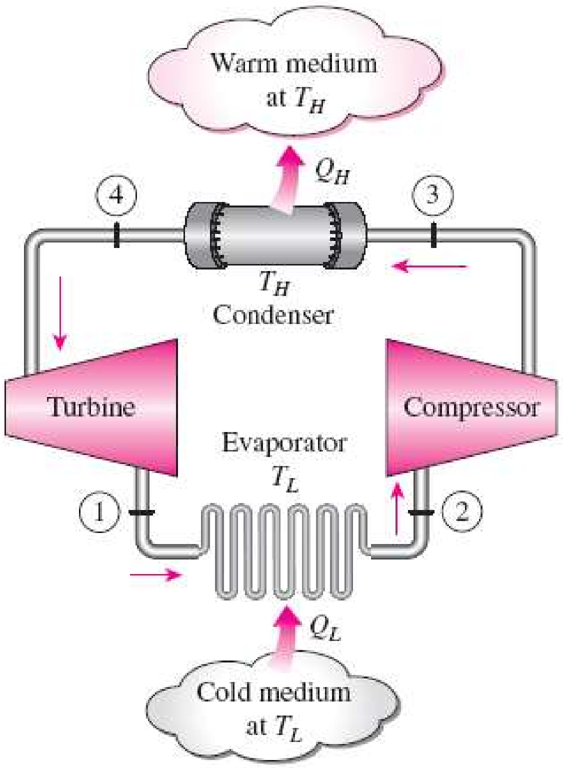
$$COP_{HP} = \frac{Desired\ Output}{Required\ Input} = \frac{Heating\ Effect}{Work\ Input} = \frac{Q_H}{W_{net,in}}$$

Both COP_R and COP_{HP} can be greater than 1.
For fixed values of Q_L and Q_H
$COP_{HP} = COP_R + 1$

THE REVERSED CARNOT CYCLE

The reversed Carnot cycle is the *most efficient* refrig. cycle operating between T_L *and* T_H.

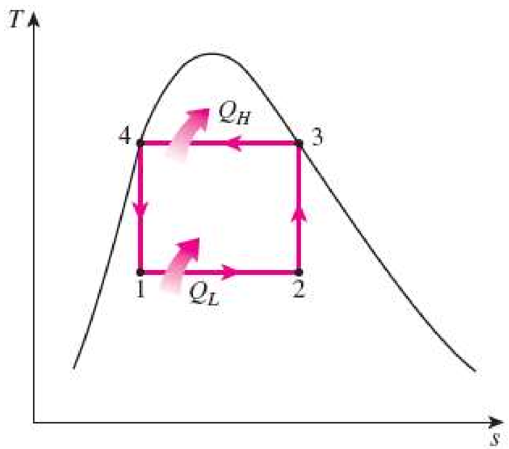
It is not a suitable model for refrigeration cycles since processes 2-3 and 4-1 are not practical because Process 2-3 involves the compression of a liquid–vapor mixture, which requires a compressor that will handle two phases, and process 4-1 involves the expansion of high-moisture-content refrigerant in a turbine.



$$\mathrm{COP}_{\mathrm{R,Carnot}} = \frac{1}{T_H/T_L - 1}$$

$$\mathrm{COP}_{\mathrm{HP,Carnot}} = \frac{1}{1 - T_L/T_H}$$

Both COPs increase as the difference between the two temperatures decreases, that is, as T_L rises or T_H falls.



Schematic of a Carnot refrigerator and *T-s* diagram of the reversed Carnot cycle.

