

SEE 224
Thermodynamics for Energy Engineering

- **Introduction, Definitions, and Basic Concepts**

Introduction

Many engineering systems, including “Mechatronic Systems”, involve the transfer, transport, and conversion of energy, and the science that deals with these subjects are broadly referred to as “thermal sciences”. Thermal sciences are usually studied under the subcategories of “thermodynamics and heat transfer”.

The design and analysis of most thermal systems such as power plants, automotive engines, and refrigerators involve all categories of thermal sciences as well as other sciences (Fig. 1). For example, designing the radiator of a car involves the determination of the amount of energy transfer from a knowledge of the properties of the coolant using thermodynamics and the determination of the size and shape of the inner tubes and the outer fins using heat transfer. Of course, the determination of the size and type of the water pump requires using fluid mechanics. Also, the determination of the materials and the thickness of the tubes require the use of material science as well as strength of materials. The reason for studying different sciences separately is simply to facilitate learning without being overwhelmed. Once the basic principles are mastered, they can then be synthesized by solving comprehensive real-world practical problems.



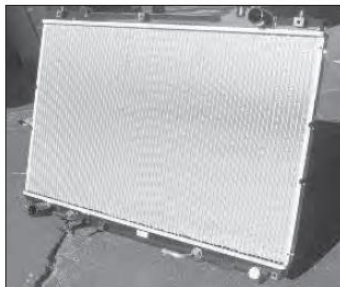
The human body



Air conditioning systems



Airplanes



Automobile radiators



Power plants



Refrigeration systems

Figure 1: Some application areas of thermal sciences.

Thermodynamics

The name thermodynamics stems from the Greek words therme (heat) and dynamis (power), which is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations, including power generation, refrigeration, and relationships among the properties of matter.

Thermodynamics can be defined as the science of energy. Although everybody has a feeling of what energy is, it is difficult to give a precise definition for it. Energy can be viewed as the ability to cause changes.

Thermodynamics Laws:

The Zeroth law of thermodynamics defines temperature! Temperature is a pointer for the direction of energy transfer as heat. When the temperatures of two bodies are the same, “thermal equilibrium” is established. The equality of temperature is the only requirement for thermal equilibrium.

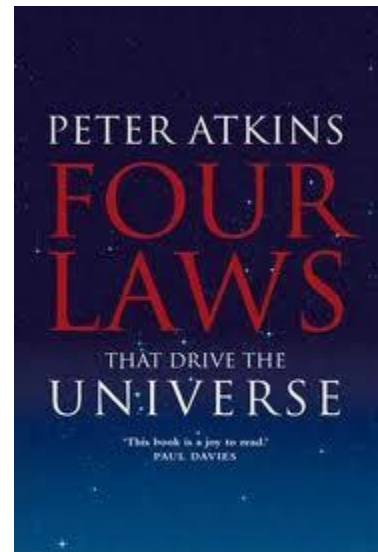
The first law of thermodynamics is simply an expression of the conservation of energy principle, and it asserts that energy is a thermodynamic property. It simply states that during an interaction (process), energy can change from one form to another but the total amount of energy remains “constant”.

The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. For example, a cup of hot coffee left on a table eventually cools, but a cup of cool coffee in the same room never gets hot by itself! The high-temperature energy of the coffee is degraded (transformed into a less useful form at a lower temperature) once it is transferred to the surrounding air.

Recommended Reading:

Four Laws that Drive the Universe, by Peter Atkins.

The laws of thermodynamics drive everything that happens in the universe. From the sudden expansion of a cloud of gas to the cooling of hot metal, and from the unfurling of a leaf to the course of life itself - everything is directed and constrained by four simple laws. They establish fundamental concepts such as temperature and heat, and reveal the arrow of time and even the nature of energy itself. Peter Atkins’ powerful and compelling introduction explains what the laws are and how they work, using accessible language and virtually no mathematics. Guiding the reader from the Zeroth Law to the Third Law, he introduces the fascinating concept of entropy, and how it not only explains why your desk tends to get messier, but also how its unstoppable rise constitutes the engine of the universe.



