MEC511

Thermodynamics & Fluids

Chapter01

Introductory Concepts of Thermodynamics and Definitions

Toronto Metropolitan University

Lecture 07

NOTE!

1 Introductory Concepts and Definitions

1.1 Using Thermodynamics

The word thermodynamics comes from the Greek words Therme (heat) and dynamis (force) . The formal study of Thermodynamics began in the early nineteenth century through consideration of motive power of heat.

Thermodynamics
- in Physics: Properties of matter
- in Engineering Science: Interaction of systems and their environment

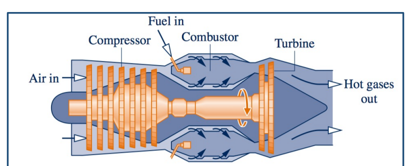
Application of Thermodynamics Studies in Engineering:

- to achieve improved designs and better performance
- to increase in the output of some desired product
- a reduced input of a scarce resource
- a reduction in total costs
- a lesser environmental impact

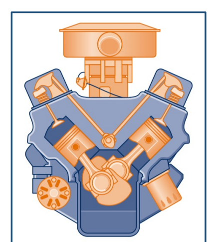
Application of Thermodynamics Studies in Engineering:

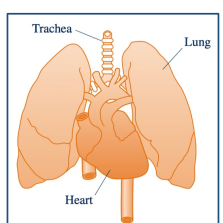
Selected Areas of Application of Engineering Thermodynamics

Aircraft and rocket propulsion
Alternative energy systems
  Fuel cells
  Geothermal systems
  Magnetohydrodynamic (MHD) converters
  Ocean thermal, wave, and tidal power generation
  Solar-activated heating, cooling, and power generation
  Thermoelectric and thermionic devices
  Wind turbines
Automobile engines
Bioengineering applications
Biomedical applications
Combustion systems
Compressors, pumps
Cooling of electronic equipment
Cryogenic systems, gas separation, and liquefaction
Fossil and nuclear-fueled power stations
Heating, ventilating, and air-conditioning systems
  Absorption refrigeration and heat pumps
  Vapor-compression refrigeration and heat pumps
Steam and gas turbines
  Power production
  Propulsion

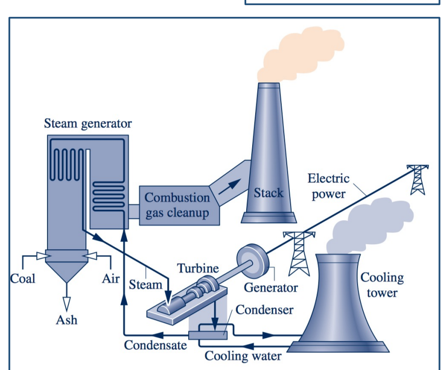


Turbojet engine


Vehicle engine



Biomedical applications



Electrical power plant

1.2 Defining Systems

In thermodynamics the term *system* is used to identify the subject of the analysis. Once the system is defined and the relevant interactions with other systems are identified, one or more physical laws or relations are applied.

Examples:
- study a quantity of matter contained within a closed, rigid-walled tank.
- considering something such as a pipeline through which natural gas flows.

Everything external to the system is considered to be part of the system's *surroundings*. The system is distinguished from its surroundings by a specified *boundary*, which may be at rest or in motion.

Type of Systems

Closed System
- fixed quantity of matter (no transfer of mass across its boundary).
- **Isolated system:** does not interact in any way with its surroundings

Control Volumes (open system)
- control volume is a region of space through which mass may flow

- ❑ The term *control mass* is sometimes used in place of *closed system*.
- ❑ The term *open system* is used interchangeably with *control volume*.
- ❑ When the terms control mass and control volume are used, the *system boundary* is often referred to as a *control surface* .

Type of Systems

Closed System

isolated system

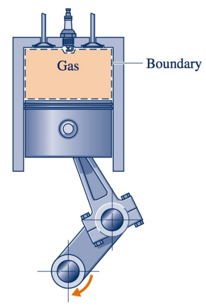


Fig. 1.1 Closed system: A gas in a piston–cylinder assembly.

Open System

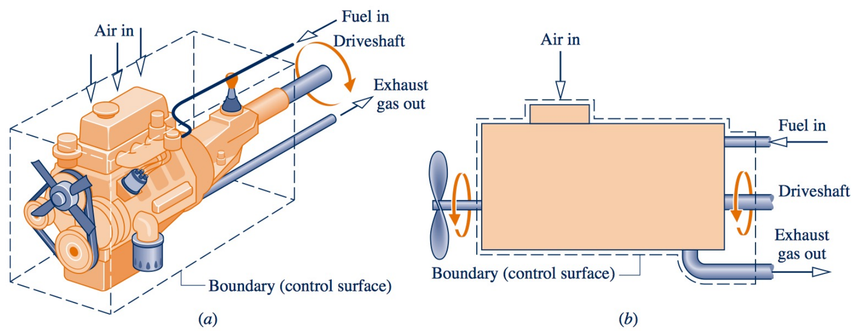
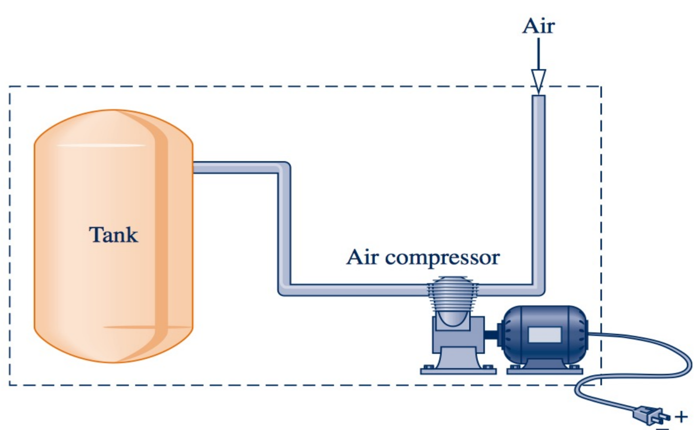


Fig. 1.2 Example of a control volume (open system). An automobile engine.

