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3. Thermodynamics: An Engineering Approach, 5/e, by Yunus A. Cengel and Michael A. Boles
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INTRODUCTION

Thermodynamics is an engineering science topic, which deals with the science of "motion" (*dynamics*) and/or the transformation of "heat" (*thermo*) and energy into various other energy–containing forms "**conservation of energy principle**". The flow of energy is of great importance to engineers involved in the design of the power generation and process industries. Examples of analyses based on thermodynamics include:

➢ The transfer or motion of energy from hot gases emerging from a burner to cooler water in a hot–water heater.

➢ The transformation of the thermal energy, i.e., heat, contained in the hot gases in an automobile engine into mechanical energy.

➢ The conversion of the chemical energy contained in fuel into thermal energy in a combustor.

Engineers use principles drawn from thermodynamics and other engineering sciences, such as fluid mechanics and heat and mass transfer, to analyze and design things intended to meet human needs.

Dimensions, Units & Symbols

Any physical quantity can be characterized by **dimensions.** The magnitudes assigned to the dimensions are called **units.** Some basic dimensions such as mass m, length L, time t, and temperature T are selected as **primary** or **fundamental dimensions,** while others such as velocity V, energy E, and volume V are expressed in terms of the primary dimensions and are called **secondary dimensions,** or **derived dimensions**.

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

Two sets of units are still in common use today: the **English system,** which is also known as the *United States Customary System* (USCS), and the metric **SI** (from International System of Units). The SI is a simple and logical system based on a decimal relationship between the various units, and it is being used for scientific and engineering work in most of the industrialized nations, including England. The English system (**Imperial**, **British Units**), however, has no apparent systematic numerical base, and various units in this system are related to each other rather arbitrarily.

Fundamental Concepts & Definitions

❖ **Area of a Circle**

$$A = \pi r^2 = (\text{circumference} * r)/2 = \frac{\pi}{4} d^2 = 0.7854 d^2$$

❖ **Volume of a Cylinder**

$$V = \frac{\pi}{4} d^2 L \qquad \text{Where L is cylinder length}$$

❖ **Density** is defined as *mass per unit volume* $\qquad \rho = \dfrac{m}{V}$

The reciprocal of density is the **specific volume** *v*, which is defined as *volume per unit mass*. That is,

$$\upsilon = \frac{V}{m} = \frac{1}{\rho}$$

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,**

$$\textit{Specific gravity:} \quad \textbf{SG} = \frac{\rho}{\rho\, H2O}$$

Example: The mass of air in a room 3 X 5 X 20 m is known to be 350 kg. Determine the density and specific volume.

$$\rho = \frac{m}{V} = \frac{350}{(3)(5)(20)} = 1.167 \text{ kg/m}^3 \qquad \upsilon = \frac{1}{\rho} = \frac{1}{1.167} = 0.857 \text{ m}^3/\text{kg}$$

❖ **Velocity**

vector property equal to $\dfrac{\text{displacement}}{\text{time}}$

In SI the basic unit is $\dfrac{m}{s}$, in Imperial $\dfrac{ft}{s}$

Other common units are $\dfrac{km}{h}$, $\dfrac{mi}{h}$

Conversions: $\qquad 1\dfrac{m}{s} = 3.28 \dfrac{ft}{s}$

$$1\frac{km}{h} = 0.621 \frac{mi}{h}$$

Speed of sound in dry air is 331 m/s at 0°C and increases by about 0.61 m/s for each °C rise .Speed of light in vacuum equals 3 x 10^8 m/s.

❖ **Acceleration** - vector property equal to change in velocity /time

In SI the basic unit is $\dfrac{m}{s^2}$, in Imperial $\dfrac{ft}{s^2}$

Conversion: $1\dfrac{m}{s^2} = 3.28 \dfrac{ft}{s^2}$

Acceleration due to gravity, symbol "g", is $9.81 \dfrac{m}{s^2}$ or $32.2 \dfrac{ft}{s^2}$

❖ **Force** In SI the unit of force is the newton, N, defined as a $\dfrac{kg\ m}{s^2}$

In Imperial the unit of force is the pound lb

Conversion: 9.81 N = 2.2 lb

❖ **Weight -** In SI weight can be calculated from

Weight = F = mg, where g = 9.81 m/s^2

In Imperial, the mass of an object (rarely used), in slugs, can be calculated from the known weight in pounds

$$m = \frac{Weight}{g} \qquad g = 32.2 \frac{ft}{s^2}$$

❖ **Kinetic Energy**

Energy due to motion

$$E_k = \frac{1}{2}mv^2$$

In Imperial this is usually expressed as $E_k = \dfrac{w}{2g}v^2$ where w is weight

❖ **Potential Energy**
Energy due to position in a force field, such as gravity
$$E_p = m\ g\ h$$
In Imperial this is usually expressed E_p = w h where w is weight, and h is height above some specified datum.

❖ **Thermal Energy**

In SI the common units of thermal energy are J, and kJ, (and kJ/kg for specific quantities). In Imperial, the units of thermal energy are British Thermal Units (Btu)

Conversions: 1 Btu = 1055 J
                       1 Btu = 778 ft-lb

❖ **Power**

In SI the unit is the Watt W (or kW)

       1 W= 1J/s

In Imperial, the units are:

       Mechanical Power - ft – lb/s, horsepower h.p.
       Thermal Power – Btu/s
       Electrical Power - W, kW, or h.p.