REFERENCE COP

The maximum COP of a refrigeration cycle operating between temperature limits of T_L and T_H

$$\mathrm{COP}_{\mathrm{R,max}} = \mathrm{COP}_{\mathrm{R,rev}} = \mathrm{COP}_{\mathrm{R,Carnot}} = \frac{T_L}{T_H - T_L} = \frac{1}{T_H/T_L - 1}$$

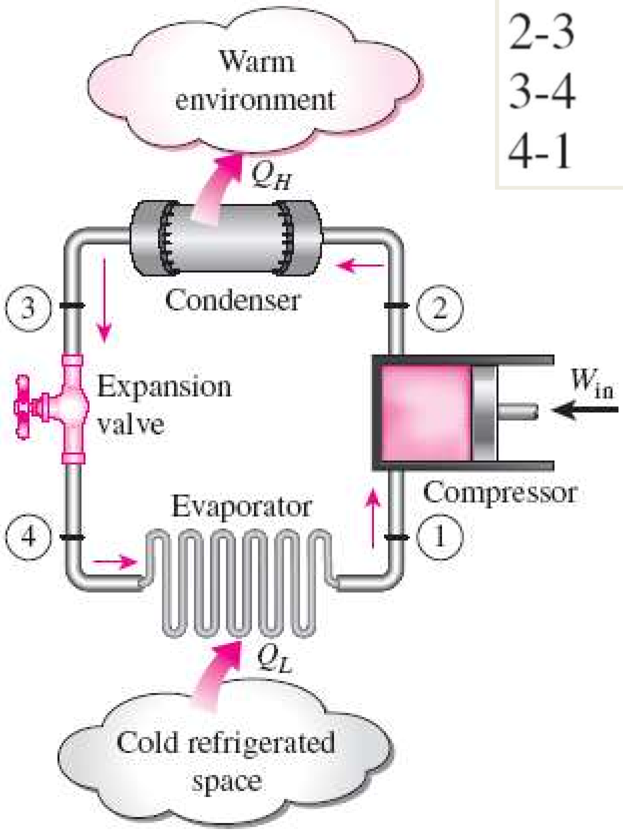
Actual refrigeration cycles are not as efficient as ideal ones like the Carnot cycle because of the irreversibilities involved. But the conclusion we can draw from the equation above that the COP is inversely proportional to the temperature difference T_H - T_L is equally valid for actual refrigeration cycles.

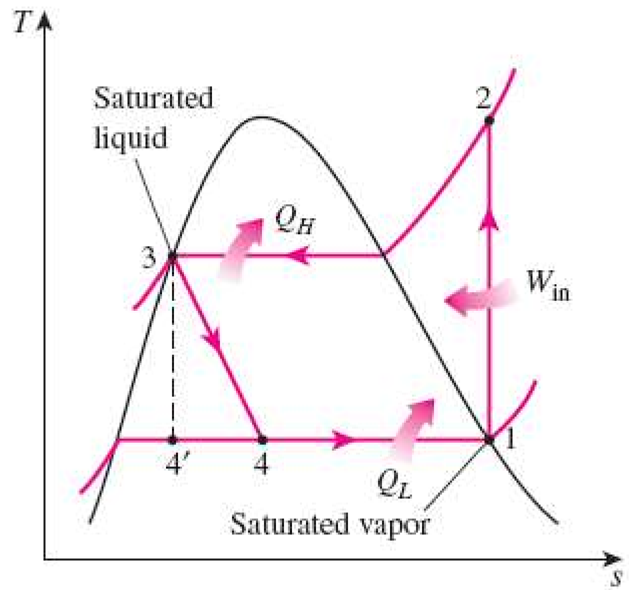
THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

Unlike the reversed Carnot cycle,

- The refrigerant is vaporized completely before it is compressed
- The turbine is replaced with a throttling device.

1-2	Isentropic compression in a compressor
2-3	Constant-pressure heat rejection in a condenser
3-4	Throttling in an expansion device
4-1	Constant-pressure heat absorption in an evaporator





This is the most widely used cycle for refrigerators, A-C systems, and heat pumps.

Schematic and ***T-s* diagram** for the ideal vapor-compression refrigeration cycle.