1.2.3 Selecting the System Boundary



In general, the choice of system boundary is governed by two considerations:

1. ***What is known about a possible system, particularly at its boundaries, and***
2. ***The objective of the analysis.***

1.3 Describing Systems and Their Behavior

Engineers are interested in studying systems and how they interact with their surroundings.

1.3.1 MACROSCOPIC AND MICROSCOPIC VIEWS OF THERMODYNAMICS

Systems can be studied from a *macroscopic* or a *microscopic* point of view:

Macroscopic approach → **Classical thermodynamics** → **Gross or Overall Behavior**

No model of the structure of matter at the molecular, atomic, and subatomic levels is directly used in classical thermodynamics.

Applications : For a wide range 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 approach → **Statistical thermodynamics** → **Structure of Matter**

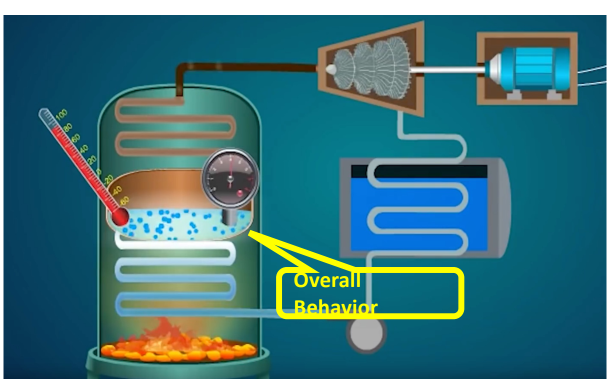
Characterize by statistical means the average behavior of the particles making up a system of interest and relate this information to the observed macroscopic behavior of the system.

Applications : lasers, plasmas, high--speed gas flows, chemical kinetics, very low temperatures (cryogenics).

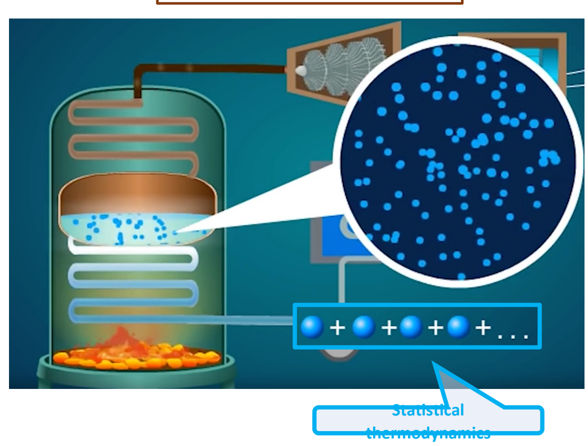
1.3 Describing Systems and Their Behavior

Systems can be studied from a *macroscopic* or a *microscopic* point of view:

Macroscopic approach



Microscopic approach



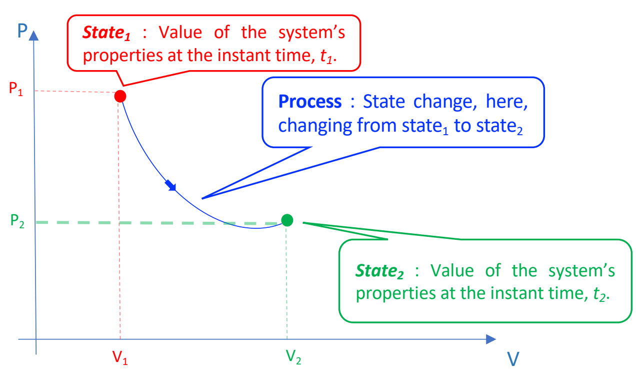
1.3.2 PROPERTY, STATE, AND PROCESS

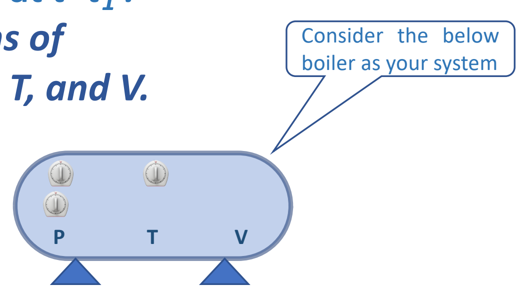
- ***Property*** **is macroscopic characteristic of a system. such as: mass, volume, energy, pressure, and temperature**
- **The word *state* refers to the condition of a system as described by its properties.**
- **A *process* is a transformation from one state to another.**
- **A system is said to be at *steady state* if none of its properties changes with time.**
- ***Thermodynamic cycle*** **is a sequence of processes that begins and ends at the same state.** Note: at the conclusion of a cycle all properties have the same values they had at the beginning. For example, steam circulating through an electrical power plant executes a cycle.
- **A quantity is a *property* if its change in value between two states is <u>independent</u> of the process.**

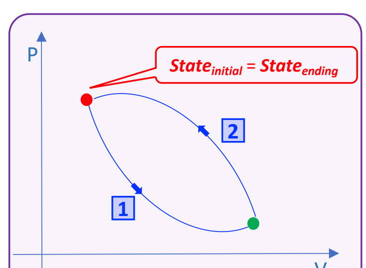
1.3.2 PROPERTY, STATE, AND PROCESS

PROPERTY, STATE, AND PROCESS (Simple Example)

What is the condition of your system at $t=t_1$?
The condition could be define in terms of characteristics (properties) such as P, T, and V.







