INTRODUCTION TO THERMODYNAMICS
GEC 221 LECTURE SLIDES

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“An impressive theory is that with greater simplicity of premises; with more different kinds of things it relates, and with more extended areas of applicability. Therefore, the deep impression classical thermodynamics made upon me. It is the only physical theory of universal content which, within the framework of the applicability of its basic concepts, I am convinced will never be overthrown.”

…..A. Einstein

AREAS OF ENGINEERING APPLICATIONS OF THERMODYNAMICS

- **Automobile engines, Turbines, Compressors, pumps**

- **Fossil- and nuclear-fueled power stations**

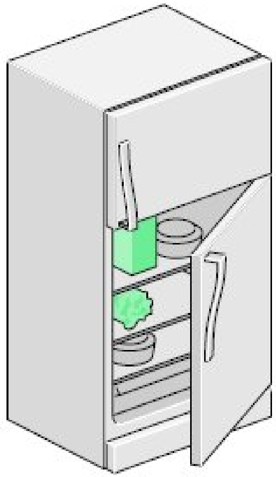
- **Propulsion systems for aircraft and rockets, Combustion systems**

- **Cryogenic systems, gas separation, and liquefaction.**

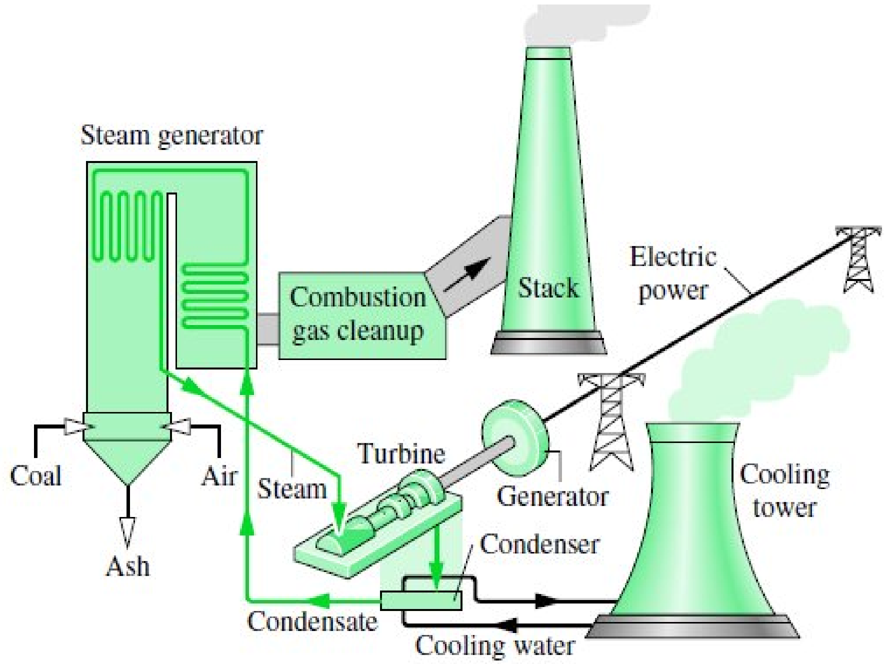
- **Heating, ventilating, and air-conditioning systems, Vapor compression and absorption refrigeration,Heat pumps, Cooling of electronic equipment.**

- **Alternative energy systems, Fuel cells,Thermoelectric and thermionic devices,Magnetohydrodynamic (MHD) converters.**

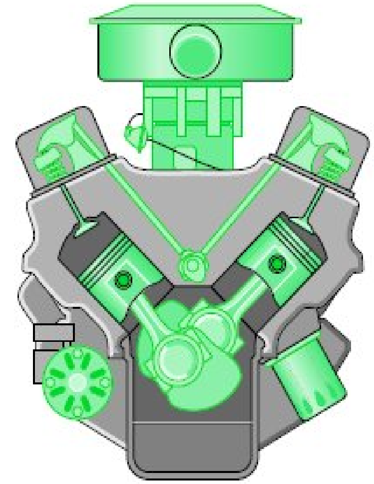
- **Solar-activated heating, cooling, and power generation,Geothermal systems, Ocean thermal, wave, and tidal power generation Wind power, Biomedical applications,Life-support systems, Artificial organ**



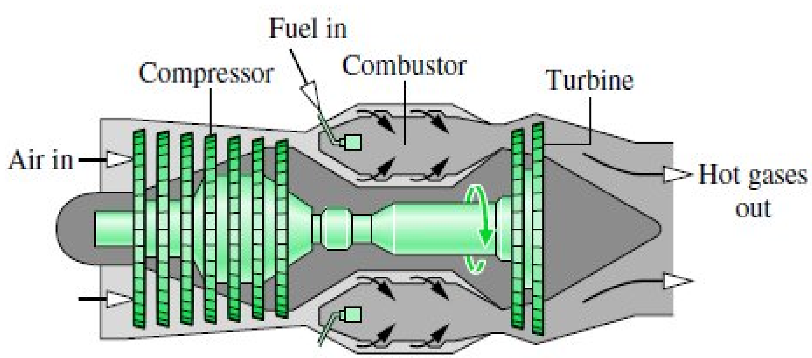
Refrigerator



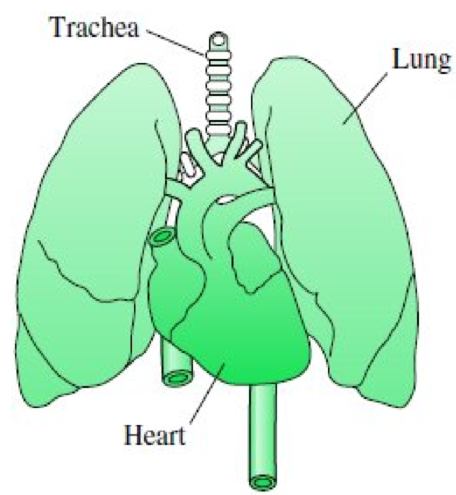
Electrical power plant



Automobile engine

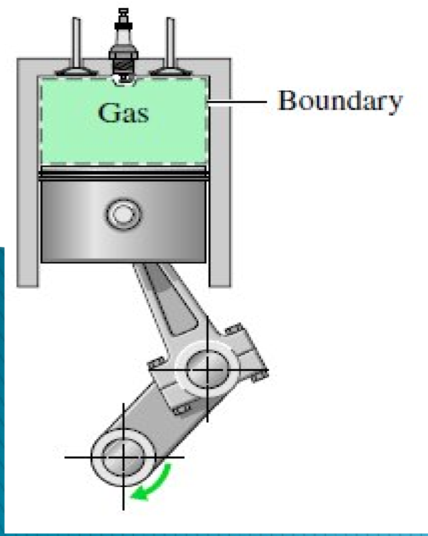


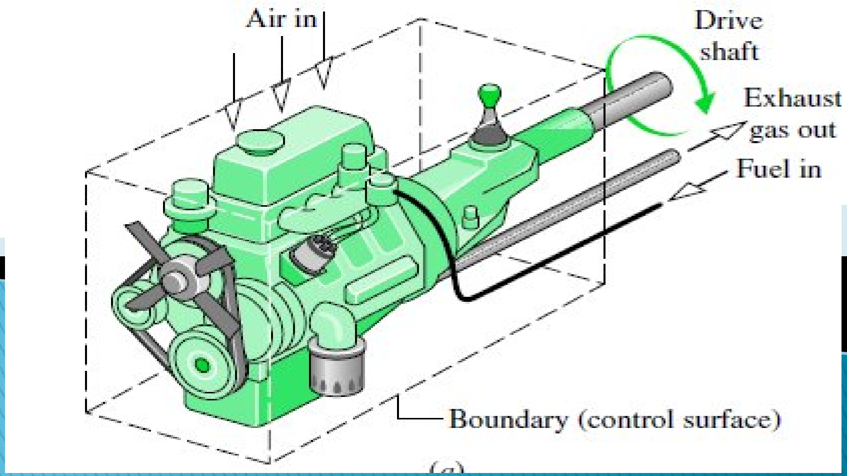
Turbojet engine



Biomedical applications

- What is a thermodynamic system ?
- What are the types of thermodynamic system?
- Universe = system + surroundings
- Control Mass = Closed System
- Control Volume = Open System
  - System Boundary and Control Surface





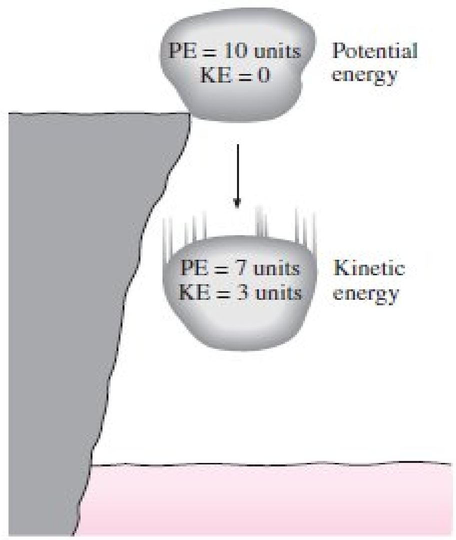
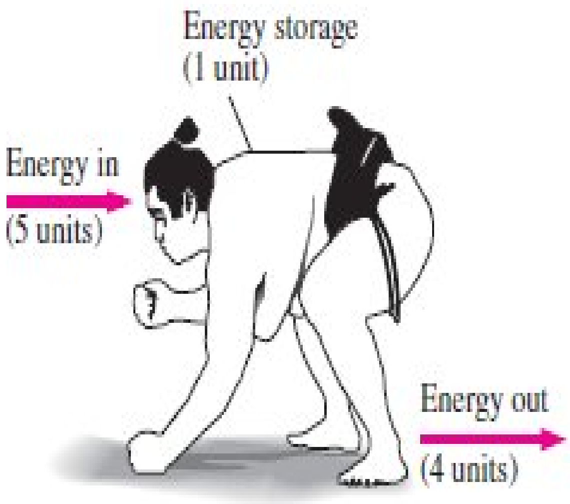
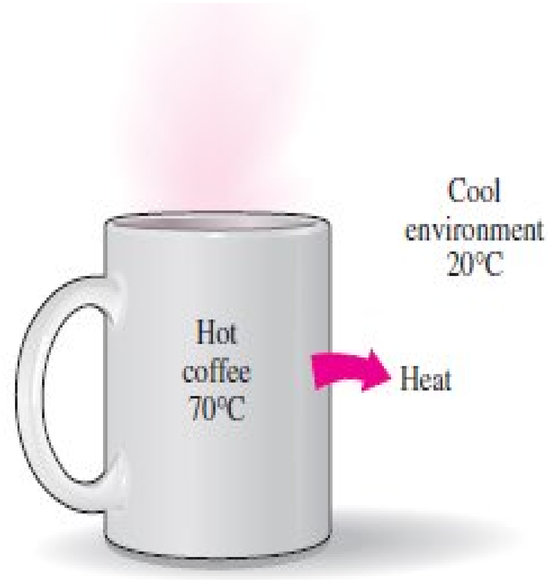


FIGURE 1–1

Energy cannot be created or destroyed; it can only change forms (the first law).





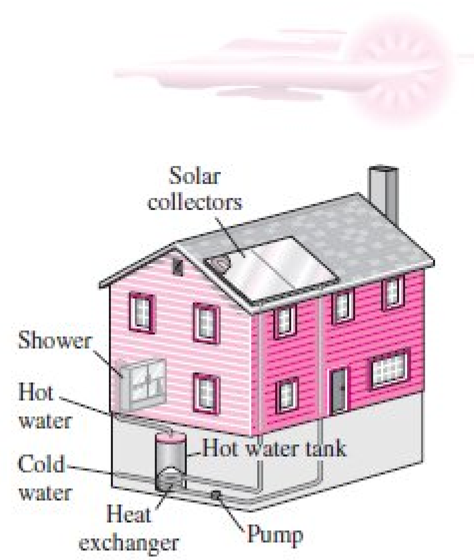


FIGURE 2–1

A refrigerator operating with its door open in a well-sealed and well-insulated room.

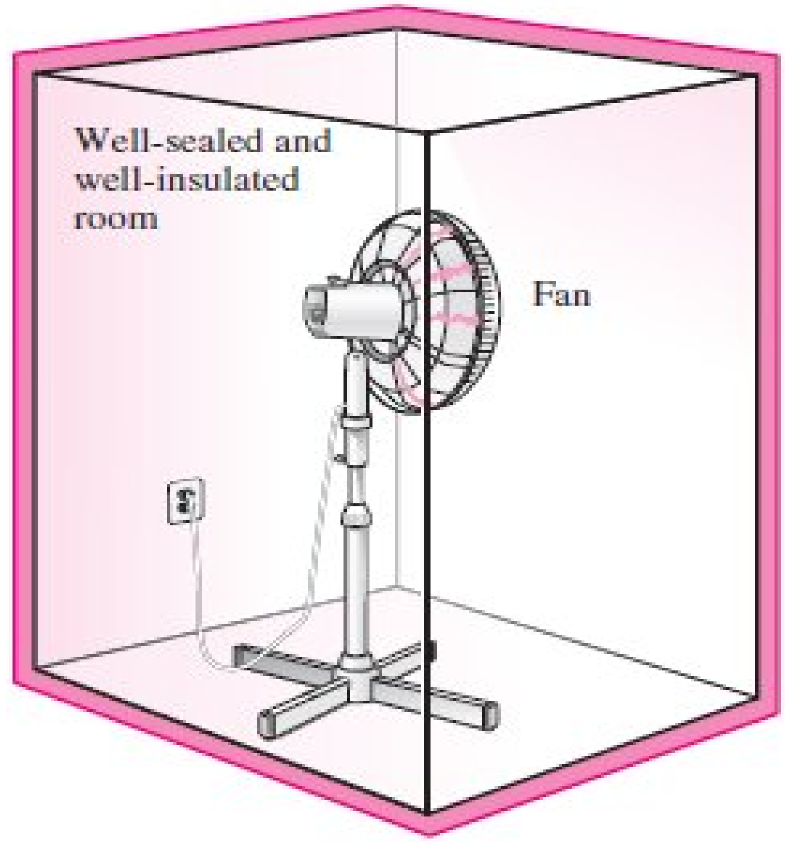


FIGURE 2–2

A fan running in a well-sealed and well-insulated room will raise the temperature of air in the room.