Conversions: 746 W = 1 h.p.
                       1 h.p. = 550 ft – lb/s
                       1 kW = 0.948 Btu/s

❖ **Pressure**

A vector quantity, force per unit area

In SI the basic units of pressure are pascals Pa and kPa

$1 Pa = 1 N/m^2$

In Imperial, the basic unit is the pound per square inch, psi

Atmospheric Pressure

At sea level atmospheric pressure equals 101.3 kPa or 14.7 psi

Pressure Conversions

       1 psi = 6.895 kPa

Pressure may be expressed in standard units, or in units of static fluid head, in both SI and Imperial systems

Common equivalencies are:

       1 kPa = 0.294 in. mercury = 7.5 mm mercury
       1 kPa = 4.02 in. water = 102 mm water
       1 psi = 2.03 in. mercury = 51.7 mm mercury
       1 psi = 27.7 in. water = 703 mm water
       $1 m H_2O = 9.81 kPa$

Other pressure unit conversions:

       1 bar = 14.5 psi = 100 kPa
       $1 kg/cm^2 = 98.1 kPa = 14.2 psi = 0.981 bar$
       1 atmosphere (atm) = 101.3 kPa = 14.7 psi

Temperature and pressure measurements

Several types of temperature and pressure measurements are used during discussions of thermodynamics. Operators must recognize the different types and their interrelationships in order to understand thermodynamics.
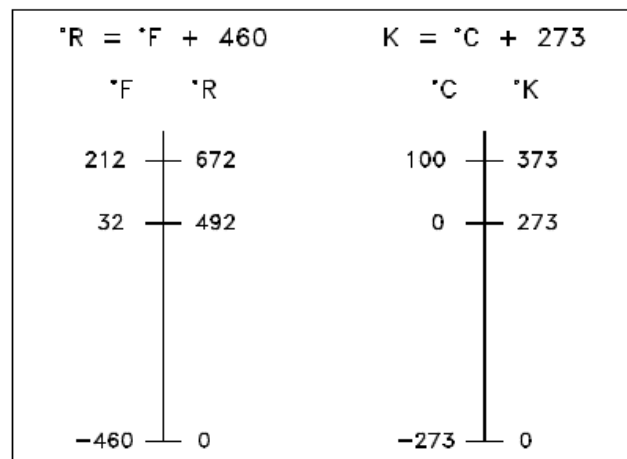
Temperature

Temperature is a measure of the molecular activity of a substance. The greater the movement of molecules, the higher the temperature. It is a relative measure of how "hot" or "cold" a substance is and can be used to predict the direction of heat transfer.

Temperature Scales

The two temperature scales normally employed for measurement purposes are the Fahrenheit (F) and Celsius (C) scales. These scales are based on a specification of the number of increments between the freezing point and boiling point of water at standard atmospheric pressure. The Celsius scale has 100 units between these points, and the Fahrenheit scale has 180 units. The zero points on the scales are arbitrary. The freezing point of water was selected as the zero point of the Celsius scale. The coldest temperature achievable with a mixture of ice and salt water was selected as the zero point of the Fahrenheit scale. The temperature at which water boils was set at 100 on the Celsius scale and 212 on the Fahrenheit scale. The relationship between the scales is represented by the following equations.

$$°F = 32.0 + (9/5) \ °C$$
$$°C = (°F - 32.0) \ (5/9)$$

It is necessary to define an absolute temperature scale having only positive values. The absolute temperature scale that corresponds to the Celsius scale is called the Kelvin (K) scale, and the absolute scale that corresponds to the Fahrenheit scale is called the Rankine (R) scale. The zero points on both absolute scales represent the same physical state. This state is where there is no molecular motion of individual atoms. The relationships between the absolute and relative temperature scales are shown in the following equations.
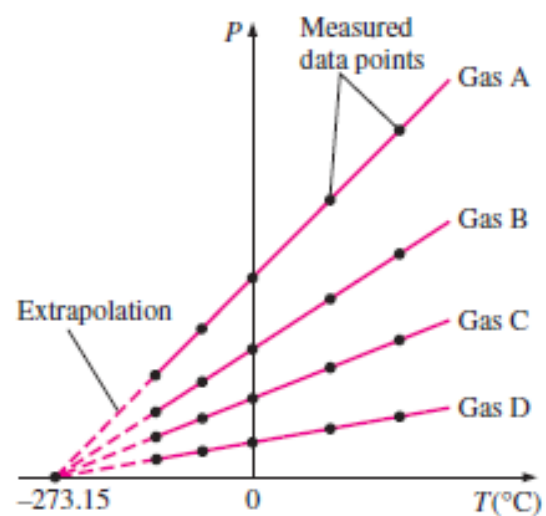

$$°R = °F + 460$$
$$°K = °C + 273$$

A temperature scale that becomes nearly identical to the Kelvin scale is the **ideal-gas temperature scale.** The temperatures on this scale are measured using a **constant-volume gas thermometer,** which is basically a rigid vessel filled with a gas, usually hydrogen or helium, at low pressure. This thermometer is based on the principle that *at low pressures, the temperature of a gas is proportional to its pressure at constant volume*. That is, the temperature of a gas of fixed volume varies *linearly* with pressure at sufficiently low pressures. Then the relationship between the temperature and the pressure of the gas in the vessel can be expressed as

$$T = a + bP \qquad \text{------ } 1$$

Where the values of the constants a and b for a gas thermometer are determined experimentally. The values of the constants will be different for each thermometer, depending on the type and the amount of the gas in the vessel, and the temperature values assigned at the two reference points. If the ice and steam points are assigned the values 0°C and 100°C, respectively, then the gas temperature scale will be identical

to the Celsius scale. In this case the value of the constant a (which corresponds to an absolute pressure of zero) is determined to be -273.15°C regardless of the type and the amount of the gas in the vessel of the gas thermometer. That is, on a *P-T* diagram, all the straight lines passing through the data points in this case will intersect the temperature axis at -273.15°C when extrapolated, as shown in Fig. This is the lowest temperature that can be obtained by a gas thermometer, and thus we can obtain an *absolute gas temperature scale* by assigning a value of zero to the constant a in Eq. 1. In that case Eq. 1 reduces to $T = bP$, and thus we need to specify the temperature at only *one* point to define an absolute gas temperature scale.