Heat Transfer

Energy exists in various forms. In heat transfer, we are primarily interested in heat, which is the form of energy that can be transferred from one system to another as a result of temperature difference. The science that deals with the determination of the rates of such energy transfers is heat transfer.

The basic requirement for heat transfer is the presence of a temperature difference. There can be no net heat transfer between two mediums that are at the same temperature.

Thermodynamics or Heat Transfer?

You may be wondering why we need the science of heat transfer. After all, we can determine the amount of heat transfer for any system undergoing any process using a thermodynamic analysis alone. The reason is that thermodynamics is concerned with the amount of heat transfer as a system undergoes a process “from one equilibrium state to another equilibrium state”, and it gives no indication about how long the process will take. But in engineering, we are often interested in the rate of heat transfer, which is the topic of the science of heat transfer.

In other words, “thermodynamics deals with equilibrium states” and changes from one equilibrium state to another. Heat transfer, on the other hand, deals with systems that lack thermal equilibrium, and thus it is a nonequilibrium phenomenon. Therefore, the study of heat transfer cannot be based on the principles of thermodynamics alone. However, the laws of thermodynamics lay the framework for the science of heat transfer. The first law requires that the rate of energy transfer into a system be equal to the rate of increase of the energy of that system. The second law requires that heat be transferred in the direction of decreasing temperature. This is analogous to a car parked on an inclined road; it must go downhill in the direction of decreasing elevation when its brakes are released. It is also analogous to the electric current flowing in the direction of decreasing voltage or the fluid flowing in the direction of decreasing pressure.

Systems

Thermodynamic system is defined as a quantity of matter or a region in space chosen for study. A thermodynamic system (only referred to as “system” from now on) should be a closed surface (curve). The mass or region outside the system is called the “surroundings”. The real or imaginary surface (curve) that separates the system from its surroundings is called the “boundary”; see Fig. 2. The boundaries of a system can be fixed or movable. Mathematically, the boundary of a system has zero thickness, no mass, and no volume.

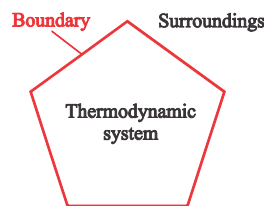


Figure 2: System, surroundings, and boundary.

Open system or control volume (CV) is a properly selected region in space that usually encloses a device. Both mass and energy can cross the boundary of a control volume. Boundaries of a control volume (open system) are usually shown by dashed lines (Fig. 3).

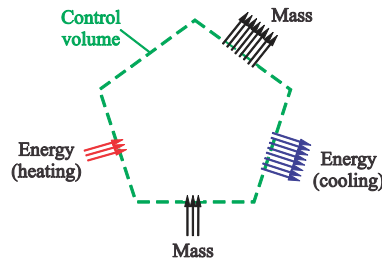


Figure 3: In open system also known as control volume energy and mass can cross the boundary.

Isolated system is a system that does not communicate with the surroundings by any means.

Closed system also known as control mass consists of a fixed amount of mass, and no mass can cross its boundary. But, energy in the form of heat or work, can cross the boundary, and the volume of a closed system does not have to be fixed; see Fig. 4.