Analysis

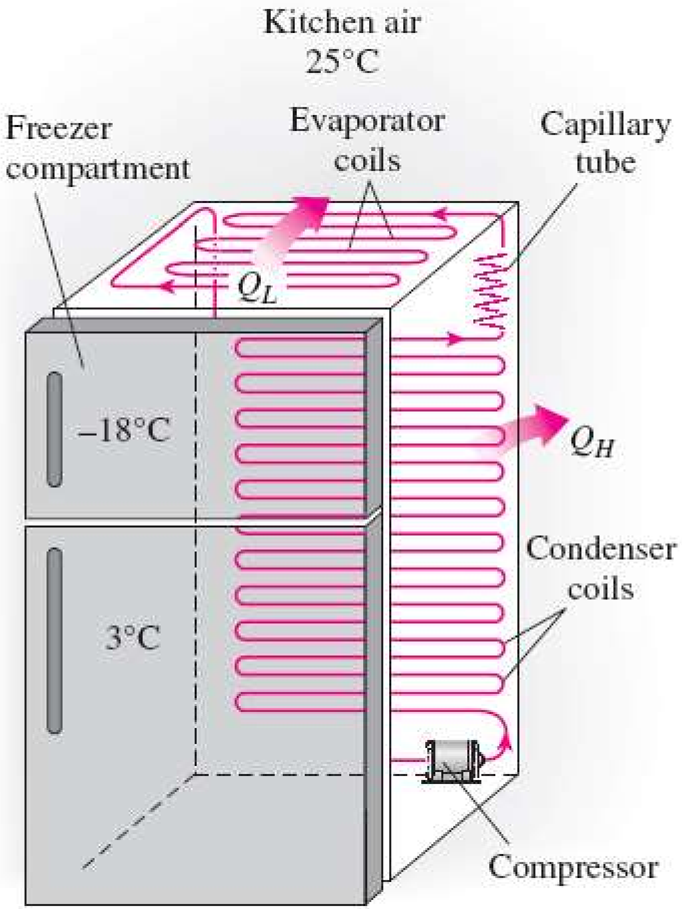
Each component is treated separately as open system with steady flow

Steady-flow energy balance $(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$

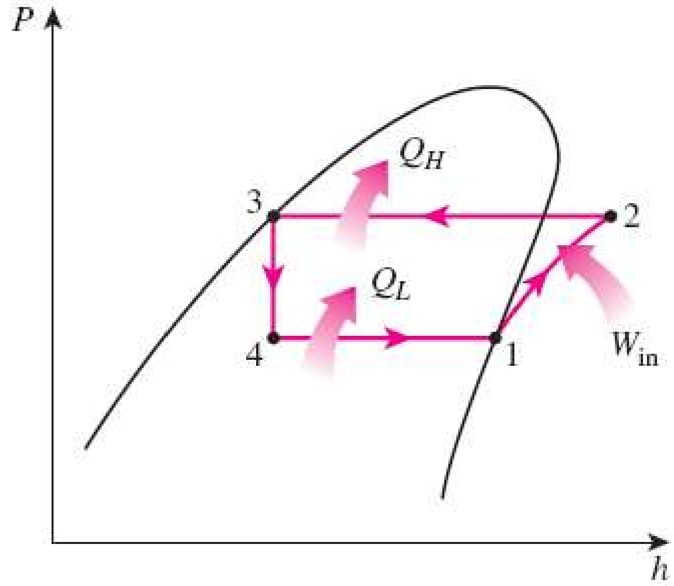
$$\mathrm{COP_R} = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$\mathrm{COP_{HP}} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

$h_1 = h_{g\,@\,P_1}$ and $h_3 = h_{f\,@\,P_3}$ for the ideal case



An ordinary household refrigerator.



The ***P-h* diagram** of an ideal vapor-compression refrigeration cycle.

Problem

Ideal and Actual Vapor-Compression Refrigeration Cycles

11–12

A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.12 and 0.7 MPa. The mass flow rate of the refrigerant is 0.05 kg/s. Show the cycle on a T-s diagram with respect to saturation lines. Determine:

a) the rate of heat removal from the refrigerated space,

b) the power input to the compressor,

c) the rate of heat rejection to the environment, and

d) the coefficient of performance.