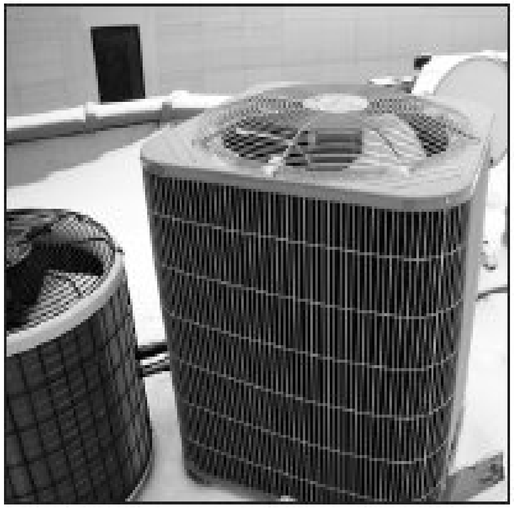
THE ESSENCE OF THERMODYNAMICS TO ENGINEERS

Consider a room whose door and windows are tightly closed, and whose walls are well-insulated so that heat loss or gain through the walls is negligible. Now let's place a refrigerator in the middle of the room with its door open, and plug it into a wall outlet.

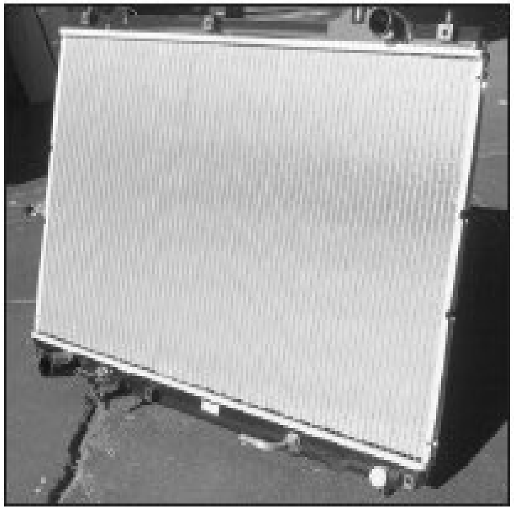
THE BIG QUESTION IS:

Now, what do you think will happen to the average temperature of air in the room? Will it be increasing or decreasing? Or will it remain constant?


The human body


Air conditioning systems


Airplanes


Car radiators


Power plants


Refrigeration systems

- ***Views of thermodynamicists:***
  - **Macroscopic view of system: CLASSICAL THERMODYNAMICS.**
    - **It allows important aspects of system behavior to be evaluated from observations of the overall system.**
    - **NO USE OF ATOMIC AND SUB-ATOMIC MODELS**
    - **For the great majority of engineering applications, classical thermodynamics not only provides a considerably more direct approach for analysis and design but also requires far fewer mathematical complications**

- **Microscopic view of system: STATISTICAL THERMODYNAMICS.**

  - **It is concerned directly with the structure of matter.**

  - **The objective of statistical thermodynamics is to characterize by statistical means the average behavior of the particles making up a system of interest and relate this information to the observed macroscopic behavior of the system.**

  - **For applications involving lasers, plasmas, high-speed gas flows, chemical kinetics, very low temperatures (cryogenics), and others, the methods of statistical thermodynamics are essential.**

PROPERTY, STATE, AND PROCESS

A *property is a macroscopic characteristic of a system, e.g* mass, volume, energy, pressure, and temperature to which a numerical value can be assigned at a given time without knowledge of the previous behavior (*history) of the system.*

Types of properties:

- ***INTENSIVE PROPERTIES and EXTENSIVE PROPERTIES***

***INTRINSIC PROPERTIES AND EXTRINSIC PROPERTIES.* Their values are in/dependent of the size or extent of a system??**

- **The word** ***state refers to the condition of a system as described by its properties.***

- **When any of the properties of a system change, the state changes and the system is said to have undergone a** ***process.***

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

- ***A quantity is a property if its change in value between two states is independent of the process.***

PHASE AND PURE SUBSTANCE

- **The term *phase refers to a quantity of matter that is homogeneous throughout in both chemical* composition and physical structure.**

- **Homogeneity in physical structure means that the matter is all *solid, or all liquid, or all vapor (or equivalently all gas).***

- ***How many phases exist in the given mixture below:***

KEROSINE AND WATER MIXTURE

ETHANOL AND WATER MIXTURE

ENGINE OIL AND BENZENE MIXTURE

ACETIC ACID, WATER AND BENZENE MIXTURE

A *pure substance is one that is uniform and invariable in chemical composition*

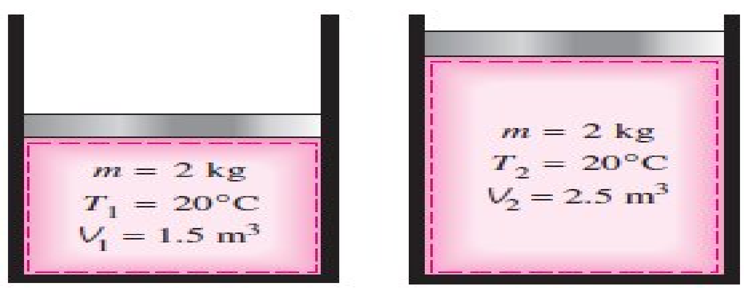
***NB:* A pure substance can exist in more than one phase, but its chemical composition must be the same in each phase.**

IS WATER AND WATER VAPOUR MIXTURE PURE?

IS AIR A PURE MIXTURE?

STATE AND EQUILIBRIUM

- Consider a system not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system, which gives us a set of properties that completely describes the condition, or the state, of the system.
- At a given state, all the properties of a system have fixed values.
- If the value of even one property changes, the state will change to a different one.



(a) State 1 (b) State 2

- **Thermodynamics deals with *equilibrium states.***
- ***The word equilibrium* implies a state of balance.**

- **A system in equilibrium experiences no changes when it is isolated from its surroundings.**

- **There are many types of equilibrium, and a system is not in thermodynamic equilibrium unless the conditions of all the relevant types of equilibrium are satisfied.**

- **A system is in thermal equilibrium if the temperature is the same throughout the entire system i.e. That is, the system involves no temperature differential, which is the driving force for heat flow.**

Mechanical equilibrium is related to pressure, and a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time.

If a system involves two phases, it is in phase equilibrium when the mass of each phase reaches an equilibrium level and stays there.

A system is in chemical equilibrium if its chemical composition does not change with time, that is, no chemical reactions occur

State Postulate:

A system is called a simple compressible system in the absence of electrical, magnetic, gravitational, motion, and surface tension effects.

These effects are due to external force fields and are negligible for most engineering problems.

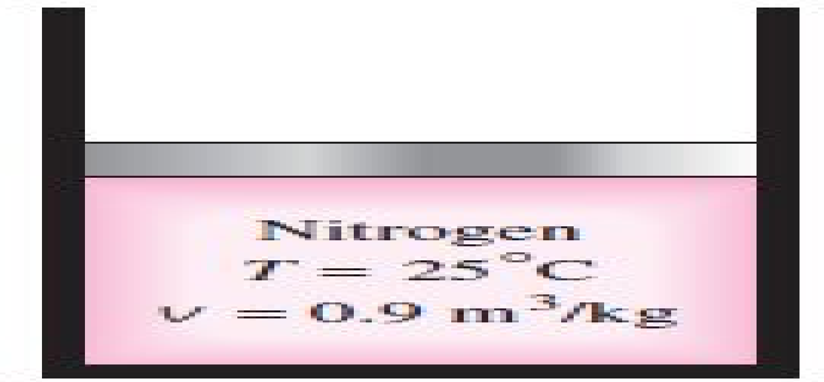
The state postulate is given below:

The state of a simple compressible system is completely specified by two independent, intensive properties.

The state postulate requires that the two properties specified be independent to fix the state.

Two properties are independent if one property can be varied while the other one is held constant.

Temperature and specific volume, for example, are always independent properties, and together they can fix the state of a simple compressible system



Temperature and pressure, however, are independent properties for single-phase systems, but are dependent properties for multiphase systems.

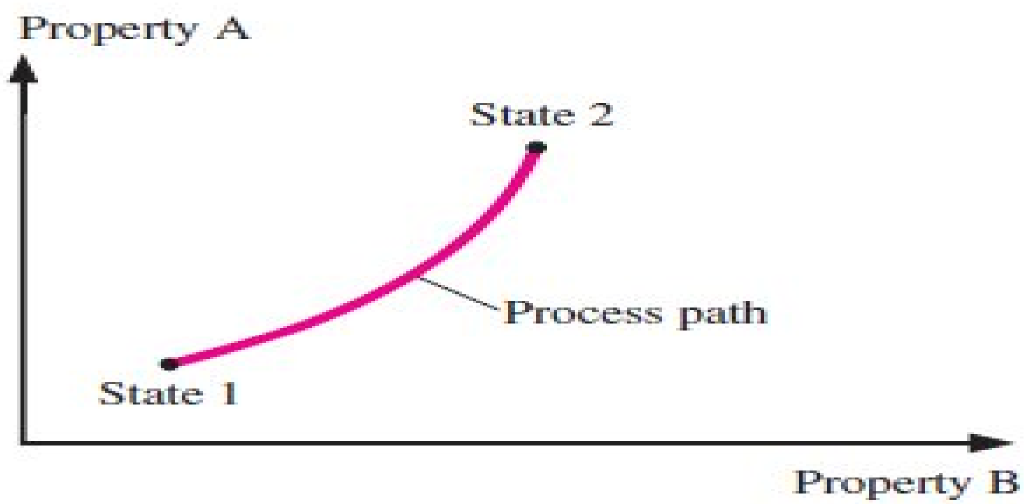
EXAMPLE 1:

At sea level (*P 1 atm*), water boils at 100°C, but on a mountaintop where the pressure is lower, water boils at a lower temperature. That is, *T f(P) during a phase-change* process; thus, temperature and pressure are not sufficient to fix the state of a two-phase system.

PROCESSES AND CYCLES

Any change that a system undergoes from one equilibrium state to another is called a process.

The series of states through which a system passes during a process is called the path of the process.


Property A
State 2
Process path
State 1
Property B

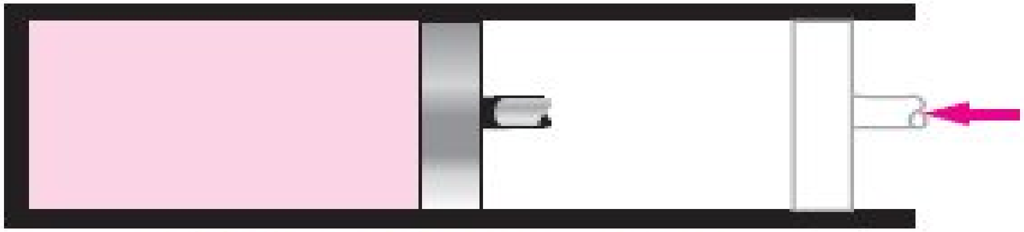
When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a quasistatic, or quasi-equilibrium, process.

A quasi-equilibrium process can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.

Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared.

A process between states 1 and 2 and the process path.


(*a*) Slow compression
(quasi-equilibrium)


(*b*) Very fast compression
(nonquasi-equilibrium)

It should be pointed out that a quasi-equilibrium process is an idealized process and is not a true representation of an actual process.

But many actual processes closely approximate it, and they can be modeled as quasi-equilibrium with negligible error.

Engineers are interested in quasi-equilibrium processes for two reasons.