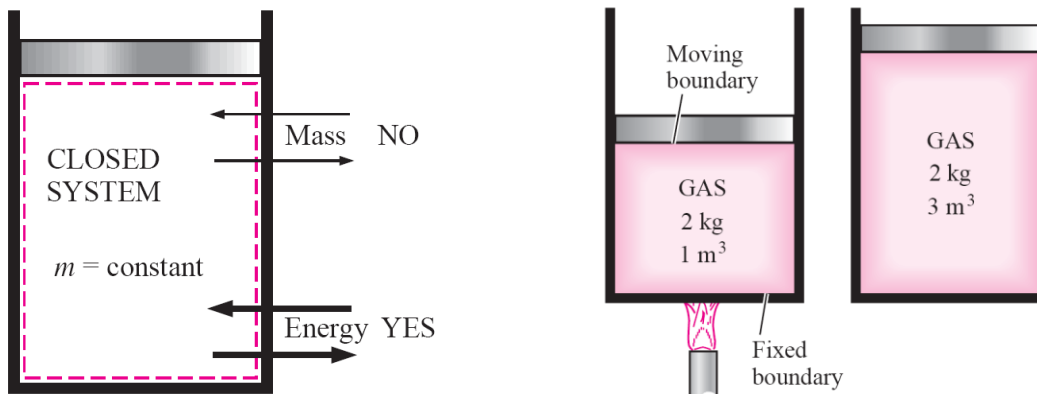


Figure 4: Left) Mass cannot cross the boundaries of a closed system, but energy can, as shown in the right hand-side drawings. Right) The same closed system is heated, i.e., energy is added. The system (gas inside the cylinder) expands and its boundaries have to move with the gas, because based on the definition of closed systems, mass is not allowed to cross the boundary.

Note: Some thermodynamics relations that are applicable to closed and open systems are different. Thus, it is extremely important to recognize the type of system we have before start analyzing it.

Adiabatic system is a closed or open system that does not exchange energy with the surroundings by heat.

The Principal Physical Quantities and Units

The principal (primary) physical quantities (have names and symbols) and are characterized by units for measurement purposes. There are several unit systems in engineering applications. The most common unit system is International System (abbreviated from French name *Le Système International d' Unités*), followed by English system, which is also known as United States Customary System (USCS). In this course (and in the textbook) SI units along with English units will be used.

Table 1: Primary physical quantities and their corresponding units.

Physical quantity name	Physical quantity symbol (italic)	Unit name	Unit symbol (non-italic)	Dimensional symbol*	English unit name (and unit symbol)	Conversion factor
length	L	meter	m	L	foot (ft)	1 ft = 0.3048 m
time	t	second	s	T	second (s)	1 s = 1 s
mass	m	kilogram	kg	M	Pound-mass (lbm)	1 lbm = 0.45359 kg
temperature	T	Kelvin	K	£	Rankine (°R)	1 K = 1.8 °R
electric current	I	ampere	A	I	-	-
amount of substance	n	mole	mol	N	-	-
luminous intensity	I_v	candela	cd	J	-	-

* Dimensional symbols are defined to be applied in dimensional analysis.

Prefixes for SI units:

The prefixes used to express the multiples of the various SI units are listed in Table 2.

Table 2: Prefixes in SI units.

Multiple	Prefix
10^{12}	tera, T
10^9	giga, G
10^6	mega, M
10^3	kilo, k
10^2	hecto, h
10^1	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

Examples of Secondary Physical Quantities and Units

All physical quantities which are not listed in Table 1, are called secondary (derived) quantities, and they can be expressed based on principal (primary) physical quantities via laws (relations) in physics.

Force:

Force F , with the unit of Newton (N), is the capacity to do work, and causes an object to undergo a change in speed, a change in direction, or a change in shape. Based on Newton's second law the force is defined as,

$$F = (\text{Mass})(\text{Acceleration}) = m a \left[\text{kg} \frac{\text{m}}{\text{s}^2} \equiv \text{N} \right]$$

The force unit, Newton, is defined as the force required to accelerate a mass of 1 kg at a rate of 1 m/s². In the English system, the force unit is the pound-force (lbf) and is defined as the force required to accelerate a mass of 32.174 lbm (1 slug) at a rate of 1 ft/s²

Weight W , is the force caused by the gravitational acceleration g ,

$$W = m g \text{ [N]}$$

where g is 9.807 m/s² or 32.174 ft/s² at sea level.

Pressure:

Pressure P , is the compression force per unit area,

$$P = \frac{\text{Normal Force}}{\text{Area}} = \frac{F}{A} \left[\frac{\text{N}}{\text{m}^2} \equiv \text{Pa} \right]$$

Density:

Density ρ , is mass per unit volume,

$$\rho = \frac{\text{Mass}}{\text{Volume}} = \frac{m}{V} \left[\frac{\text{kg}}{\text{m}^3} \right]$$

The density of a substance, in general, depends on temperature and pressure. The density of most gases is proportional to pressure and inversely proportional to temperature. Liquids and solids are essentially incompressible substances, that means their density is almost constant.