Thermodynamic cycle

1.3.3 EXTENSIVE AND INTENSIVE PROPERTIES

Properties are categorized in two types:

Extensive: **its value for an overall system is the sum of its values for the parts into which the system is divided.**

Examples: Mass, volume, energy.

Intensive: **Their values are independent of the size or extent of a system and may vary from place to place within the system at any moment.**

Examples: Specific volume, pressure, and temperature

PHASE AND PURE SUBSTANCE

Phase: **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).**
- **A system can contain one or more phases.** For example, a system of liquid water and water vapor (steam) contains two phases.

pure substance: **Is one that is uniform and invariable in chemical composition.**

For example, if liquid water and water vapor form a system with two phases, the system can be regarded as a pure substance because each phase has the same composition.

1.3.4 Equilibrium

The concept of equilibrium is fundamental.

- ❑ ***In mechanics*, equilibrium means a condition of balance maintained by an equality of opposing forces.**
- ❑ ***In thermodynamics*, the concept is more far-reaching, including not only a balance of forces but also a balance of other influences which are: *mechanical, thermal, phase,* and *chemical* equilibrium.**
  - **Thermal equilibrium:** Equality in temperature (no heat flow within the system)
  - **Mechanical equilibrium:** Equality in forces (pressure should not change by space & time)
  - **Chemical equilibrium :** Chemical compositions should not change with time (no chemical reactions by time)
  - **Phase equilibrium:** Mass of each phase should not change with time

Note: all of the above four equilibriums must be met in order to have a thermodynamics equilibrium.

1.4 Measuring Mass, Length, Time, Force, and Temperature

- ❑ The SI base units for mass, length, and time are listed below.
- ❑ The SI base unit for temperature is the kelvin, K.

Units for Mass, Length, Time, and Force

Quantity	SI Unit	SI Symbol
mass	kilogram	kg
length	meter	m
time	second	s
force	newton (= 1 kg · m/s^2)	N

SI Unit Prefixes

Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Example :

A communications satellite weighs 4400 N on Earth where g = 9.81 m/s^2 . What is the weight of the satellite, in N, as it orbits Earth where the acceleration of gravity is 0.224 m/s^2 ?

1.5 Specific Volume (Measurable Intensive Properties)

Density for a continuum:

$$\rho = \lim_{V \to V'} \left(\frac{m}{V} \right)$$

Where; V' is the smallest volume for which a definite value of the ratio exists.

Mass is defined as:

$$m = \int_V \rho dV$$

1.5 Specific Volume (Measurable Intensive Properties)

The *specific volume* , v, is defined as the reciprocal of the density

- **specific volume on mass basis**

$$v = \frac{1}{\rho} \quad \left(\frac{m^3}{kg}\right)$$

- **specific volume on a molar basis in terms of kmol (kilomole)**
  - **Molecular weight, *M*:**

$$\boxed{n = \frac{m}{M}}$$

where; *n*, the number of kilomoles of a substance
m, mass in kg
M, molecular weight in kg/kmol

  - **To signal that a property is on a molar basis, a bar is used over its symbol. Thus, $\bar{v}$ signifies the volume per kmol. The unit used for $\bar{v}$ is m³/kmol.**