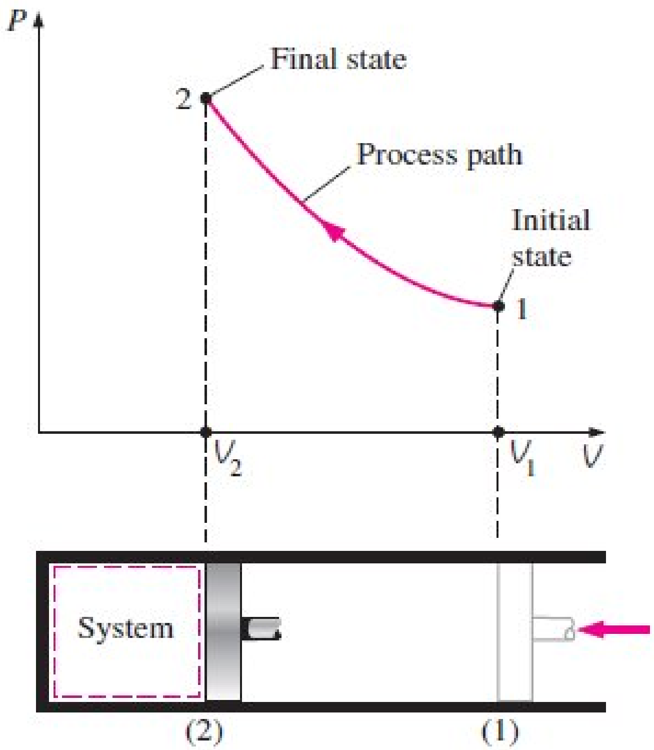
First: they are easy to analyze.

Second: work-producing devices deliver the most work when they operate on quasi-equilibrium processes.

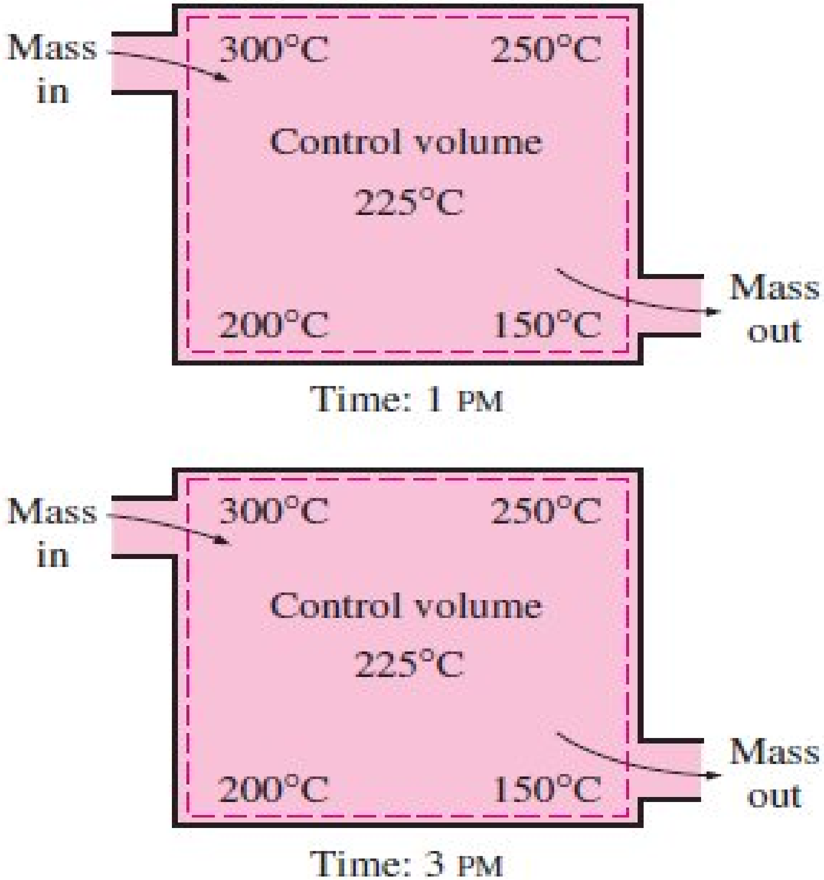
- **Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes. Some common properties that are used as coordinates are temperature *T, pressure P, and* volume *V (or specific volume v).***

- **Note that the process path indicates a series of equilibrium states through which the system passes during a process and has significance for quasiequilibrium processes only.**

- **For nonquasi-equilibrium processes, we are not able to characterize the entire system by a single state, and thus we cannot speak of a process path for a system as a whole.**



The *P*-*V* diagram of a compression process.



During a steady-flow process, fluid properties within the control volume may change with position but not with time.

STEADY-STATE PROCESSES

The terms *steady and uniform are used frequently in engineering.*

The term *steady implies no change with time. The opposite of steady is unsteady, or transient.*

The term *uniform, however, implies no change with location over* a specified region.

- The fluid properties can change from point to point within the control volume, but at any fixed point they remain the same during the entire process.

- Therefore, the volume *V, the mass m, and the total* energy content *E of the control volume remain constant during a steady flow* process.

- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

- **Some cyclic devices, such as reciprocating engines or compressors, do not satisfy any of the conditions stated above since the flow at the inlets and the exits will be pulsating and not steady.**

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

- **Limitation in our sensory perception's accuracy**

e.g. A metal chair, for example, will feel much colder than a wooden one even when both are at the same temperature.

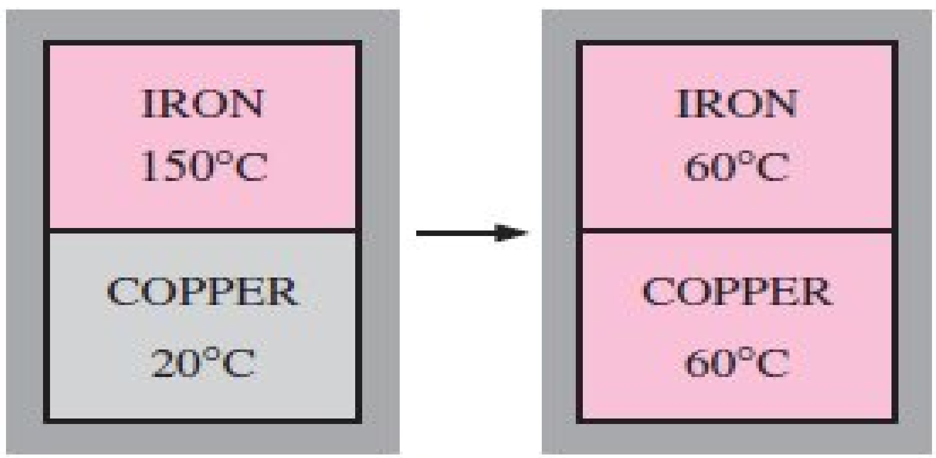
- **Fortunately, several properties of materials change with temperature in a *repeatable and predictable way, and this forms the basis for accurate temperature* measurement.**

- **The commonly used mercury-in-glass thermometer, for example, is based on the expansion of mercury with temperature. Temperature is also measured by using several other temperature-dependent properties.**

- **It is a common experience that a cup of hot coffee left on the table eventually cools off and a cold drink eventually warms up.**

- **That is, when a body is brought into contact with another body that is at a different temperature, heat is transferred from the body at higher temperature to the one at lower temperature until both bodies attain the same temperature**

- At that point, the heat transfer stops, and the two bodies are said to have reached thermal equilibrium.
- The equality of temperature is the only requirement for thermal equilibrium.



- **The zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.**
- **With the third body being thermometer, the Zeroth law can be restated as given below:**
- ***Two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.***

THERMODYNAMIC UNITS QUESTIONS

- **During a heating process, the temperature of a system rises by 10°C. Express this rise in temperature in K, °F, and R.**

- **A vacuum gage connected to a chamber reads 5.8 psi at a location where the atmospheric pressure is 14.5 psi. Determine the absolute pressure in the chamber.**

- **The pressure relative to absolute vacuum is called the *absolute pressure.***

- ***The difference between the absolute* pressure and the local atmospheric pressure is called the *gauge pressure.***

- ***Pressures below atmospheric pressure are* called *vacuum pressures. The absolute, gauge, and vacuum* pressures are related by:**

- **The pressure at a point in a fluid has the same magnitude in all directions. The variation of pressure with elevation is given by**

$$dP/dz = -\rho g$$

where the positive *z direction is taken to be upward.*

- ***The pressure in a stationary fluid remains constant* in the horizontal direction.**

- ***Pascal's Principle states that* the pressure applied to a confined fluid increases the pressure throughout by the same amount.**

- **What is the difference between the classical and the statistical approaches to thermodynamics?**

- **Why does a bicyclist pick up speed on a downhill road even when he is not pedaling? Does this violate the conservation of energy principle?**

- **An office worker claims that a cup of cold coffee on his table warmed up to 80°C by picking up energy from the surrounding air, which is at 25°C. Is there any truth to his claim? Does this process violate any thermodynamic laws?**

- **Classical thermodynamics is based on experimental observations whereas statistical thermodynamics is based on the average behavior of large groups of particles.**

- **On a downhill road the potential energy of the bicyclist is being converted to kinetic energy, and thus the bicyclist picks up speed. There is no creation of energy, and thus no violation of the conservation of energy principle.**

- **At 45° latitude, the gravitational acceleration as a function of elevation** ***z above sea level is given by g = a - bz,*** **where** ***a= 9.807 m/s2 and b= 3.32 x 10^-6 s2. Determine*** **the height above sea level where the weight of an object will decrease by 1 percent.**

1-9 The variation of gravitational acceleration above the sea level is given as a function of altitude. The height at which the weight of a body will decrease by 1% is to be determined.

Analysis The weight of a body at the elevation z can be expressed as

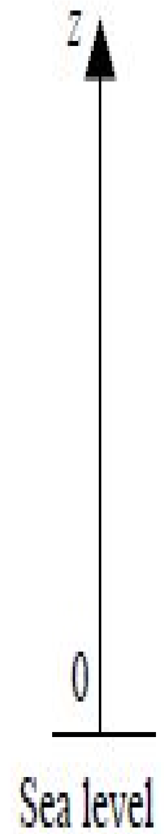
$$W = mg = m(9.807 - 3.32 \times 10^{-6} z)$$

In our case,

$$W = 0.99W_s = 0.99mg_s = 0.99(m)(9.807)$$

Substituting,

$$0.99(9.81) = (9.81 - 3.32 \times 10^{-6} z) \longrightarrow z = \mathbf{29{,}539\ m}$$



- **Is the state of the air in an isolated room completely specified by the temperature and the pressure? Explain.**

- **Yes, because temperature and pressure are two independent properties and the air in an isolated room is a simple compressible system.**

INTRODUCTION TO THE SECOND LAW

- **Energy is a conserved property, and no process is known to have taken place in violation of the first law of thermodynamics.**

- **Therefore, it is reasonable to conclude that a process must satisfy the first law to occur. However, as explained here, satisfying the first law alone does not ensure that the process will actually take place.**

- **This process satisfies the first law of thermodynamics since the amount of energy lost by the coffee is equal to the amount gained by the surrounding air.**

PdV WORK

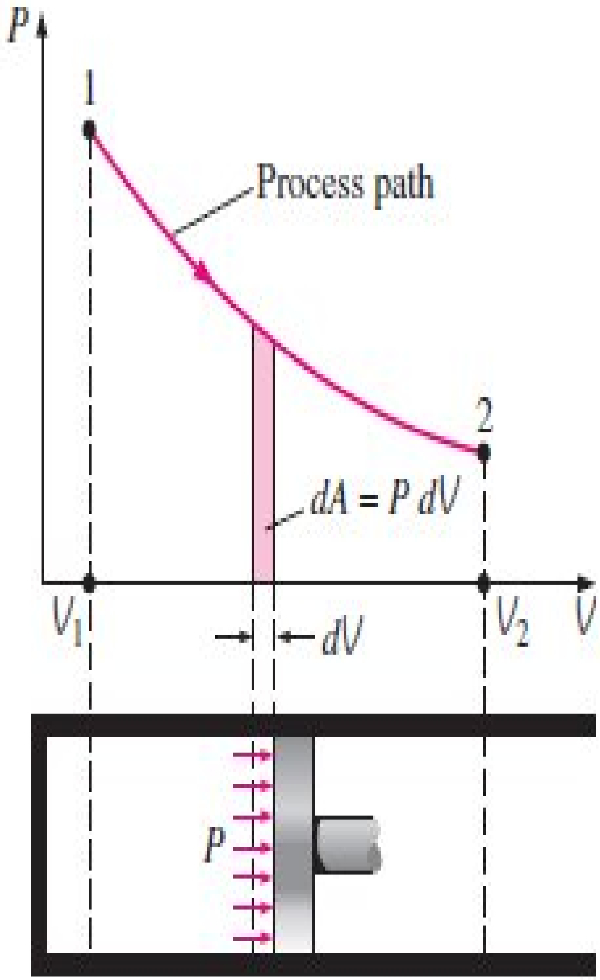
- **It is the mechanical work associated with the expansion or compression of a gas in a piston–cylinder device.**