EXAMPLE: The temperature of a body is 50°F. Find its temperature in $°C$, K, and °R **.** Using the conversion equations.

$$\mathbf{t_C} = \frac{5}{9}(50 - 32) = 10°C \text{ , } \mathbf{T_K} = 10 + 273 = 283K \text{ ,} \mathbf{T_R} = 50 + 460 = 510°R$$
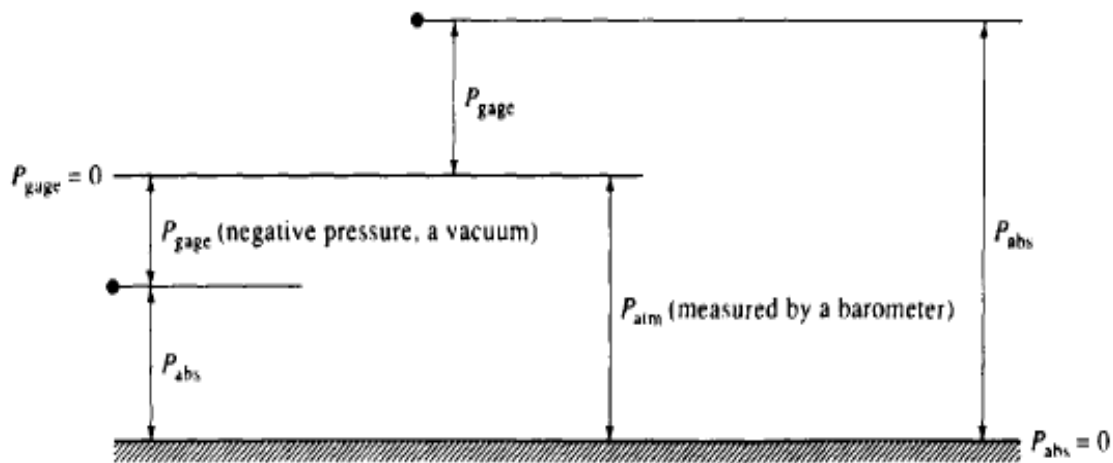
Pressure

Pressure is defined as *a normal force exerted by a fluid per unit area*. We speak of pressure only when we deal with a gas or a liquid. The counterpart of pressure in solids is *normal stress*. Since pressure is defined as force per unit area, it has the unit of Newton per square meter (N/m2), which is called a **pascal** (Pa)

The actual pressure at a given position is called the **absolute pressure,** and it is measured relative to absolute vacuum (i.e., absolute zero pressure). Most pressure-measuring devices, however, are calibrated to read zero in the atmosphere, and so they indicate the difference between the absolute pressure and the local atmospheric pressure. This difference is called the **gage pressure.** Pressures below atmospheric pressure are called **vacuum pressures** and are measured by vacuum gages that indicate the difference between the atmospheric pressure and the absolute pressure. Absolute, gage, and vacuum pressures are all positive quantities and are related to each other by
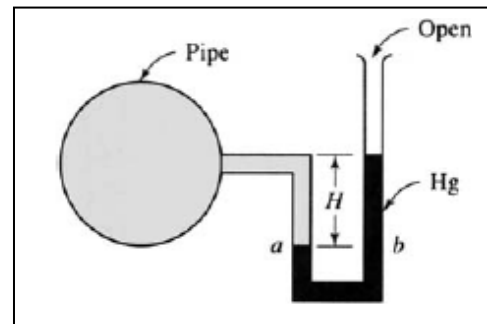
$$Pgage = Pabs - Patm$$
$$Pvac = Patm - Pabs$$

In thermodynamic relations and tables, absolute pressure is almost always used. Throughout this text, the pressure *P* will denote *absolute pressure* unless specified otherwise. Often the letters "a" (for absolute pressure) and "g" (for gage pressure) are added to pressure units (such as psia and psig) to clarify what is meant.

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Example: The manometer shown in Fig. below is used to measure the pressure in the water pipe. Determine the water pressure if the manometer reading is 0.6 m. Mercury is 13.6 times heavier than water.
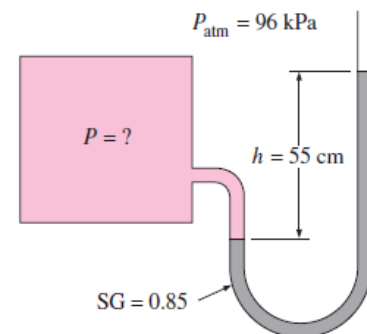

P + (0.6 m)(9810 N/m3) =
 (0.6 m)(13.6)(9810 N/m3)
       P = 74 200 Pa or 74.2 kPa gage.

Example: 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.

$$P\text{abs} = P\text{atm} - P\text{vac} = 14.5 - 5.8 = \textbf{8.7 psi}$$

Example: A manometer is used to measure the pressure in a tank. The fluid used has a specific gravity of 0.85, and the manometer column height is 55 cm, as shown in Fig. below. If the local atmospheric pressure is 96 kPa, determine the absolute pressure within the tank.

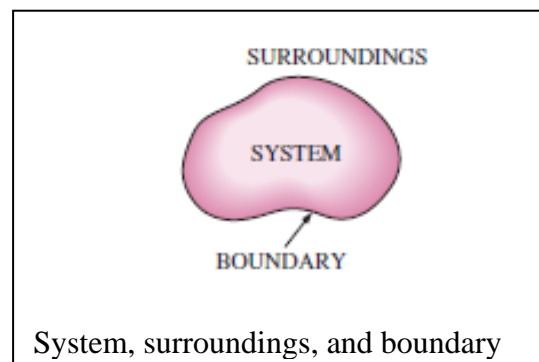ρ = SG (ρ_{H2O}) = (0.85) (1000 kg/m^3) = 850 kg/m^3

$P = P_{atm} + \rho\, gh$
= 96 kPa + (850 kg/m^3) (9.81 m/s^2) (0.55 m) $\left(\dfrac{1\ \text{kPa}}{1000\ \text{N}/\text{m2}}\right)$ = **100.6 kPa**

Thermodynamic System

       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.