$$\boxed{\bar{v} = M\, v}$$

1.6 Pressure (Measurable Intensive Properties)

$$p = \lim_{A \to A'} \left(\frac{F_{\text{normal}}}{A}\right)$$

$$1\,pascal = 1\; N/m^2$$

$$1\,kpa = 10^3\; N/m^2$$

$$1\,bar = 10^5\; N/m^2$$

$$1\,Mpa = 10^6\; N/m^2$$

1 standard atmosphere (1 atm)= $1.01325 \times 10^5\; N/m^2$

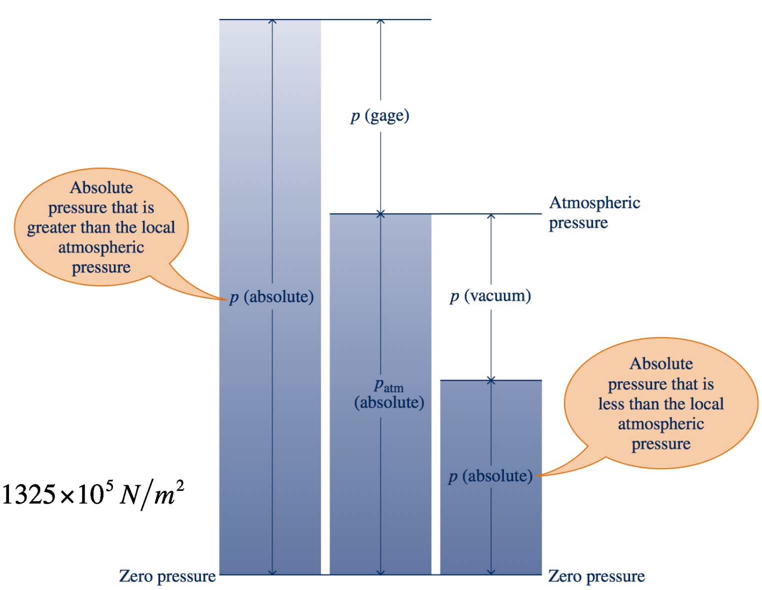


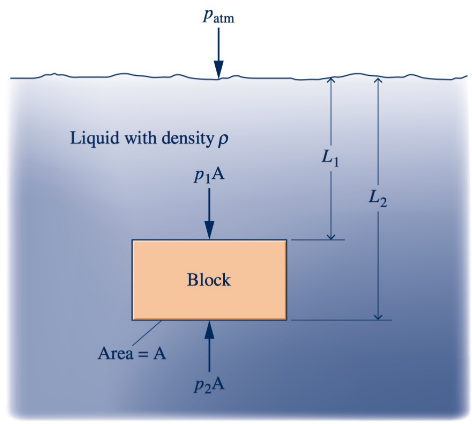
Fig. 1.12 Relationships among the absolute, atmospheric, gage, and vacuum pressures.

1.6.2 Buoyancy

When a body is completely or partially submerged in a liquid, the resultant pressure force acting on the body is called the *buoyant* force.

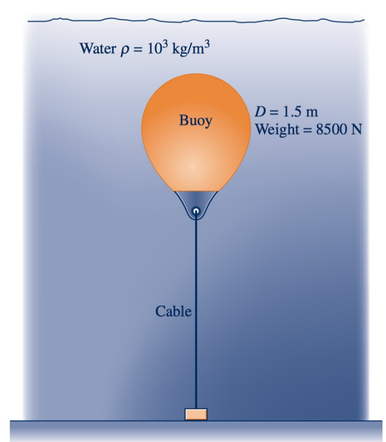
- **The buoyant force acts vertically upward.**
- **The buoyant force has a magnitude equal to the weight of the displaced liquid (Archimedes' principle).**

$$\begin{aligned} F &= A(p_2 - p_1) = A(p_{atm} + \rho g L_2) - A(p_{atm} + \rho g L_1) \\ &= \rho g A(L_2 - L_1) \\ &= \rho g V \end{aligned}$$



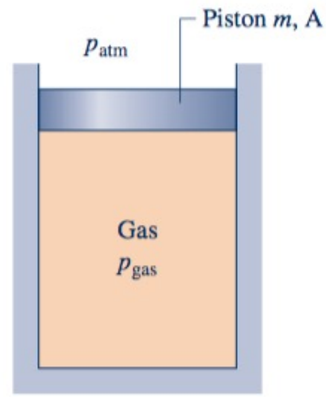
Example:

The below figure shows a spherical buoy, having a diameter of 1.5 m and weighing 8500 N, anchored to the floor of a lake by a cable. Determine the force exerted by the cable, in N. The density of the lake water is 10^3 kg/m^3 and g = 9.81 m/s^2 .



Example :

As shown in the figure, a gas is contained in a piston-cylinder assembly. The piston mass and cross-sectional area are denoted *m* and *A*, respectively. The only force acting on the top of the piston is due to atmospheric pressure, p_{atm}. Assuming the piston moves smoothly in the cylinder and the local acceleration of gravity *g* is constant, show that the pressure of the gas acting on the bottom of the piston remains constant as gas volume varies. What would cause the gas volume to vary?



Example :

A gas contained within a piston-cylinder assembly undergoes four processes in series:

Process 1-2: Constant-pressure expansion at 1 bar from $V_1 = 0.5\ m^3$ to $V_2 = 2\ m^3$

Process 2-3: Constant volume to 2 bar

Process 3-4: Constant-pressure compression to 1 m^3

Process 4-1: Compression with pV^{-1} = constant

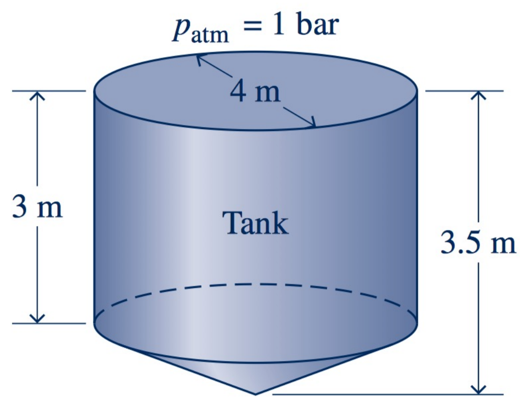
Sketch the process in series on a p-V diagram labeled with pressure and volume values at each numbered state.

Example:

shows a tank used to collect rainwater having a diameter of 4 m. As shown in the figure, the depth of the tank varies linearly from 3.5 m at its center to 3 m along the perimeter. The local atmospheric pressure is 1 bar, the acceleration of gravity is 9.8 m/s^2 , and the density of the water is 987.1 kg/m^3 . When the tank is filled with water, determine;

(a) the pressure, in kPa, at the bottom center of the tank.

(b) the total force, in kN, acting on the bottom of the tank.