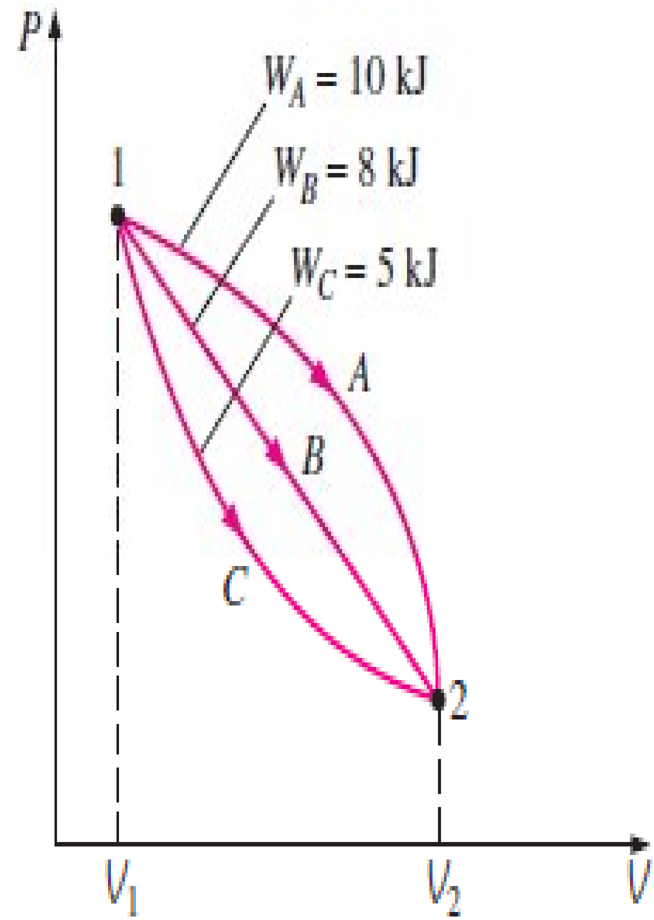
- **During this process, part of the boundary (the inner face of the piston) moves back and forth. Therefore, the expansion and compression work is often called moving boundary work. *Moving boundary* work is the primary form of work involved in *automobile engines. During* their expansion, the combustion gases force the piston to move, which in turn forces the crankshaft to rotate.**

- **The moving boundary work associated with real engines or compressors cannot be determined exactly from a thermodynamic analysis alone because the piston usually moves at very high speeds, making it difficult for the gas inside to maintain equilibrium. Then the states through which the system passes during the process cannot be specified, and no process path can be drawn. Work, being a path function, cannot be determined analytically without a knowledge of the path.**

- **Therefore, the boundary work in real engines or compressors is determined by direct measurements.**

- **In this section, we analyze the moving boundary work for a *quasiequilibrium process, a process during which the system remains nearly in* equilibrium at all times. A quasi-equilibrium process, also called a *quasistatic process, is closely approximated by real engines, especially when the* piston moves at low velocities.**


P
1
Process path
2
dA = P dV
V1
dV
V2
V
P


P
W_A = 10 kJ
1
W_B = 8 kJ
W_C = 5 kJ
A
B
C
2
V1
V2
V

Boundary Work for a Constant-Pressure Process

QUESTION:

A frictionless piston–cylinder device contains 10 lbm of steam at 60 psia and 320F. Heat is now transferred to the steam until the temperature reaches 400F. If the piston is not attached to a shaft and its mass is constant, determine the work done by the steam during this process, assuming an isobaric process.

Solution:

- ***The expansion process is quasi-equilibrium.***
- **This is a constant-pressure process**

$$W_b = \int_1^2 P\,dV = P_0 \int_1^2 dV = P_0(V_2 - V_1)$$

$$W_b = mP_0(v_2 - v_1)$$

***From STEAM TABLE, the specific* volumes are:**

***v1 =7.4863 ft3/lbm (60 psia,*320F)**

v2 =8.3548 ft3/lbm (60 psia, 400F)

***Substituting* these values yields**

$$W_b = (10\,\text{lbm})(60\,\text{psia})[(8.3548 - 7.4863)\,\text{ft}^3/\text{lbm}]\left(\frac{1\,\text{Btu}}{5.404\,\text{psia}\cdot\text{ft}^3}\right)$$

$$= 96.4\,\text{Btu}$$

Isothermal Compression of an Ideal Gas

A piston–cylinder device initially contains 0.4 m3 of air at 100 kPa and 80°C. The air is now compressed to 0.1 m3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

$$W_b = \int_1^2 P\,dV = \int_1^2 \frac{C}{V}\,dV = C\int_1^2 \frac{dV}{V} = C\ln\frac{V_2}{V_1} = P_1V_1\ln\frac{V_2}{V_1}$$

$$W_b = (100\text{ kPa})(0.4\text{ m}^3)\left(\ln\frac{0.1}{0.4}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = -55.5\text{ kJ}$$

The negative sign indicates that this work is done on the system (a work input), which is always the case for compression processes.

Polytropic Process

During actual expansion and compression processes of gases, pressure and volume are often related by *PVn =C, where n and C are constants. A* process of this kind is called a polytropic process.

Below we develop a general expression for the work done during a polytropic process.

The pressure for a polytropic process can be expressed as

$$P = CV^{-n}$$

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

$$W_b = \frac{mR(T_2 - T_1)}{1-n} \qquad n \neq 1$$

QUESTION:

A piston–cylinder device initially contains 0.07 m3 of nitrogen gas at 130 kPa and 120°C. The nitrogen is now expanded polytropically to a state of 100 kPa and 100°C. Determine the boundary work done during this process.

SOLUTION:

The mass and volume of nitrogen at the initial state are

$$m = \frac{P_1 V_1}{R T_1} = \frac{(130\ \text{kPa})(0.07\ \text{m}^3)}{(0.2968\ \text{kJ/kg.K})(120 + 273\ \text{K})} = 0.07802\ \text{kg}$$

$$V_2 = \frac{m R T_2}{P_2} = \frac{(0.07802\ \text{kg})(0.2968\ \text{kPa.m}^3/\text{kg.K})(100 + 273\ \text{K})}{100\ \text{kPa}} = 0.08637\ \text{m}^3$$

The polytropic index is determined from

$$P_1 V_1^n = P_2 V_2^n \longrightarrow (130\ \text{kPa})(0.07\ \text{m}^3)^n = (100\ \text{kPa})(0.08637\ \text{m}^3)^n \longrightarrow n = 1.249$$

The boundary work is determined from

$$W_b = \frac{P_2 V_2 - P_1 V_1}{1 - n} = \frac{(100\ \text{kPa})(0.08637\ \text{m}^3) - (130\ \text{kPa})(0.07\ \text{m}^3)}{1 - 1.249} = \mathbf{1.86\ kJ}$$

PRACTICE QUESTIONS

1. **A mass of 2.4 kg of air at 150 kPa and 12°C is contained in a gas-tight, frictionless piston–cylinder device. The air is now compressed to a final pressure of 600 kPa. During the process, heat is transferred from the air such that the temperature inside the cylinder remains constant. Calculate the work input during this process.**

Answer: 272 KJ

2. **A frictionless piston–cylinder device contains 2 kg of nitrogen at 100 kPa and 300 K. Nitrogen is now compressed slowly according to the relation *PV1.4 constant until it* reaches a final temperature of 360 K. Calculate the work input during this process.**

Answer: 89 KJ

4–149 The specific heat of a material is given in a strange unit to be $c = 3.60$ kJ/kg · °F. The specific heat of this material in the SI units of kJ/kg · °C is

(*a*) 2.00 kJ/kg · °C
(*b*) 3.20 kJ/kg · °C
(*c*) 3.60 kJ/kg · °C
(*d*) 4.80 kJ/kg · °C
(*e*) 6.48 kJ/kg · °C

4–153 A 2-kW baseboard electric resistance heater in a vacant room is turned on and kept on for 15 min. The mass of the air in the room is 75 kg, and the room is tightly sealed so that no air can leak in or out. The temperature rise of air at the end of 15 min is

(*a*) 8.5°C
(*b*) 12.4°C
(*c*) 24.0°C
(*d*) 33.4°C
(*e*) 54.8°C

4–160 3 kg of liquid water initially at 12°C is to be heated at 95°C in a teapot equipped with a 1200-W electric heating element inside. The specific heat of water can be taken to be 4.18 kJ/kg · °C, and the heat loss from the water during heating can be neglected. The time it takes to heat water to the desired temperature is

(*a*) 4.8 min
(*b*) 14.5 min
(*c*) 6.7 min
(*d*) 9.0 min
(*e*) 18.6 min

SECOND LAW OF THERMODYNAMICS

- **As another familiar example, consider the heating of a room by the passage of electric current through a resistor. Again, the first law dictates that the amount of electric energy supplied to the resistance wires be equal to the amount of energy transferred to the room air as heat. Now let us attempt to reverse this process. It will come as no surprise that transferring some heat to the wires does not cause an equivalent amount of electric energy to be generated in the wires.**

- **Consider a paddle-wheel mechanism that is operated by the fall of a mass. The paddle wheel rotates as the mass falls and stirs a fluid within an insulated container. As a result, the potential energy of the mass decreases, and the internal energy of the fluid increases in accordance with the conservation of energy principle. However, the reverse process, raising the mass by transferring heat from the fluid to the paddle wheel, does not occur in nature, although doing so would not violate the first law of thermodynamics.**

- **It is clear from these arguments that processes proceed in a *certain direction* and not in the reverse direction. The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur.**

- **This inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the *second law of thermodynamics.***

- **HEAT RESERVOIR is defined as a hypothetical body with a relatively large thermal energy capacity (mass specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature.**

- **A reservoir that supplies energy in the form of heat is called a HEAT SOURCE and one that absorbs energy in the form of heat is called a HEAT SINK.**

CHARACTERISTICS OF HEAT ENGINE

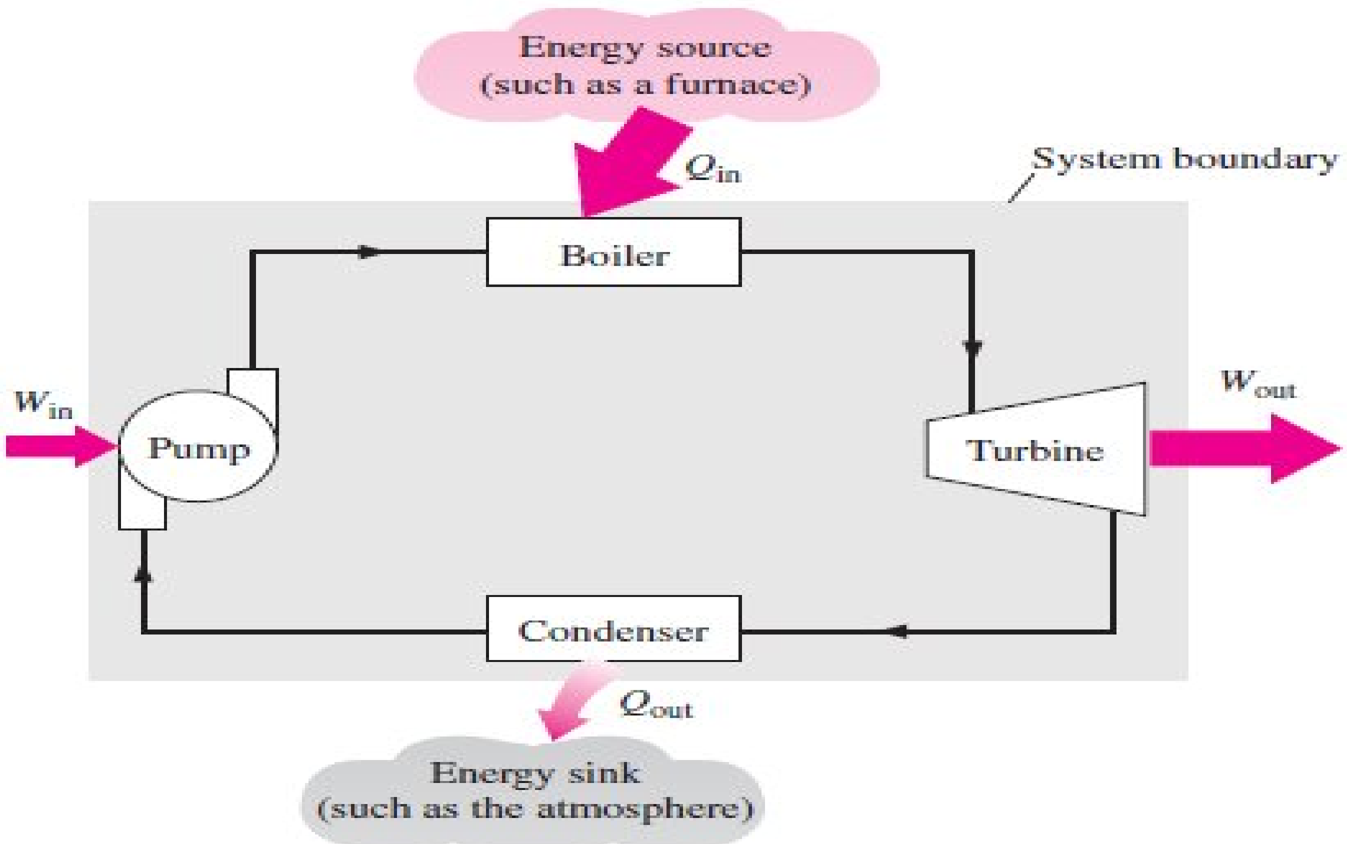
- **They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).**

- **They convert part of this heat to work (usually in the form of a rotating shaft ESPECIALLY IN TURBINE).**

- **They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).**

- **They operate on a cycle.**

- **Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the working fluid.**



Schematic of a steam power plant.