A system is defined as a *quantity of matter or a region in space chosen for study*. The mass or region outside the system is called the **surroundings.** The

System, surroundings, and boundary

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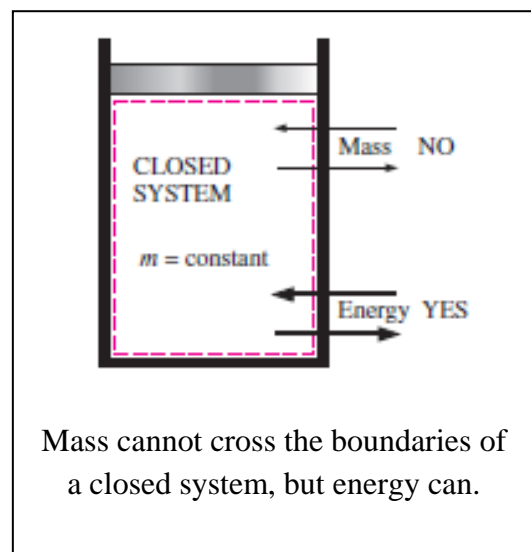
real or imaginary surface that separates the system from its surroundings is called the **boundary.** The boundary of a system can be *fixed* or *movable* (**Physical, Imaginary & Party Physical and Party Imaginary**).
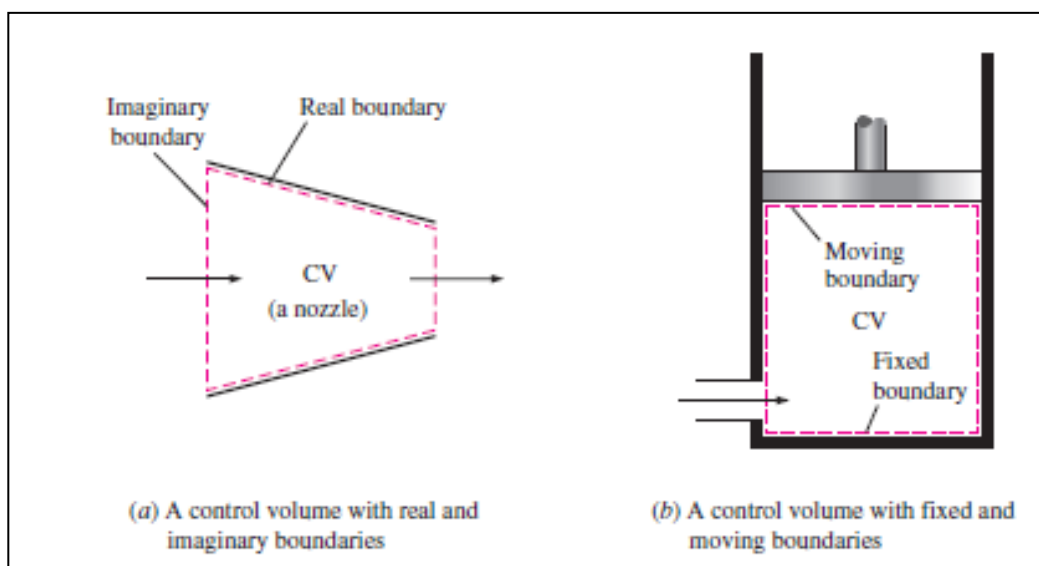
We may want to study a quantity of matter contained within a closed, rigid-walled tank, or we may want to consider something such as a pipeline through which natural gas flows. The composition of the matter inside the system may be fixed or may be changing through chemical or nuclear reactions. The shape or volume of the system being analyzed is not necessarily constant, as when a gas in a cylinder is compressed by a piston or a balloon is inflated.

Types of systems

Systems may be considered to be *closed* or *open,* depending on whether a fixed mass or a fixed volume in space is chosen for study. A **closed system** (also known as a **control mass**) consists of a fixed amount of mass, and no mass can cross its boundary. That is, no mass can enter or leave a closed system, as shown in Fig. 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. If, as a special case, even energy is not allowed to cross the boundary, that system is called an **isolated system.**

Mass cannot cross the boundaries of a closed system, but energy can.

An **open system,** or a **control volume,** as it is often called, is a properly selected region in space. It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle. Flow through these devices is best

(a) A control volume with real and imaginary boundaries

(b) A control volume with fixed and moving boundaries

studied by selecting the region within the device as the control volume. Both mass and energy can cross the boundary of a control volume.

A *composite* system consists of a combination of two or more subsystems that exist in a state of constrained equilibrium.

Macroscopic & Microscopic Analysis

Systems can be studied from a macroscopic or a microscopic point of view. The macroscopic approach to thermodynamics is concerned with the gross or overall behavior. This is sometimes called *classical* thermodynamics. No model of the structure of matter at the molecular, atomic, and subatomic levels is directly used in classical thermodynamics.

Although the behavior of systems is affected by molecular structure, classical thermodynamics allows important aspects of system behavior to be evaluated from observations of the overall system.

The microscopic approach to thermodynamics, known as *statistical* thermodynamics, 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

Any characteristic of a system is called a **property.** Some familiar properties are pressure P, temperature T, volume V, and mass m. The list can be extended to include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.

Properties are considered to be either *intensive* or *extensive*. **Intensive properties** are those that are independent of the mass of a 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.
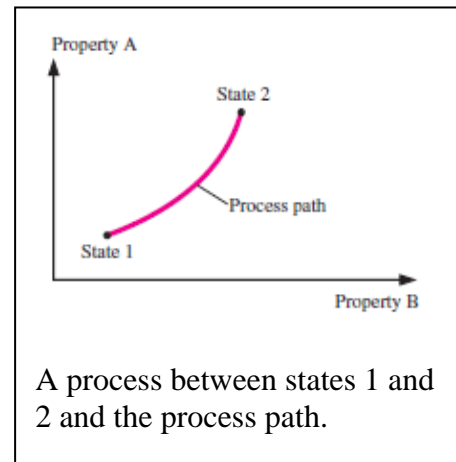
An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with an imaginary partition; each part will have the same value of intensive properties as the original system, but half the value of the extensive properties.