Specific Volume:

The specific volume v , is defined as the volume per unit mass which is the inverse of the density,

$$v = \frac{1}{\rho} = \frac{\text{Volume}}{\text{Mass}} = \frac{V}{m} \left[\frac{\text{m}^3}{\text{kg}} \right]$$

Specific Weight:

The specific weight γ , is its weight per unit volume,

$$\gamma = \frac{\text{Weight}}{\text{Volume}} = \frac{W}{V} = \frac{m g}{V} = \rho g \left[\frac{\text{N}}{\text{m}^3} \right]$$

Specific Gravity:

Sometimes the density of a substance is given relative to the density of a well-known substance. Then it is called specific gravity, or relative density, and is defined as the ratio of the density of a substance to the

density of some standard substance at a specified temperature (for example water at 4°C, for which $\rho_{\text{H}_2\text{O}} = 1000 \text{ kg/m}^3$),

$$SG_{\text{gas}} = \frac{\rho_{\text{gas}}}{\rho_{\text{air}}}, \quad \rho_{\text{air}} \text{ at standard condition (27 °C and 1 atm) is } 1.205 \text{ [kg/m}^3\text{]}$$

$$SG_{\text{liquid}} = \frac{\rho_{\text{liquid}}}{\rho_{\text{water}}}, \quad \rho_{\text{water}} \text{ at } 4 \text{ °C is } 1000 \text{ [kg/m}^3\text{]}$$

For example, the specific gravity of mercury is $SG_{\text{Hg}} = 13,580/1000 = 13.6$.

Work/Energy:

Work and energy are similar quantities, and share the same unit, Joule (J). Work is defined as force acting through a distance, and energy is always equivalent to the ability to exert pulls or pushes against forces along a path of a certain length,

$$\text{Work} = F L \text{ [Nm} \equiv \text{J]}$$

Note: 1 calorie = 4.184 joules

Potential Energy:

Potential energy PE , is the work (energy) required to elevate a system of mass m against gravity field g ,

$$PE = W_z = mg z \text{ [J]}$$

where z is the height of elevation.

Kinetic Energy:

Kinetic energy KE , is the work required to change the speed (velocity magnitude) of the mass from zero to velocity V ,

$$KE = \frac{1}{2} mV^2 \text{ [J]}$$

Note: In the notes velocity is always presented with V and volume is depicted by V .

Internal Energy:

Internal energy U , is an important thermodynamics quantity, and is defined as the energy in a substance by molecular activity (translational, vibrational, and rotational motion) and molecular bonding forces.

Note: The sum of translational, vibrational, and rotational energies of molecules is the “molecular kinetic energy”; it is also called the “sensible energy”. At higher temperatures, system will have higher sensible energy.

Note: The internal energy associated with the phase of a system is called latent heat. The intermolecular forces are strongest in solids and weakest in gases.

Note: The internal energy associated with the atomic bonds in a molecule is called “chemical or bond energy”. The tremendous amount of energy associated with the bonds within the nucleolus of atom itself is called “atomic energy”.

Total Energy:

The total energy E , of a substance is the sum of the internal, kinetic, and potential energies at a given state point,

$$E = U + \frac{1}{2}mV^2 + mgz \text{ [J]}$$

$$\frac{E}{m} = e = u + \frac{1}{2}V^2 + gz \left[\frac{\text{J}}{\text{kg}} \right]$$

where e , u , $V^2/2$, and gz are the called the specific total energy, specific internal energy, specific kinetic energy and specific potential energy (i.e., energies per unit mass).

Note: The molecular internal energy, U is a strong function of temperature.