The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine and is called the thermal efficiency,**n**

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}} \qquad \eta_{th} = \frac{W_{net,out}}{Q_{in}} \qquad \eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

Cyclic devices of practical interest such as heat engines, refrigerators, and heat pumps operate between a high-temperature medium (or reservoir) at temperature *TH and a low-temperature medium (or reservoir) at temperature TL.*

To bring uniformity to the treatment of heat engines, refrigerators, and
heat pumps, we define these two quantities:

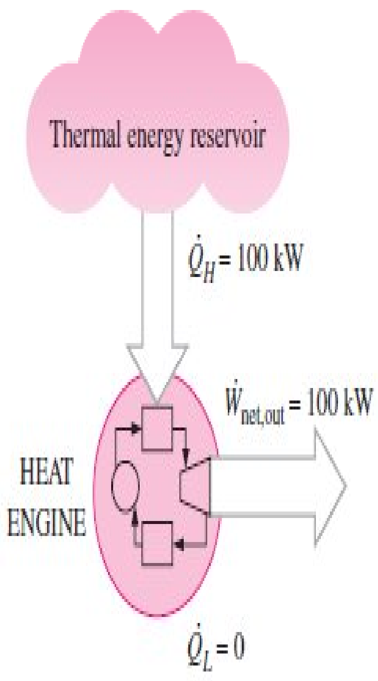
QH = magnitude of heat transfer between the cyclic device and the high temperature medium at temperature *TH*
QL = magnitude of heat transfer between the cyclic device and the low temperature m

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

The Second Law of Thermodynamics: Kelvin–Planck Statement

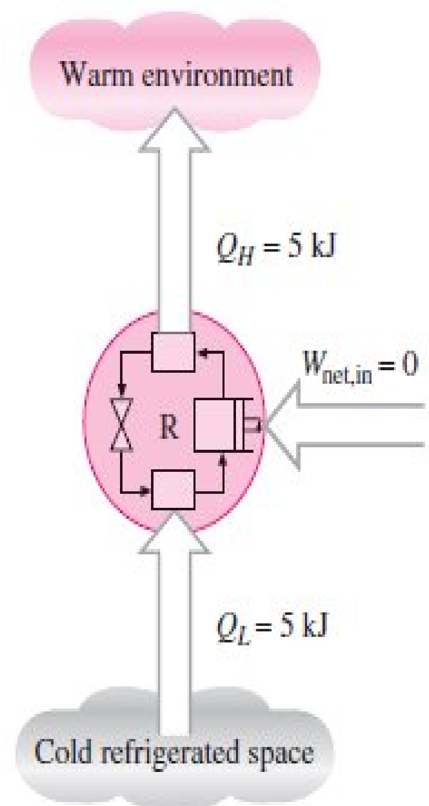
Statement States that It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

The Kelvin–Planck statement can also be expressed as *no heat engine can have a thermal efficiency of 100 percent, or as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace and it is related to heat engines.*



The Second Law of Thermodynamics: Clausius Statement: It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

Clausius statement is used to relate with refrigerators or heat pumps operations.

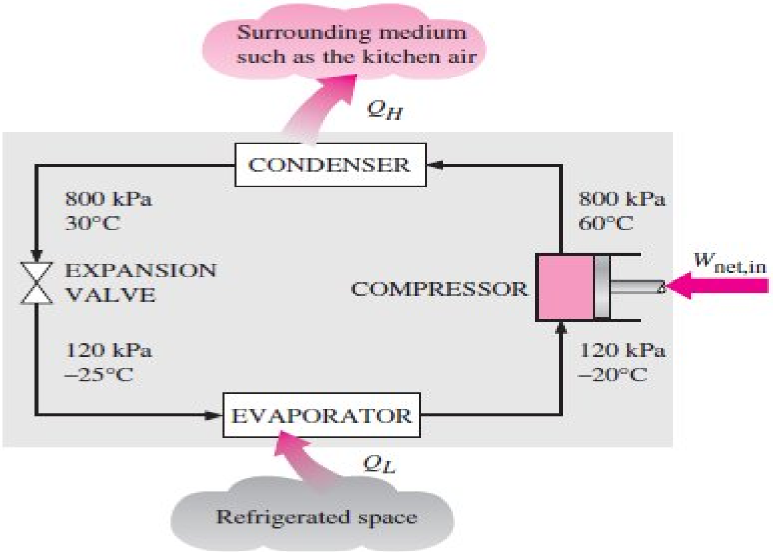


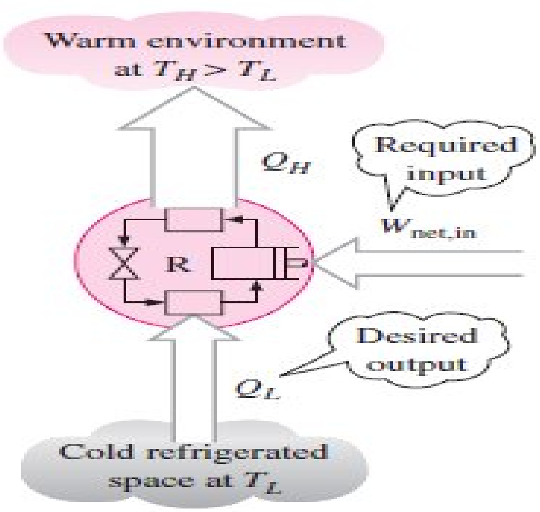
REFRIGERATORS AND HEAT PUMPS

Heat is transferred in the direction of. This heat transfer process occurs in nature without requiring any devices. The reverse process, however, cannot occur by itself.

The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called refrigerators. Refrigerators, like heat engines, are cyclic devices. The working fluid used in the refrigeration cycle is called a refrigerant.

The most frequently used refrigeration cycle is the *vapor-compression refrigeration cycle, which* involves four main components: a compressor, a condenser, an expansion valve, and an evaporator.





- **Coefficient of Performance:** The *efficiency of a refrigerator is expressed in terms of the **coefficient of*** performance (COP), denoted by COPR.

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net,in}} \qquad COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

Notice that the value of COPR can be *greater than unity. That is, the* amount of heat removed from the refrigerated space can be greater than the amount of work input

Refrigerators and heat pumps operate on the same cycle but differ in their objectives. The objective of a refrigerator is to maintain the refrigerated space at a low temperature by removing heat from it but the objective of a heat pump, however, is to maintain a heated space at a high temperature.

The measure of performance of a heat pump is also expressed in terms of the coefficient of performance COPHP, defined as

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}} \qquad COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H} \qquad COP_{HP} = COP_R + 1$$

Air conditioners: A special Cyclic Device

Air conditioners are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment. A window air conditioning unit cools a room by absorbing heat from the room air and

discharging it to the outside.

The same air-conditioning unit can be used as a heat pump in winter by installing it backwards. In this mode, the unit absorbs heat from the cold outside and delivers it to the room.

Air-conditioning systems that are equipped with proper controls and a reversing valve operate as air conditioners in summer and as heat pumps in winter.

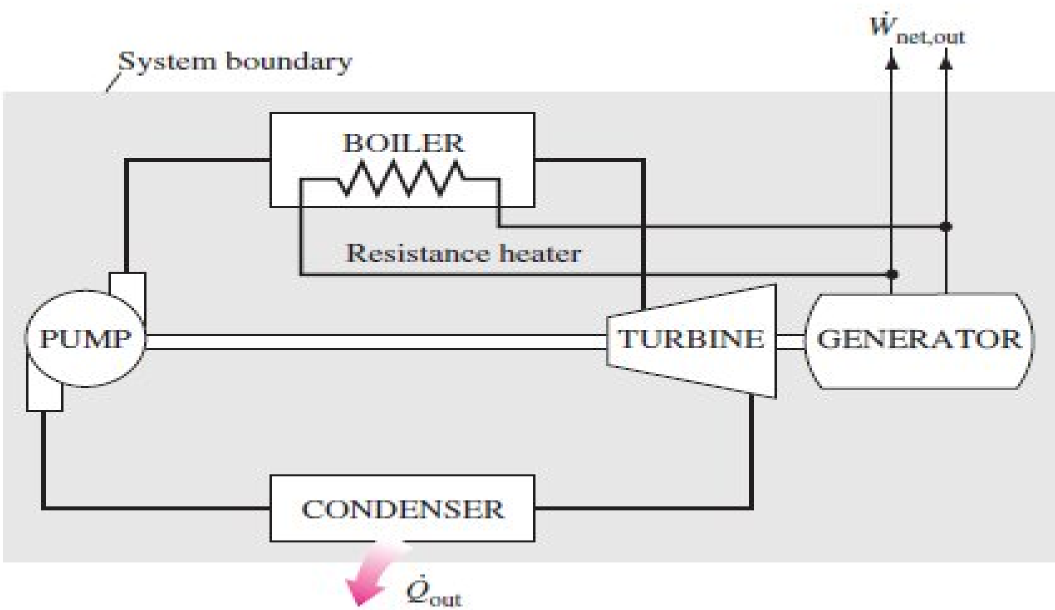
The performance of refrigerators and air conditioners is often expressed in terms of the energy efficiency rating (EER), which is the amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

$$EER = 3.412\, COP_R$$

Perpetual-Motion Machine

A device that violates the first law of thermodynamics (by *creating* energy) is called a perpetual-motion machine of the first kind (PMM1),

and a device that violates the second law of thermodynamics is called a

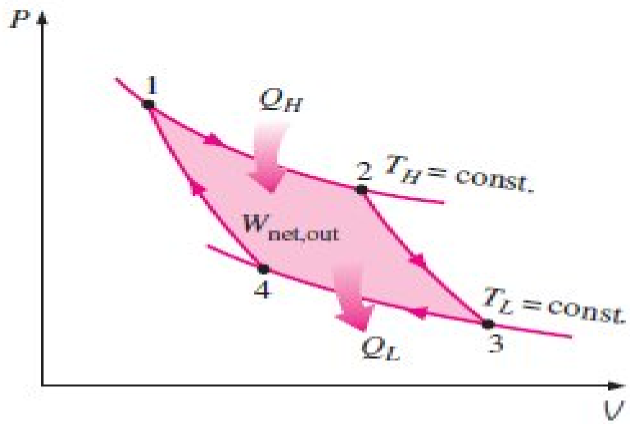


M2).

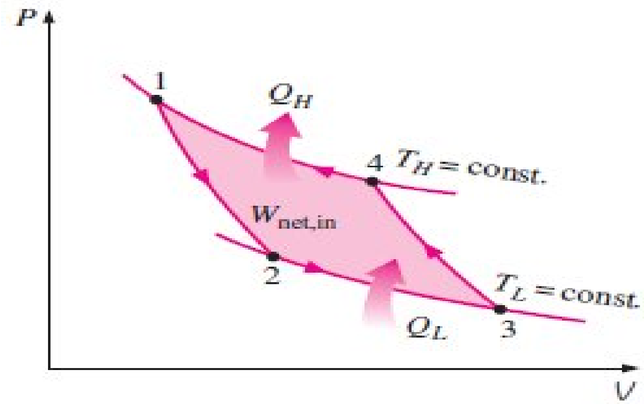
CARNOT CYCLE

- **Probably the best known reversible cycle is the Carnot cycle.**
- **The theoretical heat engine that operates on the Carnot cycle is called the Carnot heat engine.**
- **The Carnot cycle is composed of four reversible processes—two isothermal and two adiabatic—and it can be executed either in a closed or a steady-flow system.**

T



P-*V* diagram of the Carnot cycle.



P-*V* diagram of the reversed Carnot cycle.

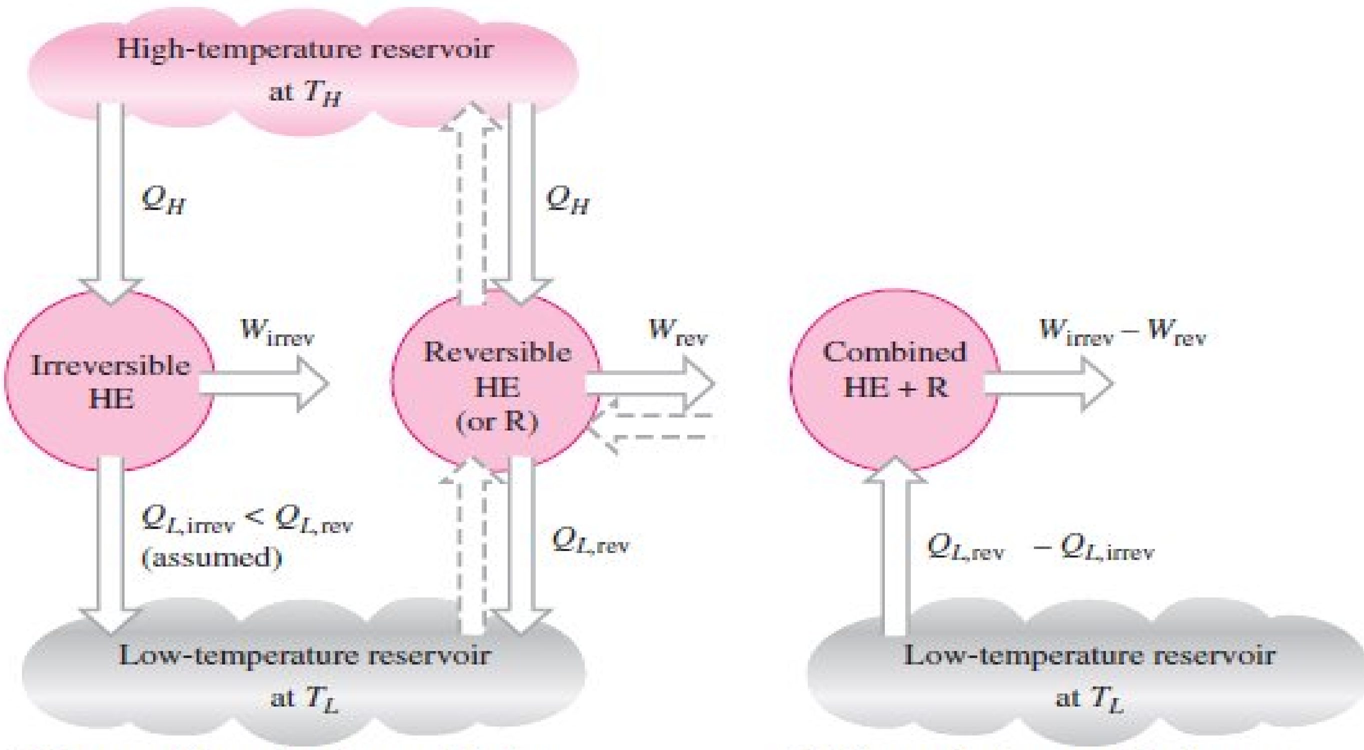
The Carnot heat-engine cycle just described is a totally reversible cycle.