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

The word *state* refers to the condition of a system as described by its properties. Since there are normally relations among the properties of a system, the state often can be specified by providing the values of a subset of the properties. All other properties can be determined in terms of these few.

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

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

through which a system passes during a process is called the **path** of the process**.**

A process is a transformation from one state to another. However, if a system exhibits the same values of its properties at two different times, it is in the same state at these times. A system is said to be at *steady state* if none of its properties changes with time.

A *thermodynamic cycle* is a sequence of processes that begins and ends at the same state. At the conclusion of a cycle all properties have the same values they had at the beginning.

The prefix *iso-* is often used to designate a process for which a particular property remains constant. An **isothermal process,** for example, is a process during which the temperature T remains constant; an **isobaric process** is a process during which the pressure P remains constant; and an **isochoric (or isometric) process** is a process during which the specific volume v remains constant.

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 *vapors* (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. When more than one phase is present, the phases are separated by *phase boundaries.* Note that gases say oxygen and nitrogen can be mixed in any

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proportion to form a *single* gas phase. Certain liquids, such as alcohol and water, can be mixed to form a *single* liquid phase. But liquids such as oil and water, which are not miscible, form *two* liquid phases.

A ***pure substance*** is one that is uniform and invariable in chemical composition. A pure substance can exist in more than one phase, but its chemical composition must be the same in each phase. A system consisting of air can be regarded as a pure substance as long as it is a mixture of gases; but if a liquid phase should form on cooling, the liquid would have a different composition from the gas phase, and the system would no longer be considered a pure substance.A system that consists of more than a single component (or species) is called a **mixture**.
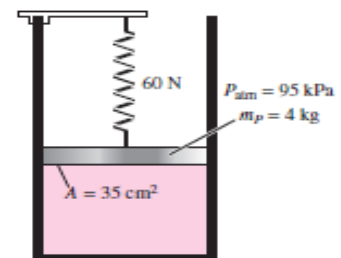
Thermodynamic Equilibrium

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. For example, a system is in **thermal equilibrium** if the temperature is the same throughout the entire system,

When two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with one another. This statement, which is sometimes called the ***zeroth law of thermodynamics,*** the third body is usually a *thermometer*. It was named the zeroth law since it should have preceded the first and the second laws of thermodynamics.

Example: A gas is contained in a vertical, frictionless piston–cylinder device. The piston has a mass of 4 kg and a cross-sectional area of 35 cm². A compressed spring above the piston exerts a force of 60 N on the piston. If the atmospheric pressure is 95 kPa, determine the pressure inside the cylinder.
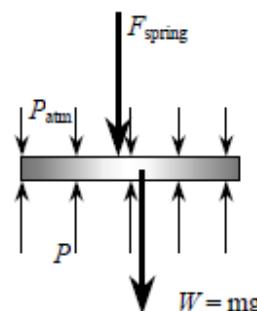
$$PA = P_{atm}A + W + F_{spring}$$

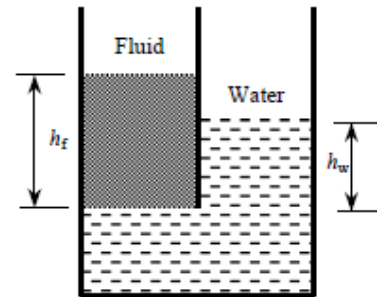$$P = P_{atm} + \frac{mg + F_{spring}}{A}$$

$$= (95\,kPa) + \frac{(4\,kg)(9.81\,m/s^2) + 60\,N}{35 \times 10^{-4}\,m^2}\left(\frac{1\,kPa}{1000\,N/m^2}\right)$$

$$= 123.4\,kPa$$

Example: The top part of a water tank is divided into two compartments, as shown in Figure. Now a fluid with an unknown density is poured into one side, and the water level rises a certain amount on the other side to compensate for this effect. Based on the final fluid heights shown on the figure, determine the density of the fluid added. Assume the liquid does not mix with water.

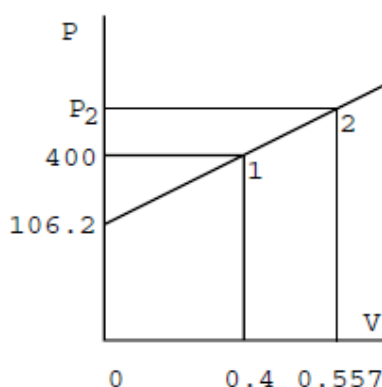$$P_{contact} = P_{atm} + \rho_f g h_f = P_{atm} + \rho_w g h_w$$

$$\rho_f g h_f = \rho_w g h_w$$

$$\rho_f = \frac{h_w}{h_f} \rho_w = \frac{45\,cm}{80\,cm}(1000\,kg/m^3) = \mathbf{562.5\,kg/m^3}$$

Example: A 5-kg piston in a cylinder with diameter of 100 mm is loaded with a linear spring and the outside atmospheric pressure of 100 kPa. The spring exerts no force on the piston when it is at the bottom of the cylinder and for the state shown, the pressure is 400 kPa with volume 0.4 L. The valve is opened to let some air in, causing the piston to rise 2 cm. Find the new pressure.

A linear spring has a force linear proportional to displacement. F = k x, so the equilibrium pressure then varies linearly with volume: P = a + bV, with an intersect a and a slope b = dP/dV. Look at the balancing pressure at zero volume (V -> 0) when there is no spring force F = PA=PoA + m_pg and the initial state. These two points determine the straight line shown in the P-V diagram.