Answers: (a) 7.41 kW, 1.83 kW, (b) 9.23 kW, (c) 4.06

Problem – Class Exercise

11–15

Consider a 300 kJ/min refrigeration system that operates on an ideal vapor-compression refrigeration cycle with refrigerant-134a as the working fluid. The refrigerant enters the compressor as saturated vapor at 140 kPa and is compressed to 800 kPa. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine the:

a) quality of the refrigerant at evaporator inlet,
b) coefficient of performance, and
c) power input to the compressor.

ACTUAL VAPOR-COMPRESSION REFRIGERATION CYCLE

An actual vapor-compression refrigeration cycle differs from the ideal one owing mostly to the irreversibilities that occur in various components, mainly due to fluid friction (causes pressure drops) and heat transfer to or from the surroundings. As a result, the COP decreases.

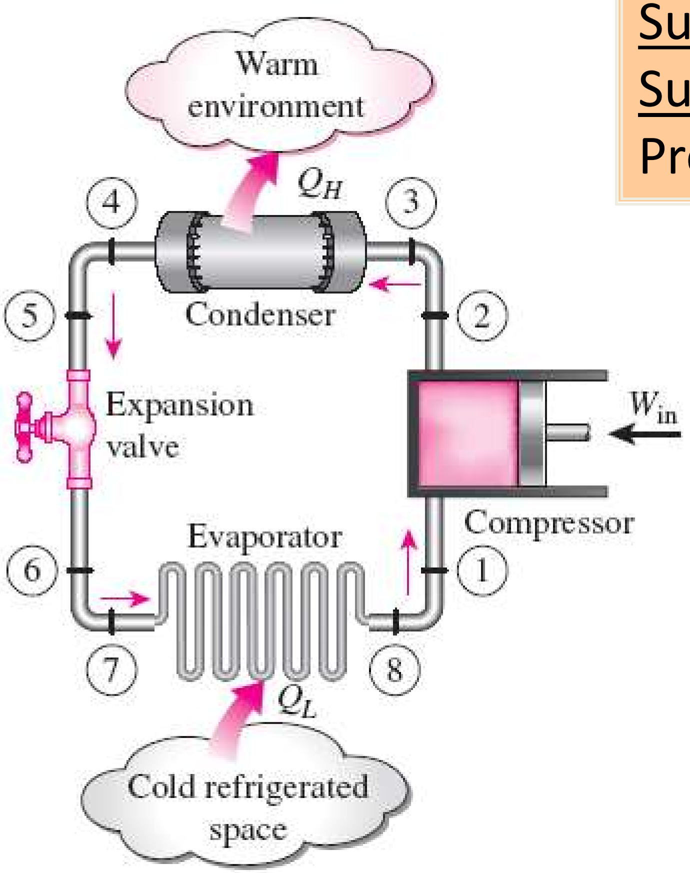
DIFFERENCES

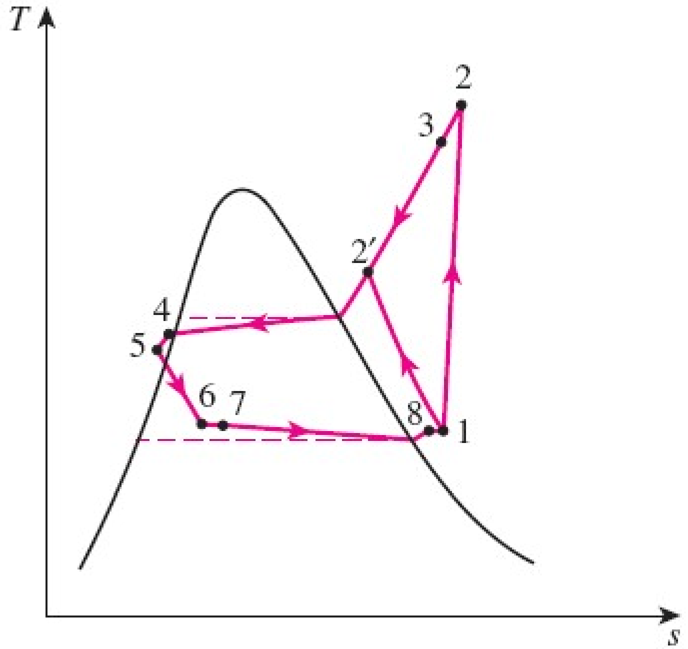
Non-isentropic compression

Superheated vapor at evaporator exit

Subcooled liquid at condenser exit

Pressure drops in condenser and evaporator

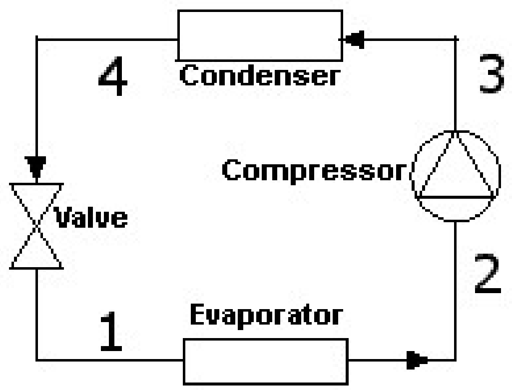


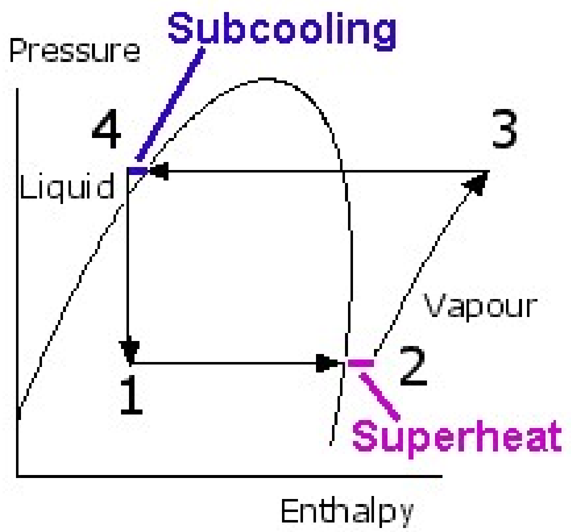


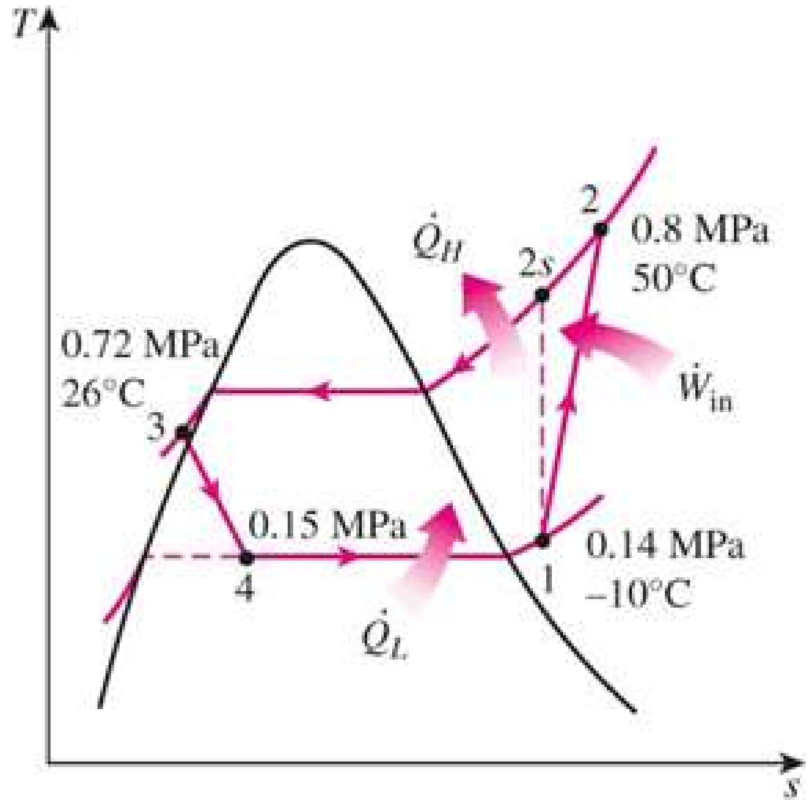
Schematic and *T-s* diagram for the actual vapor-compression refrigeration cycle.