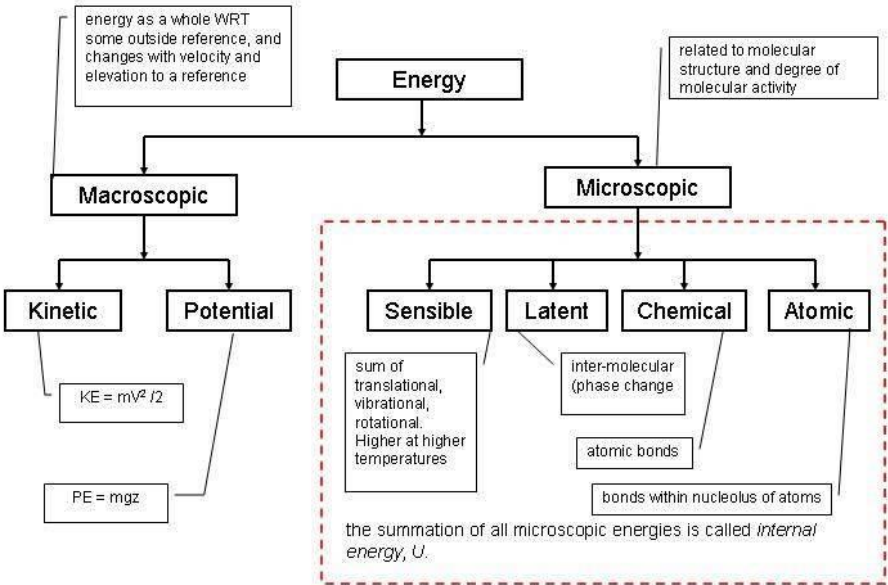


Figure 5: Different forms of energy.

Power:

Power P , is the rate at which energy (or work) is transferred, used, or transformed. The SI unit for power is watt (W),

$$P = \frac{\text{Work}}{\text{Time}} = \frac{W}{t} = FV \left[\frac{\text{J}}{\text{s}} \equiv \text{W} \right]$$

Intensive and Extensive Properties

Properties are considered to be either *intensive* or *extensive*. Intensive properties are those that are independent of the mass of the system, such as temperature, pressure, and density. Extensive properties are those whose values depend on the size—or extent—of the system. Total mass, total volume and total momentum are some examples of extensive properties.

An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with an imaginary partition, as shown in Fig. 6. Each part will have the same value of intensive properties as the original system, but half the value of the extensive properties.

Note: Generally, uppercase letters are used to denote extensive properties (with mass m being a major exception), and lowercase letters are used for intensive properties (with pressure P and temperature T being the obvious exceptions).

Note: Extensive properties per unit mass are called *specific properties*. Some examples of specific properties are specific volume ($v = V / m$) and specific total energy ($e = E / m$).

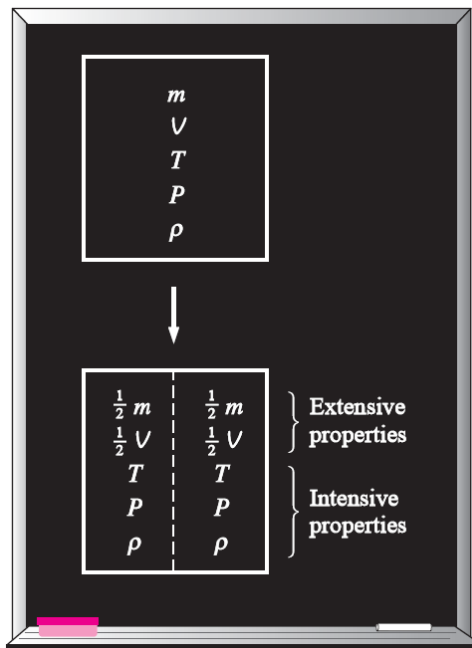


Figure 6: Criteria to differentiate intensive and extensive properties.

State

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. In Fig. 7 a system is shown at two different states.

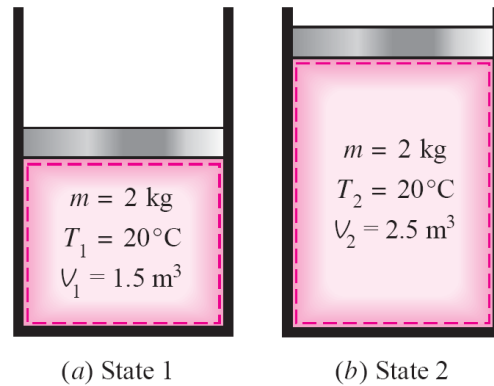


Figure 7: A system at two different states.