Piston area = A_P = $(\pi/4) \times 0.1^2 = 0.00785\,m^2$

$$a = P_0 + \frac{m_p g}{A_p} = 100\,kPa + \frac{5 \times 9.80665}{0.00785}\,Pa$$

$$= 106.2\,kPa \text{ intersect for zero volume}$$

$$V_2 = 0.4 + 0.00785 \times 20 = 0.557\,L$$

$$P_2 = P_1 + \frac{dP}{dV}\Delta V$$

$$= 400 + \frac{(400-106.2)}{0.4 - 0}(0.557 - 0.4)$$

$$= \mathbf{515.3\,kPa}$$

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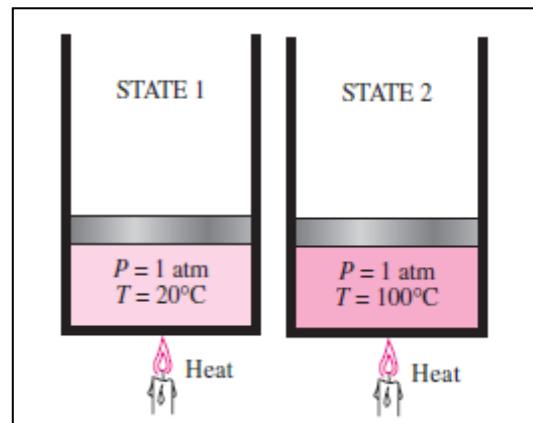
Properties of Pure Substances

In this lecture the relationships between pressure, specific volume, and temperature will be presented for a pure substance. We all know from experience that substances exist in different phases. At room temperature and pressure, copper is a solid, mercury is a liquid, and nitrogen is a gas. Under different conditions, each may appear in a different phase. Even though there are three principal phases—solid, liquid, and gas—a substance may have several phases within a principal phase, each with a different molecular structure. Carbon, for example, may exist as graphite or diamond in the solid phase. Helium has two liquid phases; iron has three solid phases. Ice may exist at seven different phases at high pressures.

Phase-change processes of pure substances

There are many practical situations where two phases of a pure substance coexist in equilibrium. Water exists as a mixture of liquid and vapor in the boiler and the condenser of a steam power plant. The refrigerant turns from liquid to vapor in the freezer of a refrigerator. Attention in this section is focused on the liquid and vapor phases and their mixture. As a familiar substance, water is used to demonstrate the basic principles involved. Remember, however, that all pure substances exhibit the same general behavior.
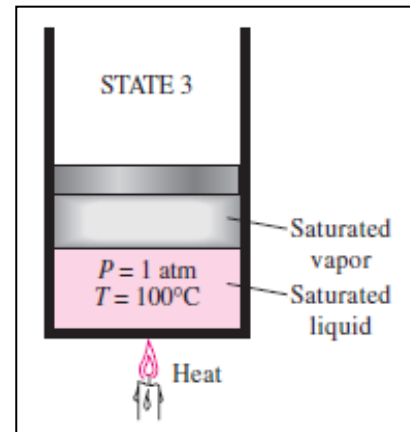
Compressed Liquid and Saturated Liquid

Consider a piston–cylinder device containing liquid water at 20°C and 1 atm pressure (state 1). Under these conditions, water exists in the liquid phase, and it is called a **compressed liquid,** or a **subcooled liquid,** meaning that it is *not about to vaporize.* Heat is now transferred to the water until its temperature rises to, say, 40°C. As the temperature rises, the

liquid water expands slightly, and so its specific volume increases. Water is still a compressed liquid at this state since it has not started to vaporize. As more heat is transferred, the temperature keeps rising until it reaches 100°C (state 2). At this point water is still a liquid, but any heat addition will cause some of the liquid to vaporize. That is, a phase-change process from liquid to vapor is about to take place. A liquid that is *about to vaporize* is called a **saturated liquid.** Therefore, state 2 is a saturated liquid state.

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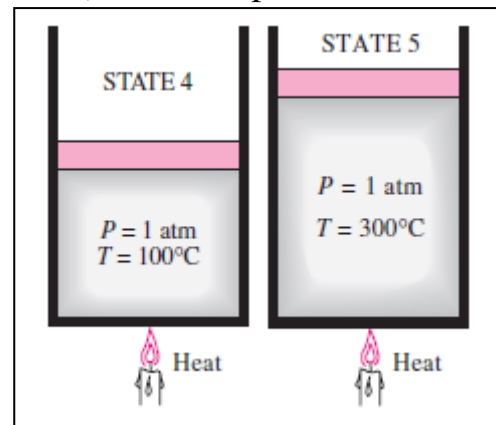قسم الهندسة الميكانيكية

Saturated Vapor and Superheated Vapor

Once boiling starts, the temperature stops rising until the liquid is completely vaporized. That is, the temperature will remain constant during the entire phase-change process if the pressure is held constant. The thermometer will always read 100°C. During a boiling process, the only change we will observe is a large increase in the volume and a steady decline in the liquid level as 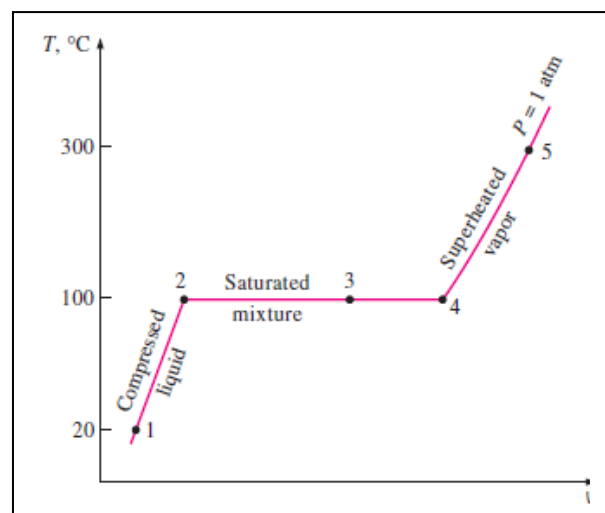a result of more liquid turning to vapor. Midway about the vaporization line (state 3), the cylinder contains equal amounts of liquid and vapor. As we continue transferring heat, the vaporization process continues until the last drop of liquid is vaporized (state 4). At this point, the entire cylinder is filled with vapor. Any heat loss from this vapor will cause some of the vapor to condense (phase change from vapor to liquid). A vapor that is *about to condense* is called a **saturated vapor.** Therefore, state 4 is a saturated vapor state. A substance at states between 2 and 4 is referred to as a **saturated liquid–vapor mixture** since the *liquid and vapor phases coexist* in equilibrium at these states.