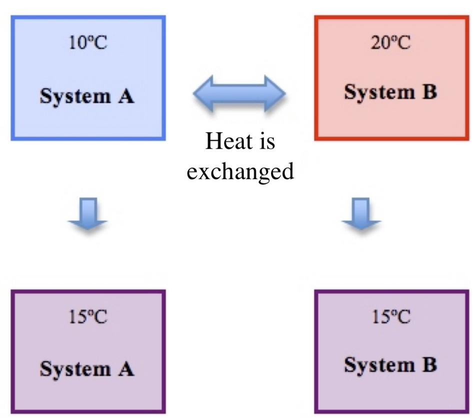


1.7 Measuring Temperature (Measurable Intensive Properties)

To measure and to quantify the hotness and coolness of body we use thermometers and temperature scale.

1.7.1 Thermal Equilibrium

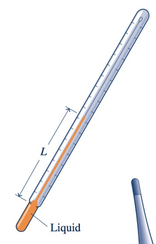
- When two systems with different temperatures reaches a condition in which there is no thermal interaction between them then we have ***Thermal Equilibrium***.
- When a system undergoes a process while it enclosed by an adiabatic wall, it experiences no thermal interaction with its surrounding. This process called ***adiabatic process***.
- A process that occurs at constant temperature is an ***isothermal process***.
- ***Zeroth law of thermodynamics***: when two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with one another.



1.7.1 Thermometers

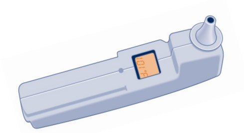
Any body with at least one measurable property that changes as its temperature changes can be used as a ***thermometer***. Such a property is called a ***thermometric property***.

The particular substance that exhibits changes in the thermometric property is known as a ***thermometric substance***.



Common devices for temperature measurement:

- ***liquid-in-glass thermometer***: consists of a glass capillary tube connected to a bulb filled with a liquid such as alcohol and sealed at the other end.
- ***Thermocouples*** (more accurate): consists of two joined dissimilar metals, an electromotive force (emf) that is primarily a function of temperature will exist in a circuit.
- ***Radiation thermometers & optical pyrometers*** (more accurate): measure temperature by sensing radiation



1.7.2 Kelvin and Rankine Temperature Scales

- The ***Kelvin scale,*** (K), is an absolute thermodynamic temperature scale, kelvin is the SI base unit;

$$T\left({}^{o}C\right) = T\left(K\right) - 273.15$$

- The ***Rankine scale***, (^{o}R), is also an absolute thermodynamic scale with an absolute zero that coincides with the absolute zero of the Kelvin scale.

$$T(^{\circ}\mathrm{R}) = 1.8T(\mathrm{K})$$

Example:

The 30-year average temperature in Toronto, Canada, during summer is 19.5^{O}C and during winter is −4.9^{O}C. What are the equivalent average summer and winter temperatures in ^{O}F and ^{O}R?

$$T(^{o}C) = T(K) - 273.15 \quad \rightarrow \quad T(K) = T(^{o}C) + 273.15$$

For summer: $T_{summer}\,(K) = 19.5^{o}C + 273.15 = 292.65\ K$

For winter: $T_{winter}\,(K) = -4.9^{o}C + 273.15 = 268.25\ K$

$$T(^{o}R) = 1.8T(K)$$

For summer: $T_{summer}\,(^{o}R) = (1.8)(292.65\ K) = \underline{\mathbf{526.77\ ^{o}R}}$

For winter: $T_{winter}\,(^{o}R) = (1.8)(268.25\ K) = \underline{\mathbf{482.85^{o}R}}$

$$T(^{o}F) = T(^{o}R) - 459.67$$

For summer: $T_{summer}\,(^{o}F) = 526.77\ ^{o}R - 459.67 = \underline{\mathbf{67.10\ ^{o}F}}$

For winter: $T_{winter}\,(^{o}F) = 482.85^{o}R - 459.67 = \underline{\mathbf{23.18\ ^{o}F}}$

MEC511

Thermodynamics & Fluids

Chapter02

Energy and the First Law of Thermodynamics

Toronto Metropolitan University

NOTE!

2 Energy and the First Law of Thermodynamics

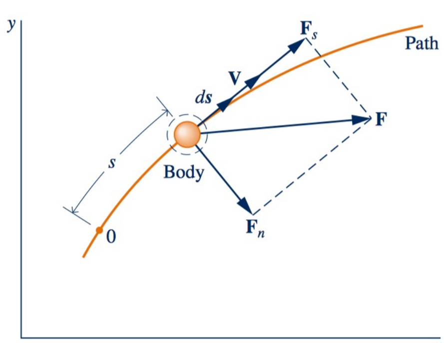
2.1 Reviewing Mechanical Concepts of Energy

2.1.1 Work and Kinetic Energy

$$F_S = m\frac{dV}{dt}$$

$$F_S = m\frac{dV}{ds}\frac{ds}{dt} = mV\frac{dV}{ds}$$

$$\int_{V_1}^{V_2} mV\,dV = \int_{S_1}^{S_2} F_s ds$$



Forces acting on a moving system.

$$\frac{1}{2}m\left(V_2^2 - V_1^2\right) = \int_{S_1}^{S_2} F_s.\, ds \Rightarrow \Delta KE = KE_2 - KE_1 = \int_{S_1}^{S_2} F_s.\, ds$$