Equilibrium States

“Thermodynamics” deals with “equilibrium states”. The word equilibrium implies a state of balance. In an equilibrium state there are no unbalanced potentials (or driving forces) within the system. **A system in equilibrium experiences no changes when it is isolated from its surroundings.**

Thermal equilibrium

When the temperature is the same throughout the entire system (Fig. 8).

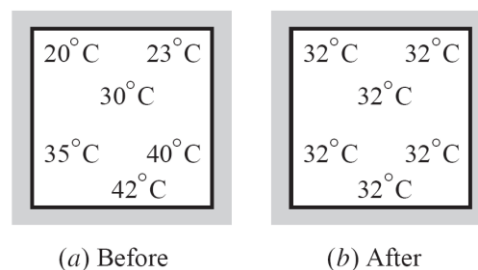


Figure 8: A closed system reaching thermal equilibrium.

Mechanical equilibrium

When there is no change in pressure at any point of the system. However, the pressure may vary within the system due to gravitational effects.

Phase equilibrium

Phase equilibrium is defined in a two phase system (for example a mixture of vapor and liquid), when the mass of each phase reaches an equilibrium level.

Chemical equilibrium

When the chemical composition of a system does not change with time, i.e., no chemical reactions occur.

The State Postulate

The state of a system is described by its properties. But we know from experience that we do not need to specify all the properties in order to fix a state. Once a sufficient number of properties are specified, the rest of the properties assume certain values automatically. That is, specifying a certain number of properties is sufficient to fix a state. The number of properties required to fix the state of a system is given by the state postulate:

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

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. Otherwise, an additional property needs to be specified for each effect that is significant. If the gravitational effects are to be considered, for example, the elevation z needs to be specified in addition to the two properties necessary to fix the state.

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 T and specific volume $\nu = V/m$, for example, are always independent properties, and together they can fix the state of a simple compressible system (Fig. 9). Temperature and pressure, however, are independent properties for single-phase systems, but are dependent properties for multiphase systems.

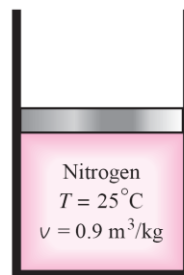


Figure 9: The state of nitrogen is fixed by two independent properties, i.e., temperature and specific volume.

Process

Any change that a system undergoes “from one equilibrium state to another equilibrium state” is called a process, and the series of states through which a system passes during a process is called the path of the process (Fig. 10, left plot).

To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings.

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). Figure 10 (right plot) shows the $P-V$ diagram of a compression process of a gas.

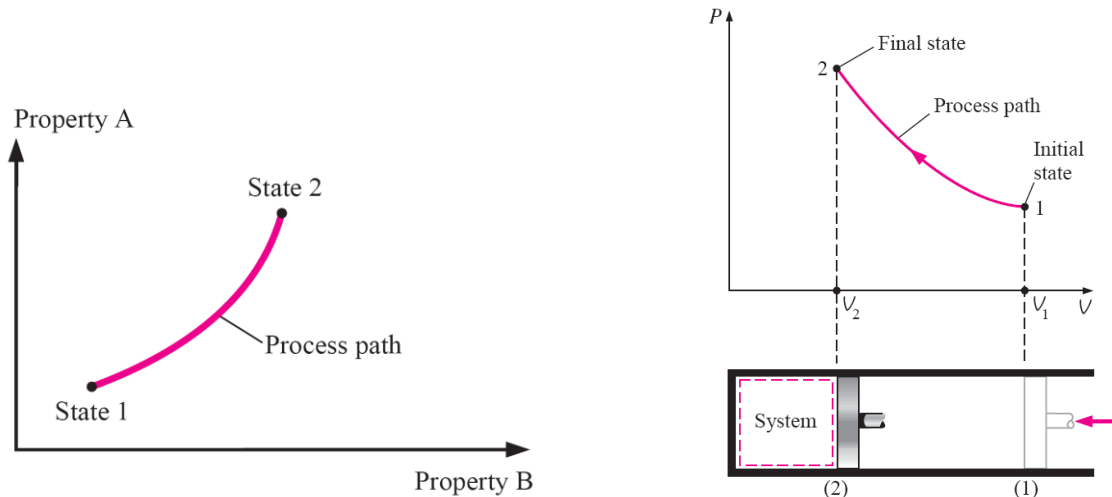


Figure 10: Left) A process between states 1 and 2 and the process path. Right) The $P-V$ diagram of a compression process.