Therefore, all the processes that comprise it can be *reversed, in which case it* becomes the Carnot refrigeration cycle.

THE CARNOT PRINCIPLES:

Two conclusions pertain to the thermal efficiency of reversible and irreversible (i.e., actual) heat engines, and they are known as the CARNOT PRINCIPLES, expressed as follows:

- **The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.**
- **The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.**



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

All irreversible (i.e.,actual) heat engines operating between these temperature limits (*TL and TH)* have lower efficiencies.

An actual heat engine cannot reach this maximum theoretical efficiency value because it is impossible to completely eliminate all the irreversibilities associated with the actual cycle.

$$\eta_{th} = 1 - \frac{Q_L}{Q_H} \qquad \eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

THE CARNOT REFRIGERATOR AND HEAT PUMP

A refrigerator or a heat pump that operates on the reversed Carnot cycle is called a Carnot refrigerator, or a Carnot heat pump.

The coefficient of performance of any refrigerator or heat pump, reversible or irreversible, is given by:

$$\text{COP}_R = \frac{1}{Q_H/Q_L - 1} \quad \text{and} \quad \text{COP}_{HP} = \frac{1}{1 - Q_L/Q_H}$$

$$\text{COP}_{R,rev} = \frac{1}{T_H/T_L - 1} \qquad \text{COP}_{HP,rev} = \frac{1}{1 - T_L/T_H}$$

$$\text{COP}_R \begin{cases} < \text{COP}_{R,rev} & \text{irreversible refrigerator} \\ = \text{COP}_{R,rev} & \text{reversible refrigerator} \\ > \text{COP}_{R,rev} & \text{impossible refrigerator} \end{cases}$$

GENERAL PHYSICAL QUESTIONS ON FIRST LAW OF THERMODYNAMICS

6–154 The drinking water needs of an office are met by cooling tab water in a refrigerated water fountain from 23 to 6°C at an average rate of 10 kg/h. If the COP of this refrigerator is 3.1, the required power input to this refrigerator is

(*a*) 197 W (*b*) 612 W (*c*) 64 W
(*d*) 109 W (*e*) 403 W

6–155 A heat pump is absorbing heat from the cold outdoors at 5°C and supplying heat to a house at 22°C at a rate of 18,000 kJ/h. If the power consumed by the heat pump is 2.5 kW, the coefficient of performance of the heat pump is

(*a*) 0.5 (*b*) 1.0 (*c*) 2.0
(*d*) 5.0 (*e*) 17.3

6–156 A heat engine cycle is executed with steam in the saturation dome. The pressure of steam is 1 MPa during heat addition, and 0.4 MPa during heat rejection. The highest possible efficiency of this heat engine is

(*a*) 8.0% (*b*) 15.6% (*c*) 20.2%
(*d*) 79.8% (*e*) 100%

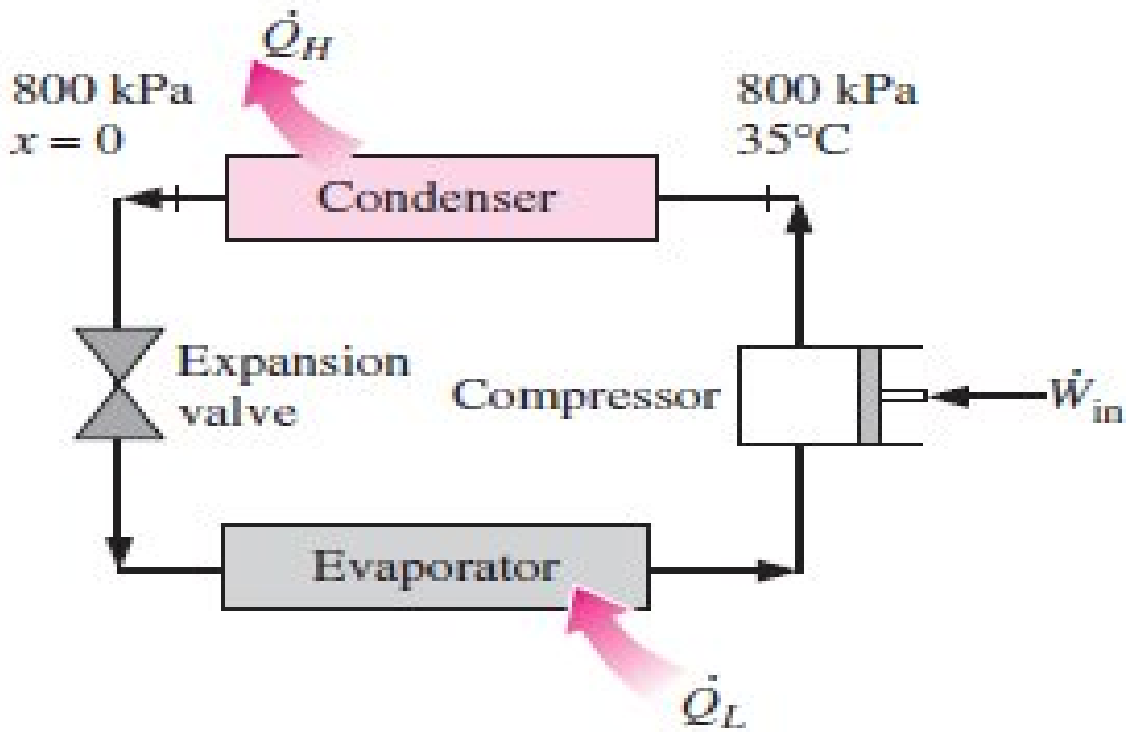
6–157 A heat engine receives heat from a source at 1000°C and rejects the waste heat to a sink at 50°C. If heat is supplied to this engine at a rate of 100 kJ/s, the maximum power this heat engine can produce is

(*a*) 25.4 kW (*b*) 55.4 kW (*c*) 74.6 kW
(*d*) 95.0 kW (*e*) 100.0 kW

6–158 A heat pump cycle is executed with R–134a under the saturation dome between the pressure limits of 1.8 and 0.2 MPa. The maximum coefficient of performance of this heat pump is

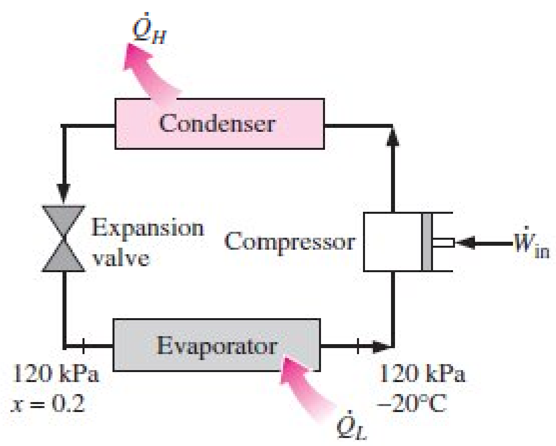
(*a*) 1.1 (*b*) 3.6 (*c*) 5.0
(*d*) 4.6 (*e*) 2.6

6–54 Refrigerant-134a enters the condenser of a residential heat pump at 800 kPa and 35°C at a rate of 0.018 kg/s and leaves at 800 kPa as a saturated liquid. If the compressor consumes 1.2 kW of power, determine (*a*) the COP of the heat pump and (*b*) the rate of heat absorption from the outside air.



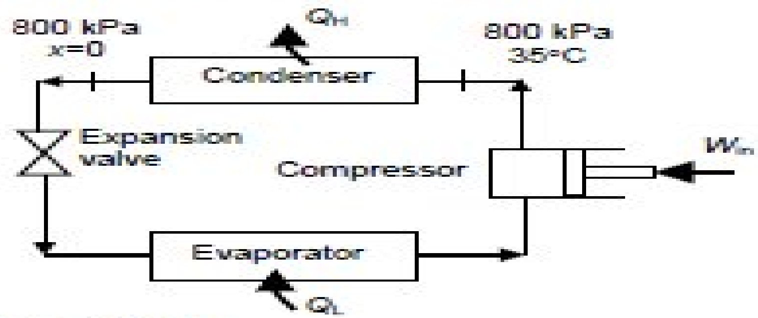
Refrigerant-134a enters the Evaporator coils placed at the back of the freezer section of a household refrigerator at 120 kPa with a quality of 20 percent and leaves at 120 kPa and 20°C. If the compressor consumes 450 W of power and the COP the refrigerator is 1.2, determine (*a) the mass flow* rate of the refrigerant and (*b) the rate of heat rejected to the* kitchen air.

Answers: (a) 0.00311 kg/s, (b) 990 W



6-54 Refrigerant-134a flows through the condenser of a residential heat pump unit. For a given compressor power consumption the COP of the heat pump and the rate of heat absorbed from the outside air are to be determined.

Assumptions **1** The heat pump operates steadily. **2** The kinetic and potential energy changes are zero.



Properties The enthalpies of R-134a at the condenser inlet and exit are

$$\left.\begin{array}{l} P_1 = 800 \text{ kPa} \\ T_1 = 35°\text{C} \end{array}\right\} h_1 = 271.22 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 800 \text{ kPa} \\ x_2 = 0 \end{array}\right\} h_2 = 95.47 \text{ kJ/kg}$$

Analysis (*a*) An energy balance on the condenser gives the heat rejected in the condenser

$$\dot{Q}_H = \dot{m}(h_1 - h_2) = (0.018 \text{ kg/s})(271.22 - 95.47) \text{ kJ/kg} = 3.164 \text{ kW}$$

The COP of the heat pump is

$$\text{COP} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{3.164 \text{ kW}}{1.2 \text{ kW}} = \mathbf{2.64}$$

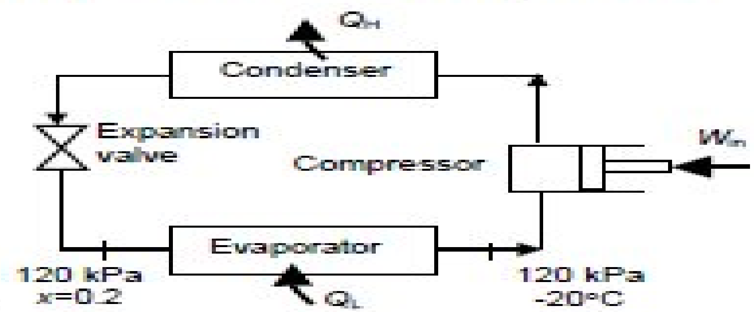
(*b*) The rate of heat absorbed from the outside air

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{in} = 3.164 - 1.2 = \mathbf{1.96 \text{ kW}}$$

6-55 A commercial refrigerator with R-134a as the working fluid is considered. The evaporator inlet and exit states are specified. The mass flow rate of the refrigerant and the rate of heat rejected are to be determined.

Assumptions **1** The refrigerator operates steadily. **2** The kinetic and potential energy changes are zero.