*** The work of the resultant force on the body equals the change in its kinetic energy.**

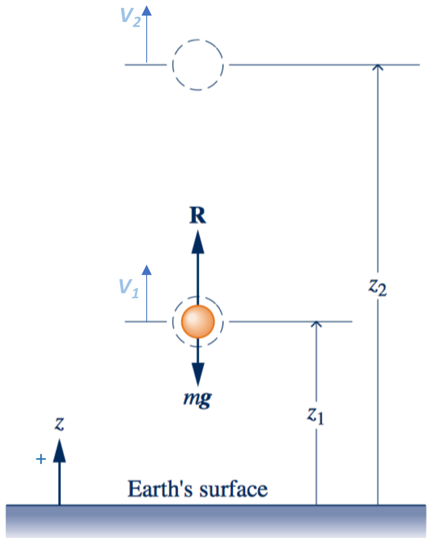
2.1 Reviewing Mechanical Concepts of Energy

2.1.2 Potential Energy

$$\frac{1}{2}m\left(V_2^2 - V_1^2\right) = \int_{z_1}^{z_2} R\,dz - \int_{z_1}^{z_2} mg\,dz$$

$$\frac{1}{2}m\left(V_2^2 - V_1^2\right) + mg\left(z_2 - z_1\right) = \int_{z_1}^{z_2} R\,dz$$

$$\Delta KE + \Delta PE = \int_{z_1}^{z_2} R\,dz$$



2.1 Reviewing Mechanical Concepts of Energy

2.1.3 Units for Energy

Work has units of force times distance. The units of kinetic energy and potential energy are the same as for work.

- In SI: newton-meter, N . m. Called joule, J.
- In BG: foot-pound force, ft . lbf,
  and the British thermal unit, Btu, where (1Btu=778 ft . lbf)

Example:

An object whose mass is 50 kg is accelerated from a velocity of 20 m/s to a final velocity of 50 m/s by the action of a resultant force. If there are no other interactions between the object and its surroundings, determine the work done by the resultant force, in kJ.

2.1 Reviewing Mechanical Concepts of Energy

2.1.4 Conservation of Energy in Mechanics

The total work of all forces acting on the body from the surroundings, with the exception of the gravitational force, equals the *sum of the changes in the kinetic and potential energies* of the body.

$$\Delta KE + \Delta PE = \int_{z_1}^{z_2} R\, dz$$

By considering the special case of a body on which the only force acting is that due to gravity, for then the right side of the equation vanishes and the equation reduces to:

$$\frac{1}{2}m\left(V_2^2 - V_1^2\right) + mg\left(z_2 - z_1\right) = 0$$

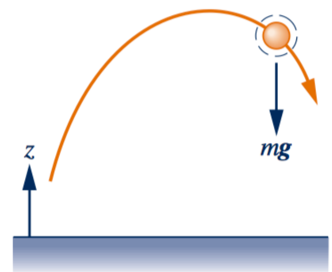
$$\frac{1}{2}mV_2^2 + mgz_2 = \frac{1}{2}mV_1^2 + mgz_1$$

2.1 Reviewing Mechanical Concepts of Energy

Under these conditions, *the sum of the kinetic and gravitational potential energies remains constant*. This equation also illustrates that energy can be converted from one form to another:

For an object falling under the influence of gravity only, the potential energy would decrease as the kinetic energy increases by an equal amount.

$$\frac{1}{2}mV_2^2 + mgz_2 = \frac{1}{2}mV_1^2 + mgz_1$$



2.2 Broadening Our Understanding of Work

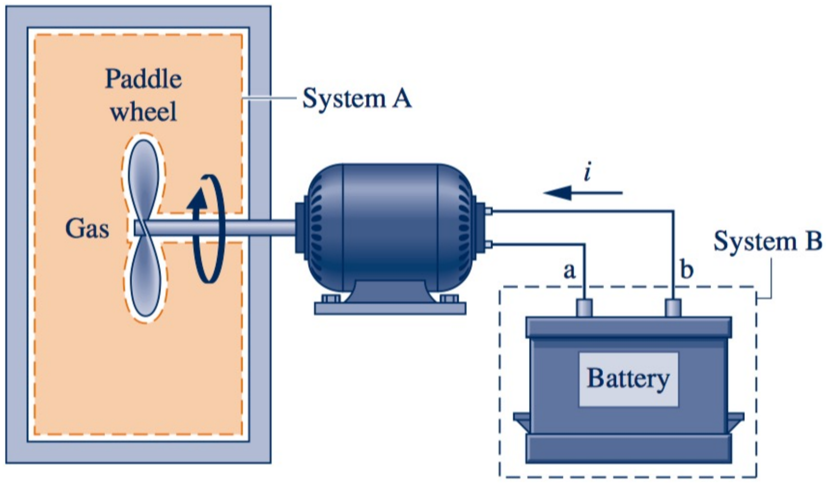
The work done by, or on, a system

$$W = \int_{s_1}^{s_2} F \,.\, ds$$

Thermodynamic definition of work:

Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.

2.2 Broadening Our Understanding of Work



At the boundary of system B, forces and motions are not evident. Rather, there is an electric current *i* driven by an electrical potential difference existing across the terminals a and b. That this type of interaction at the boundary can be classified as work follows from the thermodynamic definition of work given previously: We can Imagine the current is supplied to a hypothetical electric motor that lifts a weight in the surroundings.

2.2 Broadening Our Understanding of Work

Note that:

- Work is a means for transferring energy.
- Accordingly, the term work does not refer to what is being transferred between systems or to what is stored within systems.
- Energy is transferred and stored when work is done.