Superheating and Subcooling

- Superheating (at evaporator exit) – to ensure no liquid droplets enters compressor to damage it
- Subcooling (at condenser exit) – to increase cooling capacity







ΔT- Degree of superheating

ACTUAL VAPOR-COMPRESSION REFRIGERATION CYCLE

We will only focus on non-isentropic compression.

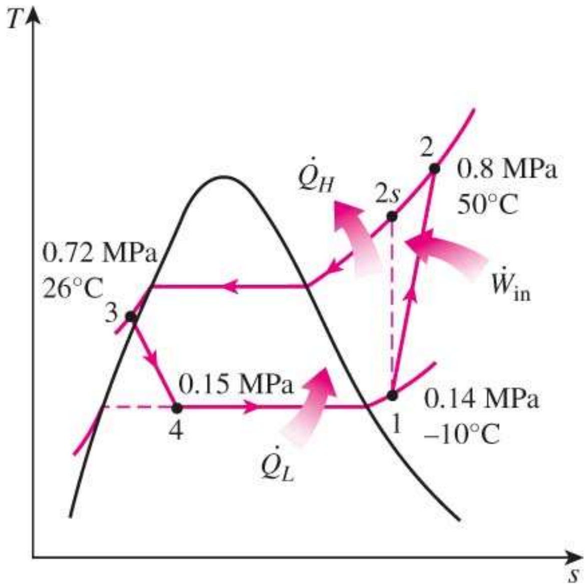


FIGURE 11–8
T-*s* diagram for Example 11–2.

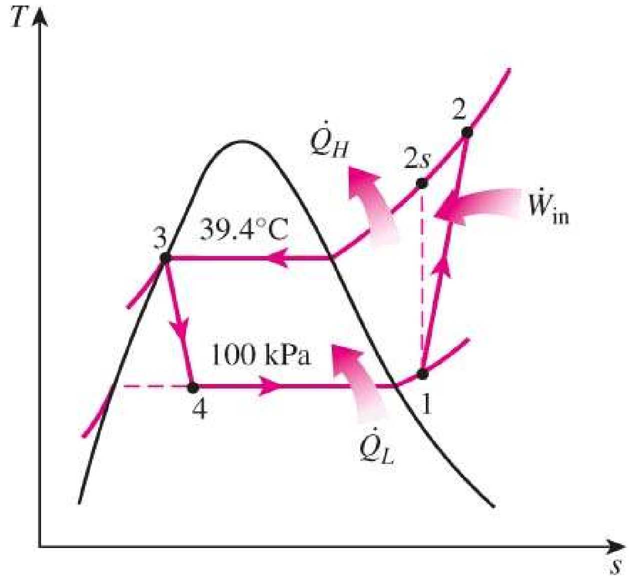


FIGURE 11–10
Temperature-entropy diagram of the vapor-compression refrigeration cycle considered in Example 11–3.

T-*s* diagram for the actual vapor-compression refrigeration cycle.

11–19 Refrigerant-134a enters the compressor of a refrigerator at 100 kPa and -20 ^oC at a rate of 0.5 m^3/min and leaves at 0.8 MPa. The isentropic efficiency of the compressor is 78 percent. The refrigerant enters the throttling valve at 0.8 MPa and 26 ^oC.