Properties The properties of R-134a at the evaporator inlet and exit states are (Tables A-11 through A-13)



$$\left.\begin{array}{l} P_1 = 120 \text{ kPa} \\ x_1 = 0.2 \end{array}\right\} h_1 = 65.38 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 120 \text{ kPa} \\ T_2 = -20°\text{C} \end{array}\right\} h_2 = 238.84 \text{ kJ/kg}$$

Analysis (*a*) The refrigeration load is

$$\dot{Q}_L = (\text{COP})\dot{W}_{in} = (1.2)(0.45 \text{ kW}) = 0.54 \text{ kW}$$

The mass flow rate of the refrigerant is determined from

$$\dot{m}_R = \frac{\dot{Q}_L}{h_2 - h_1} = \frac{0.54 \text{ kW}}{(238.84 - 65.38) \text{ kJ/kg}} = \mathbf{0.0031 \text{ kg/s}}$$

(*b*) The rate of heat rejected from the refrigerator is

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} = 0.54 + 0.45 = \mathbf{0.99 \text{ kW}}$$

VAPOUR AND COMBINED POWER CYCLE:

There are many types of ideal gas power cycles which are used for modelling many power-producing devices. It is with a bid to explain or describe those devices that an ideal cycles are designed. Some of such power cycles are:

- OTTO CYCLE: The ideal cycle for spark-ignition automobile engines.
- DIESEL CYCLE: The ideal cycle for compression-ignition engines.
- BRAYTON CYCLE: The ideal cycle for gas-turbine engines.
- RANKINE CYCLE: THE IDEAL CYCLE FOR VAPOR POWER CYCLES

Most power-producing devices operate on cycles. The cycles encountered in actual devices are difficult to analyze because of:

- the presence of complicating effects, such as friction and heat transfers in linking pipe.
- the absence of sufficient time for establishment of the equilibrium conditions during the cycle.
- Non-quasi-equilibrium status of the compression and expansion processes.

To make an analytical study of a cycle feasible, we have to keep the complexities at a manageable level and utilize some idealizations.

THE BIG QUESTION TO ASK:

If the Carnot cycle is the best possible cycle, why do we not use it as the model cycle for all the heat engines instead of bothering with several so-called *ideal cycles?*

- *ANSWER:* Most cycles encountered in practice differ significantly from the Carnot cycle, which makes it unsuitable as a realistic model. e.g. otto cycle involves isentropic expansion and compression, non adiabatic isochoric heat addition and heat rejection.

RANKINE CYCLE

Rankine cycle is an improvement over Carnot cycle in that the impracticability of the latter has been corrected in Rankine cycle by:

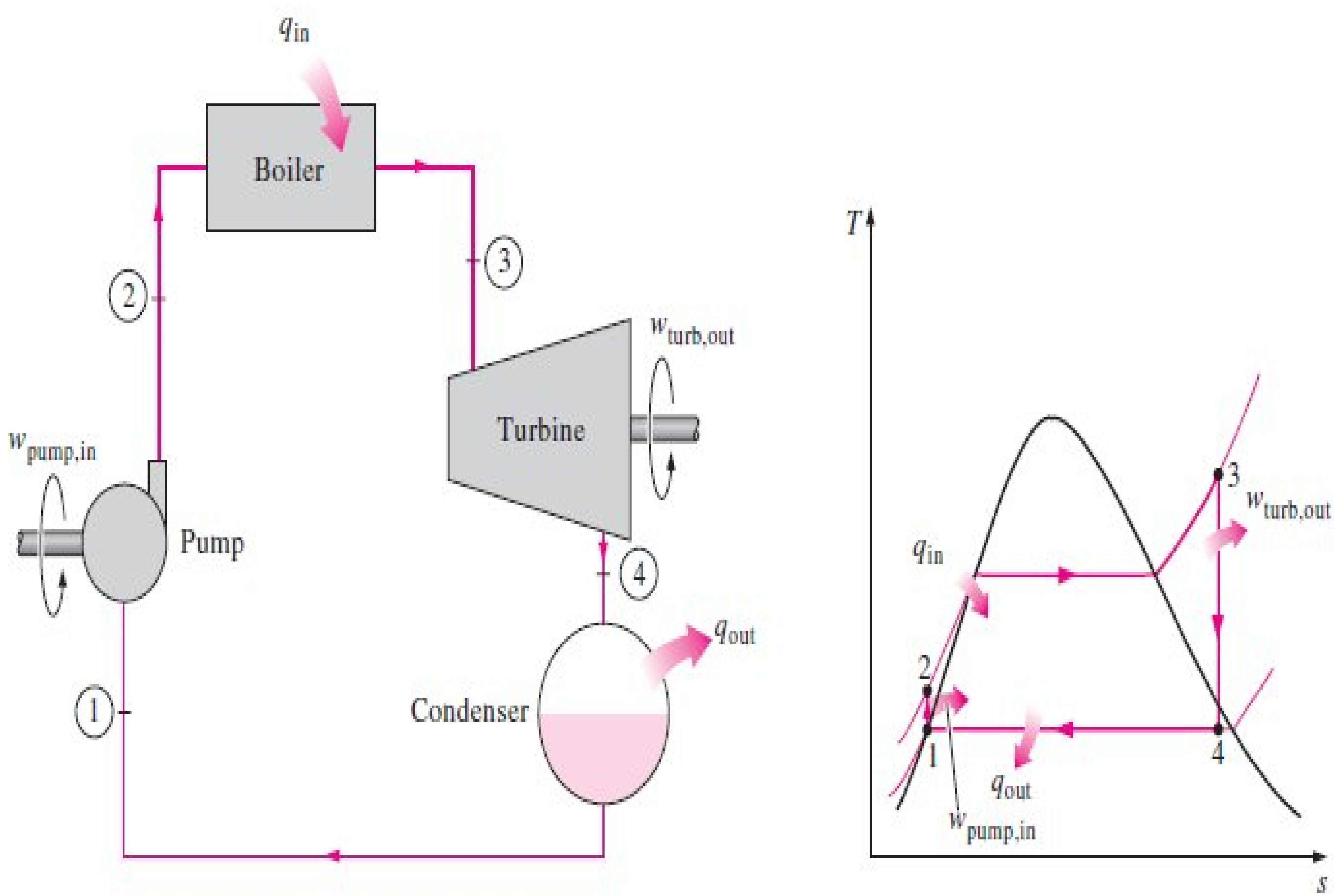
- SUPERHEATING THE STEAM IN THE BOILER AND CONDENSING IT COMPLETELY IN THE CONDENSER.
- The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes:

  1-2 Isentropic compression in a pump

  2-3 Constant pressure heat addition in a boiler

  3-4 Isentropic expansion in a turbine

  4-1 Constant pressure heat rejection in a condenser



The simple ideal Rankine cycle.

- **Water enters the *pump at state 1 as saturated liquid and is compressed* isentropically to the operating pressure of the boiler.**

- **The water temperature increases somewhat during this isentropic compression process due to a slight decrease in the specific volume of water.**

- **Water enters the *boiler as a compressed liquid at state 2 and leaves as a* superheated vapor at state 3.**

- **The boiler is basically a large heat exchanger where the heat originating from combustion gases, nuclear reactors, or other sources is transferred to the water essentially at constant pressure.**

- **The superheated vapor at state 3 enters the *turbine, where it expands isentropically* and produces work by rotating the shaft connected to an electric generator.**

- **The pressure and the temperature of steam drop during this process to the values at state 4, where steam enters the *condenser.***

Energy Analysis of the Ideal Rankine Cycle.

- **All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes.**

- **Then the *steady-flow energy equation per unit mass of steam* reduces to:**

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

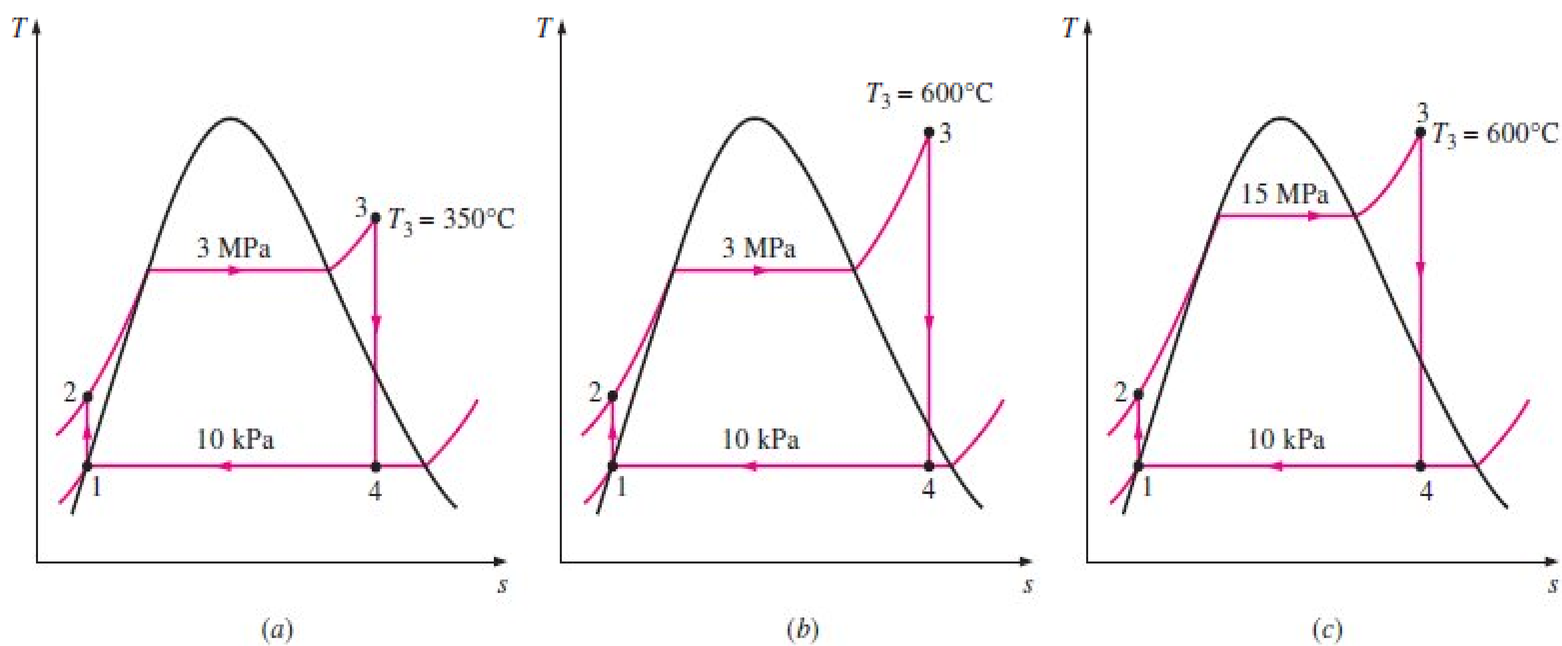
Pump ($q = 0$): $w_{pump,in} = h_2 - h_1$ $\qquad$ $w_{pump,in} = v(P_2 - P_1)$

Boiler ($w = 0$): $q_{in} = h_3 - h_2$

Turbine ($q = 0$): $w_{turb,out} = h_3 - h_4$

Condenser ($w = 0$): $q_{out} = h_4 - h_1$

- Consider a steam power plant operating on the ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 10 kPa.
- Determine (*a) the thermal efficiency of this power* plant, (*b) the thermal efficiency if steam is superheated to 600°C instead of* 350°C, and (*c) the thermal efficiency if the boiler pressure is raised to 15* MPa while the turbine inlet temperature is maintained at 600°C.



(a) This is the steam power plant discussed in Example 10–1, except that the condenser pressure is lowered to 10 kPa. The thermal efficiency is determined in a similar manner:

State 1: $\left.\begin{array}{l} P_1 = 10 \text{ kPa} \\ \text{Sat. liquid} \end{array}\right\} \quad \begin{array}{l} h_1 = h_{f @ 10 \text{ kPa}} = 191.81 \text{ kJ/kg} \\ v_1 = v_{f @ 10 \text{ kPa}} = 0.00101 \text{ m}^3\text{/kg} \end{array}$

State 2: $P_2 = 3 \text{ MPa}$
$s_2 = s_1$

$$w_{\text{pump,in}} = v_1(P_2 - P_1) = (0.00101 \text{ m}^3\text{/kg})[(3000 - 10) \text{ kPa}]\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right)$$

$$= 3.02 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pump,in}} = (191.81 + 3.02) \text{ kJ/kg} = 194.83 \text{ kJ/kg}$$

State 3: $\left.\begin{array}{l} P_3 = 3 \text{ MPa} \\ T_3 = 350°\text{C} \end{array}\right\} \quad \begin{array}{l} h_3 = 3116.1 \text{ kJ/kg} \\ s_3 = 6.7450 \text{ kJ/kg} \cdot \text{K} \end{array}$

State 4: $P_4 = 10 \text{ kPa} \quad \text{(sat. mixture)}$
$s_4 = s_3$

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

Thus,

$$h_4 = h_f + x_4 h_{fg} = 191.81 + 0.8128(2392.1) = 2136.1 \text{ kJ/kg}$$
$$q_{\text{in}} = h_3 - h_2 = (3116.1 - 194.83) \text{ kJ/kg} = 2921.3 \text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = (2136.1 - 191.81) \text{ kJ/kg} = 1944.3 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1944.3 \text{ kJ/kg}}{2921.3 \text{ kJ/kg}} = \mathbf{0.334 \text{ or } 33.4\%}$$

Therefore, the thermal efficiency increases from 33.4 to 37.3 percent as a result of superheating the steam from 350 to 600°C. At the same time, the quality of the steam increases from 81.3 to 91.5 percent (in other words, the moisture content decreases from 18.7 to 8.5 percent).