2.2 Broadening Our Understanding of Work

2.2.1 Sign Convention and Notation

- Work done *by* the system $W>0$
- Work done *on* the system $W<0$

$$W = \int_{s_1}^{s_2} F \,.\, ds$$

The value of *W* depends on the details of the interactions taking place between the system and surroundings during a process and not just the initial and final states of the system. It follows that ***work is not a property*** of the system or the surroundings.

In addition, the limits on the integral mean ***"from state 1 to state 2"*** and cannot be interpreted as the values of work at these states. The notion of work at a state has no meaning, so the value of ***this integral should never be indicated as*** $W_2 - W_1$.

2.2 Broadening Our Understanding of Work

- The differential of work, δW , is said to be **inexact** because, in general, the following integral cannot be evaluated without specifying the details of the process.

$$\int_1^2 \delta W = W$$

- On the other hand, the differential of a property is said to be **exact** because the change in a property between two particular states depends in no way on the details of the process linking the two states.

$$\int_{V_1}^{V_2} dV = V_2 - V_1$$

2.2 Broadening Our Understanding of Work

2.2.2 Power

The rate of energy transfer by work is called power and is denoted by $\dot{W}$.

$$\dot{W} = F.V$$

$$W = \int_{t_1}^{t_2} \dot{W}\, dt = \int_{t_1}^{t_2} F.V\, dt$$

- The unit for power is J/s, called the watt. In this book the kilowatt, kW, is generally used.
- Commonly used English units for power are ft.lbf/s, Btu/h, and horsepower, hp.

2.2 Broadening Our Understanding of Work

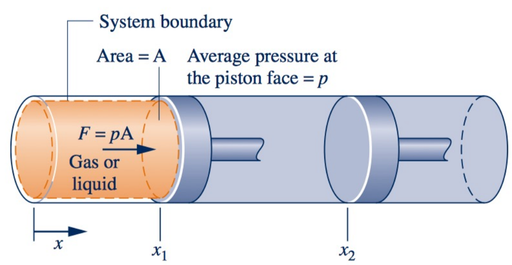
2.2.3 Modeling Expansion or Compression Work

In the below system, the work done by the system as the piston is displaced a distance dx is:

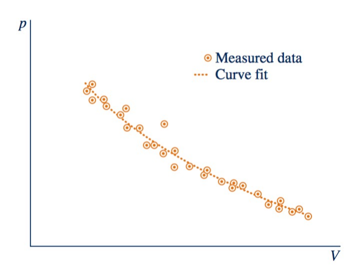
$$\delta W = pAdx$$

$$\delta W = pdV$$

$$W = \int_{V_1}^{V_2} p\, dV$$



To perform the integral ,above, requires a relationship between the gas pressure at the moving boundary and the system volume. However, due to *nonequilibrium* effects during an actual expansion or compression process, this relationship may be difficult, or even impossible, to obtain.
Note: in some cases where lack of the required pressure–volume relationship keeps us from evaluating the work from the above integral, the work can be determined alternatively from an ***energy balance***.

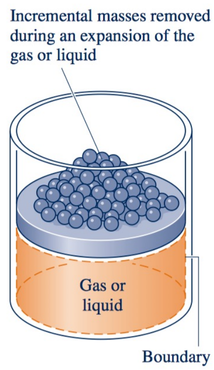


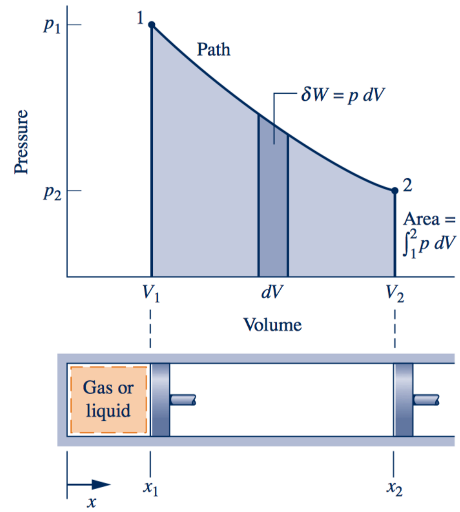
Pressure at the piston face versus cylinder volume.

2.2 Broadening Our Understanding of Work

2.2.5 Expansion or Compression Work in Quasiequilibrium Processes

- A **quasiequilibrium** *(an idealized type)* process is one in which all states through which the system passes in a quasiequilibrium process may be considered equilibrium states.
- A particularly important aspect of the quasiequilibrium process concept is that the values of the intensive properties **are uniform throughout the system**, or every phase present in the system, at each state visited.

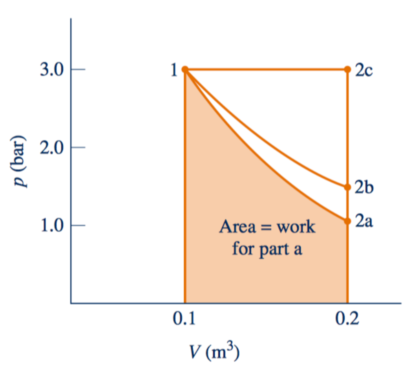


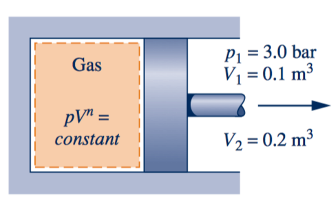


2.2 Broadening Our Understanding of Work

work depends on the process and it is not a property

- The relation between pressure and volume, or pressure and specific volume, also can be described analytically.
- A quasiequilibrium process described by pV^n=constant, where n is a constant, is called a **polytropic** process.