Quasi-equilibrium process

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.

As illustrated in Fig. 11, when a gas in a piston-cylinder device is compressed suddenly, the molecules near the face of the piston do not have enough time to escape and they will have to pile up in a small region in front of the piston, thus creating a high-pressure region there, i.e., mechanical non-equilibrium. However, if the piston is moved slowly, the molecules have sufficient time to redistribute and there won't be a molecule pileup in front of the piston. As a result, the pressure inside the cylinder will always be nearly uniform and will rise at the same rate at all locations, i.e., mechanical equilibrium. Since equilibrium is maintained at all times, this is a quasi-equilibrium process.



Figure 11: Quasi-equilibrium and nonquasi-equilibrium compression processes.

Quasi-equilibrium processes can be used to approximate many engineering processes with a 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. Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared. We will discuss this in more details later.

Note: Note that the process path indicates a series of equilibrium states through which the system passes during a process and has significance for quasi-equilibrium 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. A nonquasi-equilibrium process is denoted by a dashed line between the initial and final states instead of a solid line.

Processes with constant properties

The prefix “iso” is often used to designate a process for which a particular property remains constant.

Isothermal process is a process during which the temperature T remains constant.

Isobaric process is a process during which the pressure P remains constant.

Isochoric (or isometric) process is a process during which the specific volume v remains constant.

Cycle

A system is said to have undergone a “cycle” if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical (Fig. 12).

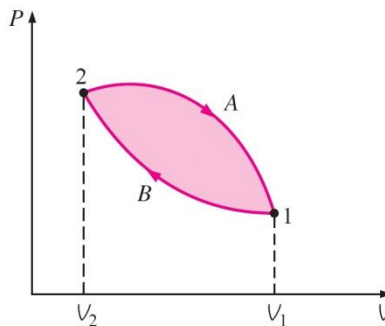


Figure 12: A cycle shown in $P-V$ diagram which consists of process paths A-B and B-A between states 1 and 2.

Steady Flow Process

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. **A steady flow process is defined as a process during which a fluid flows through a control volume steadily (Fig. 13).** That is, 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 (Fig. 14).

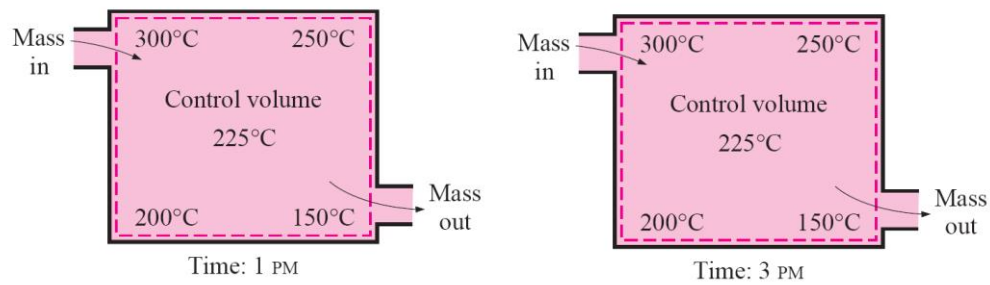


Figure 13: During a steady-flow process, fluid properties within the control volume may change with position but not with time.

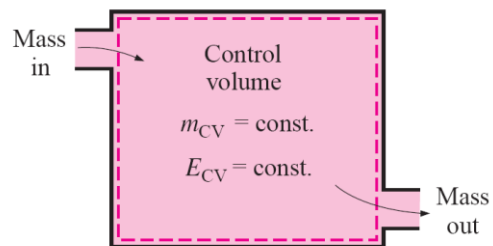


Figure 14: Under steady-flow conditions, the mass and energy contents of a control volume remain constant.