Once the phase-change process is completed, we are back to a single-phase region again (this time vapor), and further transfer of heat results in an increase in both the temperature and the specific volume (state 5). At state 5, the temperature of the vapor is, let us say, 300°C; and if we transfer some heat from the vapor, the temperature may drop somewhat but no condensation will take place as long as the temperature remains above 100°C(for $P = 1$ atm). A vapor that is *not about to condense* (i.e., not a saturated vapor) is called a **superheated vapor.** Therefore, water at state 5 is a superheated vapor. This constant-

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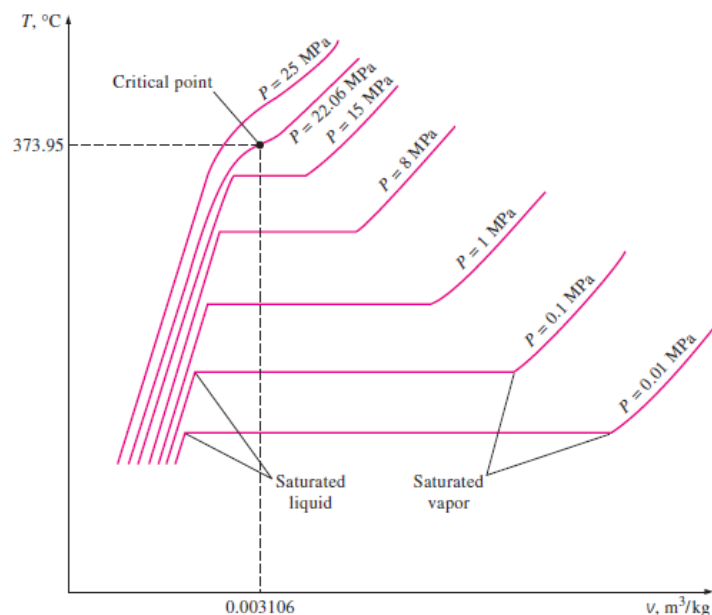pressure phase-change process is illustrated on a *T-v* diagram in Figure.

If the entire process described here is reversed by cooling the water while maintaining the pressure at the same value, the water will go back to state 1, retracing the same path, and in so doing, the amount of heat released will exactly match the amount of heat added during the heating process.

Saturation Temperature and Saturation Pressure

At a given pressure, the temperature at which a pure substance changes phase is called the **saturation temperature** T_{sat}. Also, at a given temperature, the pressure at which a pure substance changes phase is called the **saturation pressure** P_{sat}.

1-The *T-v* Diagram

We repeat this process at different pressures to develop the *T-v* diagram. Let us add weights on top of the piston until the pressure inside the cylinder reaches 1 MPa. At this pressure, water has a somewhat smaller specific volume than it does at 1 atm pressure. As heat is transferred to the water at this new pressure, the process follows a path that looks very much like the process path at 1 atm pressure, but there are some noticeable differences. First, water starts boiling at a much higher temperature (179.9°C) at this pressure. Second, the specific volume of the saturated liquid is larger and the specific volume of the saturated vapor is smaller than the corresponding values at 1 atm pressure. That is, the horizontal line t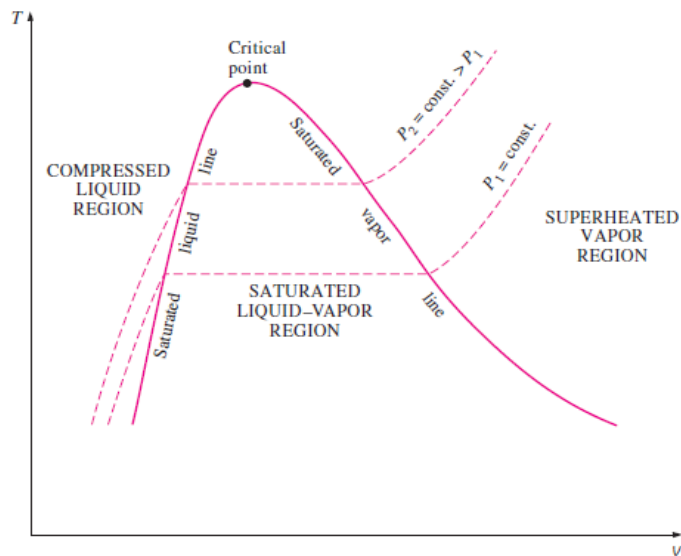hat connects the saturated liquid and saturated vapor states is much shorter, and it becomes a point when the pressure reaches 22.06 MPa for the case of water. This point is called the **critical point,** and it is defined as *the point at which the saturated liquid and saturated vapor states are identical.*

The temperature, pressure, and specific volume of a substance at the critical point are called, respectively, the *critical temperature* T_{cr}, *critical pressure* P_{cr}, and *critical specific volume* v_{cr}. The critical-point properties of water are $P_{cr} = 22.06$ MPa, $T_{cr} = 373.95$°C, and $v_{cr} = 0.003106$ m3/kg. The