Show the cycle on a *T-s* diagram with respect to saturation lines, and determine

(a) the power input to the compressor,

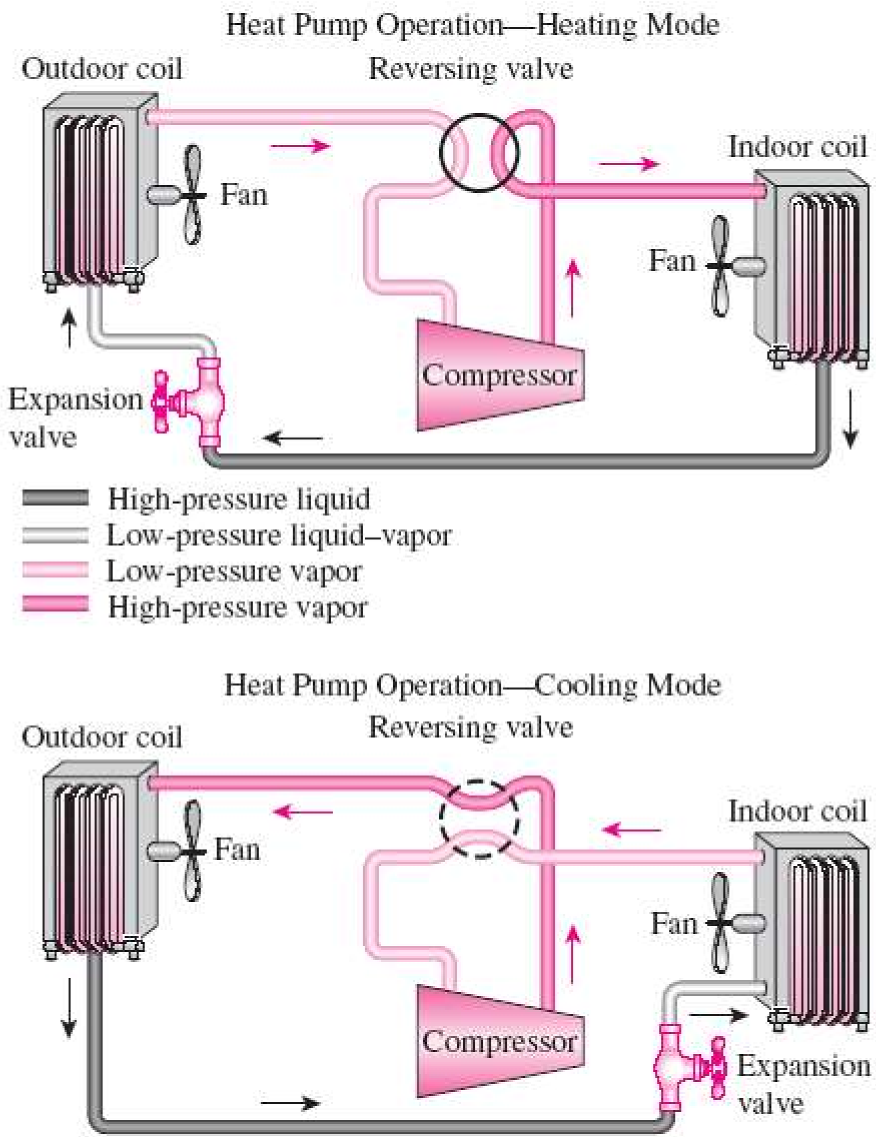
(b) the rate of heat removal from the refrigerated space, and

~~(c) the pressure drop and rate of heat gain in the line between the evaporator and the compressor~~.

Answers:

(*a*) 2.40 kW, (*b*) 6.17 kW, (*c*) 1.73 kPa, 0.203 kW

REVERSIBLE SYSTEMS



A heat pump can be used to heat a house in winter and to cool it in summer.

The most common energy source for heat pumps is atmospheric air (air-to- air systems).

Water-source systems usually use well water and ground-source (geothermal) heat pumps use earth as the energy source. They typically have higher COPs but are more complex and more expensive to install.

Both the capacity and the efficiency of a heat pump fall significantly at low temperatures. Therefore, most air-source heat pumps require a supplementary heating system such as electric resistance heaters or a gas furnace.

Heat pumps are most competitive in areas that have a large cooling load during the cooling season and a relatively small heating load during the heating season. In these areas, the heat pump can meet the entire cooling and heating needs of residential or commercial buildings.