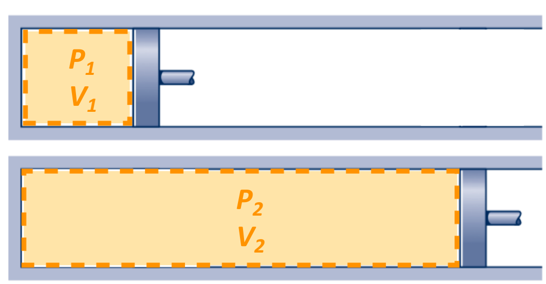


Example:

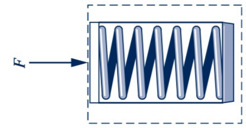
0.5 kg of a gas contained within a piston-cylinder assembly undergoes constant-pressure process at 4 bar beginning at v_1=0.72 m^3/kg. For the gas as the system, the work is -84 kJ. Determine the final volume of the gas, in m^3.

Example:

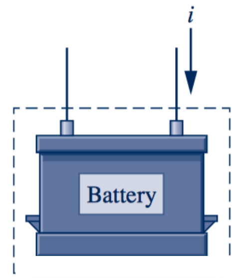
A gas expands from an initial state where p_1=500 kPa and V_1=0.1 m^3 to a final state where p_2= 100 kPa. The relationship between pressure and volume during the process is pV=*constant*. Sketch the process on a p-V diagram and determine the work, in kJ.



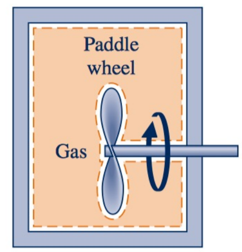
2.3 Broadening Our Understanding of Energy



- When work is done to compress a spring, energy is stored within the spring.



- When a battery is charged, the energy stored within it is increased.
- when a gas (or liquid) initially at an equilibrium state in a closed, insulated vessel is stirred and allowed to come to a final equilibrium state, the energy of the gas is increased in the process.



- In each of the above examples the change in system energy cannot be attributed to changes in the system's overall kinetic or gravitational potential energy.

2.3 Broadening Our Understanding of Energy

This change in energy can be accounted for in terms of internal energy *U*.

The internal energy is an extensive property.

The change in total energy is :

$$E_2 - E_1 = (KE_2 - KE_1) + (PE_2 - PE_1) + (U_2 - U_1)$$

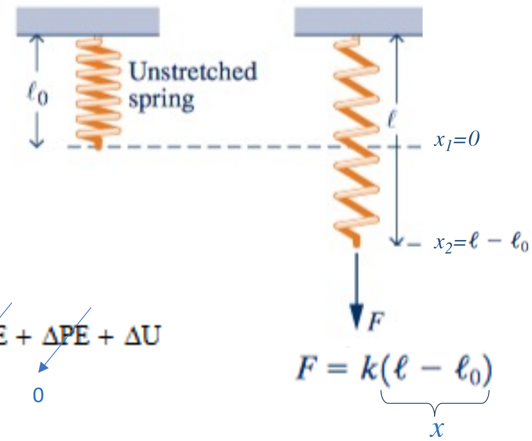
$$\Delta E = \Delta KE + \Delta PE + \Delta U$$

The internal energy of the gas includes:

- Translational kinetic energy of the molecules,
- The kinetic energy due to rotation of the molecules,
- Kinetic energy associated with vibrational motions within the molecules,
- The energy stored in the chemical bonds between the atoms that make up the molecules,
- Energy storage on the atomic level includes energy associated with electron orbital states, nuclear spin, and binding forces in the nucleus.
- In dense gases, liquids, and solids, intermolecular forces play an important role in affecting the internal energy.

2.3 Broadening Our Understanding of Energy

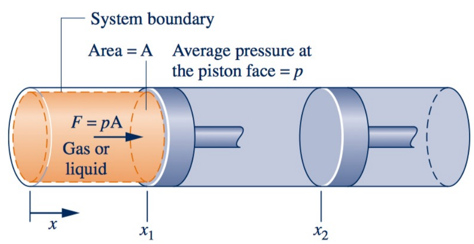
Consider expansion of an spring:



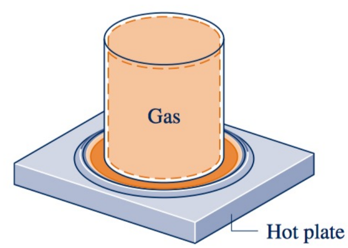
$$W = \int_{x_1}^{x_2} -k \cdot x\,dx = \frac{-1}{2} \cdot k \cdot \left(x_2^2 - x_1^2\right) = \Delta E = \underbrace{\cancel{\Delta KE}}_{0} + \underbrace{\cancel{\Delta PE}}_{0} + \Delta U$$

2.4 Energy Transfer by Heat

Interactions between a system and its surroundings can be classed as:
- Work
- Energy transfer by heat



Interactions of a system with its surroundings by work



energy transfer by heat

- Energy transfers by heat are induced only as a result of a temperature difference between the system and its surroundings and occur only in the direction of decreasing temperature.