(*c*) State 1 remains the same in this case, but the other states change. The enthalpies at state 2 (15 MPa and $s_2 = s_1$), state 3 (15 MPa and 600°C), and state 4 (10 kPa and $s_4 = s_3$) are determined in a similar manner to be

$$h_2 = 206.95 \text{ kJ/kg}$$
$$h_3 = 3583.1 \text{ kJ/kg}$$
$$h_4 = 2115.3 \text{ kJ/kg} \qquad (x_4 = 0.804)$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = 3583.1 - 206.95 = 3376.2 \text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2115.3 - 191.81 = 1923.5 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1923.5 \text{ kJ/kg}}{3376.2 \text{ kJ/kg}} = \mathbf{0.430 \text{ or } 43.0\%}$$

Discussion The thermal efficiency increases from 37.3 to 43.0 percent as a result of raising the boiler pressure from 3 to 15 MPa while maintaining the turbine inlet temperature at 600°C. At the same time, however, the quality of the steam decreases from 91.5 to 80.4 percent (in other words, the moisture content increases from 8.5 to 19.6 percent).

PRACTICE QUESTIONS

1. **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

PRACTICE QUESTIONS

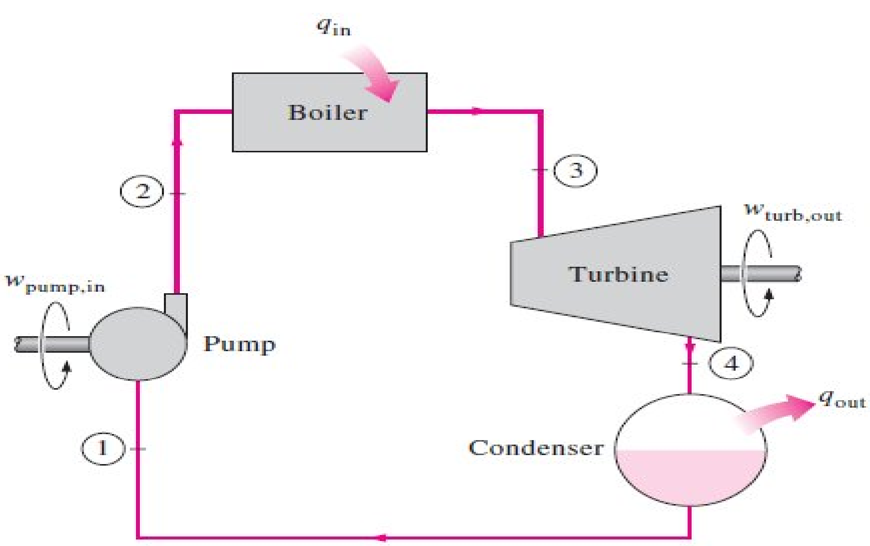
2. **A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a *T-s diagram with respect to saturation* lines, and determine (*a) the thermal efficiency of the* cycle and (*b) the net power output of the power plant.***

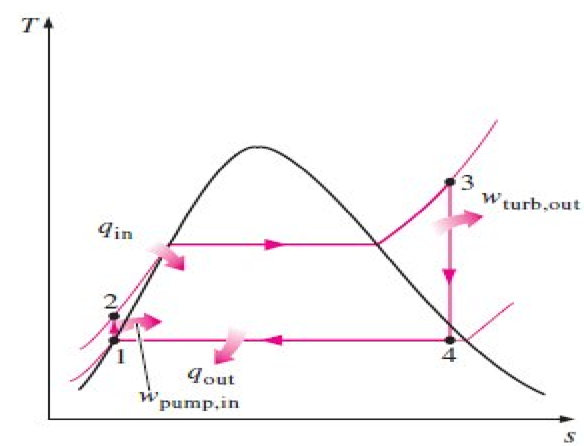
3. **Consider a steam power plant that operates on a simple ideal Rankine cycle and has a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa by running cooling water from a lake through the tubes of the condenser at a rate of 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

4. **Consider a coal-fired steam power plant that produces 300 MW of electric power. The power plant operates on a simple ideal Rankine cycle with turbine inlet conditions of 5 MPa and 450°C and a condenser pressure of 25 kPa. The coal has a heating value (energy released when the fuel is burned) of 29,300 kJ/kg. Assuming that 75 percent of this energy is transferred to the steam in the boiler and that the electric generator has an efficiency of 96 percent, determine (*a) the overall plant efficiency (the ratio of net electric power* output to the energy input as fuel) and (*b) the required rate of* coal supply.**

Answers: (a) 24.5 percent, (b) 150 t/h





10-16 A steam power plant that operates on a simple ideal Rankine cycle is considered. The quality of the steam at the turbine exit, the thermal efficiency of the cycle, and the mass flow rate of the steam are to be determined.

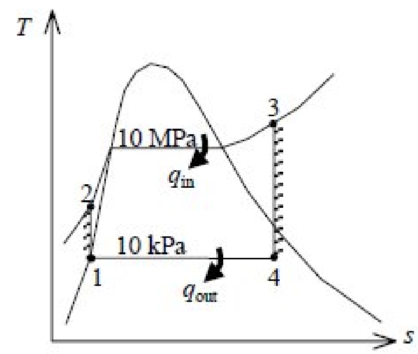
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

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

$$h_1 = h_{f @ 10\text{ kPa}} = 191.81\text{ kJ/kg}$$
$$v_1 = v_{f @ 10\text{ kPa}} = 0.00101\text{ m}^3/\text{kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1) = (0.00101\text{ m}^3/\text{kg})(10{,}000 - 10\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 10.09\text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 10.09 = 201.90\text{ kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 10\text{ MPa} \\ T_3 = 500\,^\circ\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3375.1\text{ kJ/kg} \\ s_3 = 6.5995\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 10\text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.5995 - 0.6492}{7.4996} = \mathbf{0.7934}$$

$$h_4 = h_f + x_4 h_{fg} = 191.81 + (0.7934)(2392.1) = 2089.7\text{ kJ/kg}$$

(*b*)
$$q_{\text{in}} = h_3 - h_2 = 3375.1 - 201.90 = 3173.2\text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2089.7 - 191.81 = 1897.9\text{ kJ/kg}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3173.2 - 1897.9 = 1275.4\text{ kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1275.4\text{ kJ/kg}}{3173.2\text{ kJ/kg}} = \mathbf{40.2\%}$$

(*c*)
$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{210{,}000\text{ kJ/s}}{1275.4\text{ kJ/kg}} = \mathbf{164.7\text{ kg/s}}$$

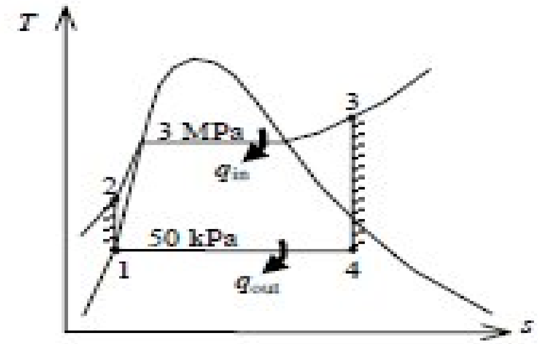
10-15 A steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The thermal efficiency of the cycle and the net power output of the plant are to be determined.

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

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

$$h_1 = h_{f@\,50\text{ kPa}} = 340.54 \text{ kJ/kg}$$
$$v_1 = v_{f@\,50\text{ kPa}} = 0.001030 \text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1) \\ &= (0.001030 \text{ m}^3\text{/kg})(3000-50)\text{kPa}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 3.04 \text{ kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{p,\text{in}} = 340.54 + 3.04 = 343.58 \text{ kJ/kg}$$



$$\left.\begin{aligned} P_3 &= 3 \text{ MPa} \\ T_3 &= 300\,°\text{C} \end{aligned}\right\} \begin{aligned} h_3 &= 2994.3 \text{ kJ/kg} \\ s_3 &= 6.5412 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_4 &= 50 \text{ kPa} \\ s_4 &= s_3 \end{aligned}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.5412 - 1.0912}{6.5019} = 0.8382$$
$$\begin{aligned} h_4 &= h_f + x_4 h_{fg} = 340.54 + (0.8382)(2304.7) \\ &= 2272.3 \text{ kJ/kg} \end{aligned}$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = 2994.3 - 343.58 = 2650.7 \text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2272.3 - 340.54 = 1931.8 \text{ kJ/kg}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 2650.7 - 1931.8 = 718.9 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1931.8}{2650.7} = \mathbf{27.1\%}$$

(*b*) $$\dot{W}_{\text{net}} = \dot{m}w_{\text{net}} = (35 \text{ kg/s})(718.9 \text{ kJ/kg}) = \mathbf{25.2\ MW}$$

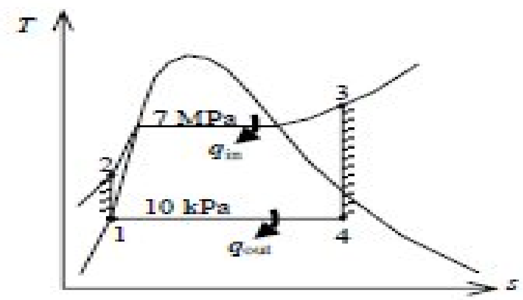
10-22 A steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The thermal efficiency of the cycle, the mass flow rate of the steam, and the temperature rise of the cooling water are to be determined.

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

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

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

$$v_1 = v_{f@10\text{ kPa}} = 0.00101 \text{ m}^3/\text{kg}$$



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

$$= (0.00101 \text{ m}^3/\text{kg})(7{,}000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

$$= 7.06 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 7.06 = 198.87 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 7 \text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3411.4 \text{ kJ/kg} \\ s_3 = 6.8000 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 10 \text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.8000 - 0.6492}{7.4996} = 0.8201$$

$$h_4 = h_f + x_4 h_{fg} = 191.81 + (0.8201)(2392.1) = 2153.6 \text{ kJ/kg}$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = 3411.4 - 198.87 = 3212.5 \text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 2153.6 - 191.81 = 1961.8 \text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3212.5 - 1961.8 = 1250.7 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1250.7 \text{ kJ/kg}}{3212.5 \text{ kJ/kg}} = 38.9\%$$

(*b*)

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{45{,}000 \text{ kJ/s}}{1250.7 \text{ kJ/kg}} = 36.0 \text{ kg/s}$$

(*c*) The rate of heat rejection to the cooling water and its temperature rise are

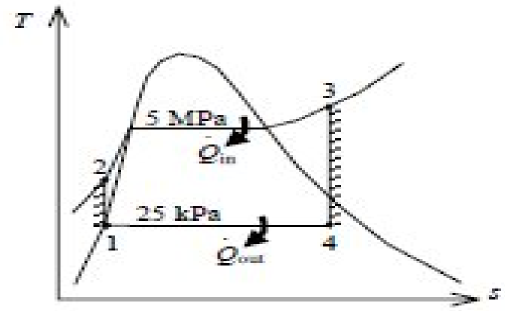
$$\dot{Q}_{\text{out}} = \dot{m} q_{\text{out}} = (35.98 \text{ kg/s})(1961.8 \text{ kJ/kg}) = 70{,}586 \text{ kJ/s}$$

$$\Delta T_{\text{coolingwater}} = \frac{\dot{Q}_{\text{out}}}{(\dot{m}c)_{\text{coolingwater}}} = \frac{70{,}586 \text{ kJ/s}}{(2000 \text{ kg/s})(4.18 \text{ kJ/kg}\cdot°\text{C})} = 8.4°\text{C}$$

10-20 A 300-MW coal-fired steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The overall plant efficiency and the required rate of the coal supply are to be determined.

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

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



$$h_1 = h_{f\,@\,25\text{ kPa}} = 271.96\text{ kJ/kg}$$
$$v_1 = v_{f\,@\,25\text{ kPa}} = 0.001020\text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1)$$
$$= (0.00102\text{ m}^3\text{/kg})(5000 - 25\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$
$$= 5.07\text{ kJ/kg}$$
$$h_2 = h_1 + w_{p,\text{in}} = 271.96 + 5.07 = 277.03\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 5\text{ MPa} \\ T_3 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3317.2\text{ kJ/kg} \\ s_3 = 6.8210\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 25\text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.8210 - 0.8932}{6.9370} = 0.8545$$
$$h_4 = h_f + x_4 h_{fg} = 271.96 + (0.8545)(2345.5) = 2276.2\text{ kJ/kg}$$

The thermal efficiency is determined from

$$q_{\text{in}} = h_3 - h_2 = 3317.2 - 277.03 = 3040.2\text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2276.2 - 271.96 = 2004.2\text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2004.2}{3040.2} = 0.3407$$

Thus,

$$\eta_{\text{overall}} = \eta_{\text{th}} \times \eta_{\text{comb}} \times \eta_{\text{gen}} = (0.3407)(0.75)(0.96) = \mathbf{24.5\%}$$

(*b*) Then the required rate of coal supply becomes

$$\dot{Q}_{\text{in}} = \frac{\dot{W}_{\text{net}}}{\eta_{\text{overall}}} = \frac{300{,}000\text{ kJ/s}}{0.2453} = 1{,}222{,}992\text{ kJ/s}$$

and

$$\dot{m}_{\text{coal}} = \frac{\dot{Q}_{\text{in}}}{C_{\text{coal}}} = \frac{1{,}222{,}992\text{ kJ/s}}{29{,}300\text{ kJ/kg}}\left(\frac{1\text{ ton}}{1000\text{ kg}}\right) = 0.04174\text{ tons/s} = \mathbf{150.3\text{ tons/h}}$$

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