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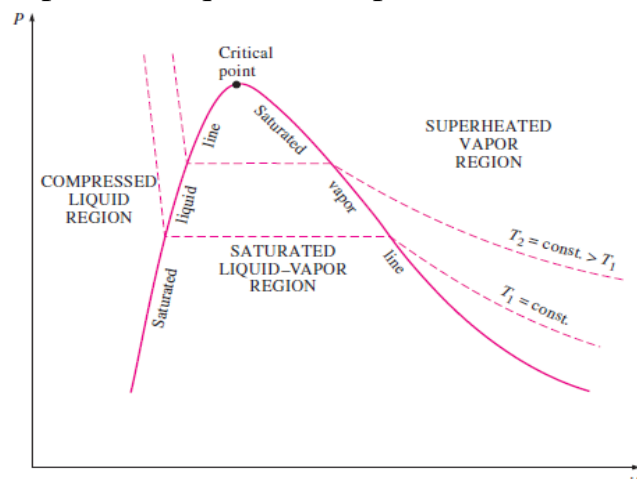مدرس المادة / م.م احمد عبد علي غيدان

saturated liquid states in Figure can be connected by a line called the **saturated liquid line,** and saturated vapor states in the same figure can be connected by another line, called the **saturated vapor line.** These two lines meet at the critical point, forming a dome as shown in Figure. All the compressed liquid states are located in the region to the left of the saturated liquid line, called the **compressed liquid region.** All the superheated vapor states are located to the right of the saturated vapor line, called the **superheated vapor region.** In these two regions, the substance exists in a single phase, a liquid or a vapor. All the states that involve both phases in equilibrium are located under the dome, called the **saturated liquid–vapor mixture region,** or the **wet region.**
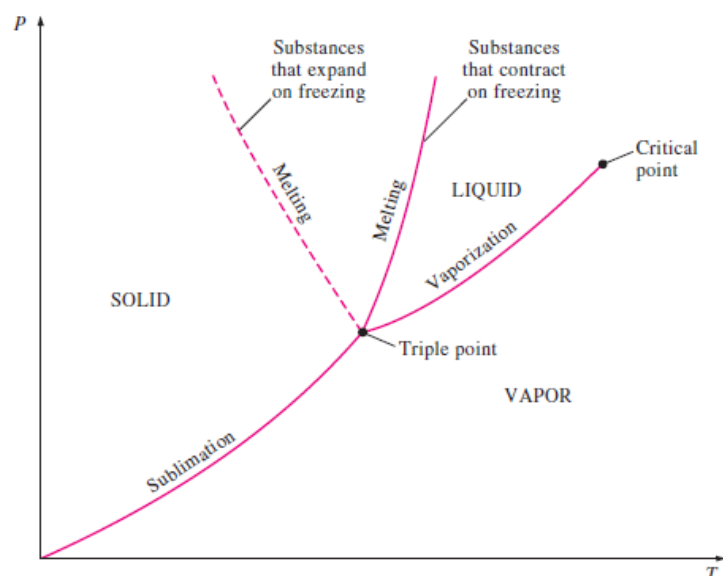
2-The *P-v* Diagram

The general shape of the *P-v* diagram of a pure substance is very much like the *T-v* diagram, but the *T*= constant lines on this diagram have a downward trend, as shown in Figure.
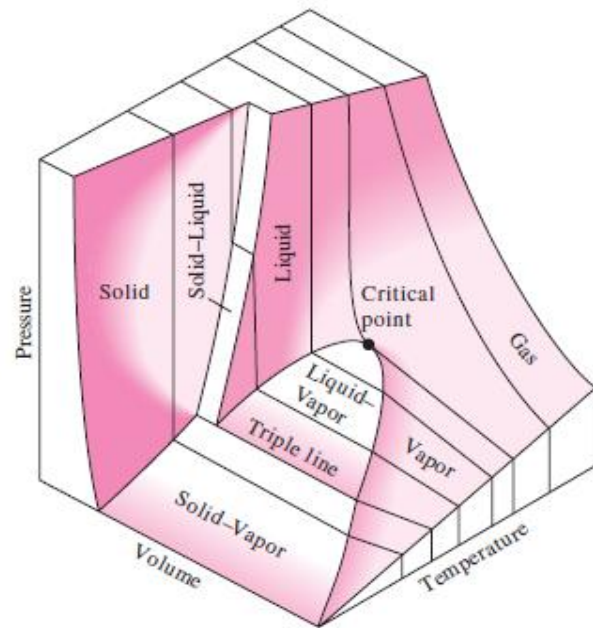
3-The *P-T* Diagram

This diagram is often called the **phase diagram** since all three phases are separated from each other by three lines. The sublimation line separates the solid and vapor regions, the vaporization line separate the liquid and vapor regions, and

the melting (or fusion) line separates the solid and liquid regions. These three lines meet at the triple point, where all three phases coexist in equilibrium. The vaporization line ends at the critical point because no distinction can be made between liquid and vapor phases above the critical point. Substances that expand and contract on freezing differ only in the melting line on the *P-T* diagram.

The *P-v-T* Surface

All the two-dimensional diagrams we have discussed so far are merely projections of this three-dimensional surface onto the appropriate planes. The *P-v-T* surfaces present a great deal of information at once, but in a thermodynamic analysis it is more convenient to work with two-dimensional diagrams, such as the *P-v* and *T-v* diagrams.

Saturation tables

For a two-phase liquid–vapor mixture, the ratio of the mass of vapor present to the total mass of the mixture is its *quality, x*. In symbols

$$x = \frac{m_{\text{vapor}}}{m_{\text{liquid}} + m_{\text{vapor}}}$$

quality, $x = m_{\text{vap}}/m$, and noting that $m_{\text{liq}}/m = 1 - x$,

$$V = V_{\text{liq}} + V_{\text{vap}}$$

$$v = \frac{V}{m} = \frac{V_{\text{liq}}}{m} + \frac{V_{\text{vap}}}{m}$$

Since the liquid phase is a saturated liquid and the vapor phase is a saturated vapor, $V_{\text{liq}} = m_{\text{liq}} v_{\text{f}}$ and $V_{\text{vap}} = m_{\text{vap}} v_{\text{g}}$, so

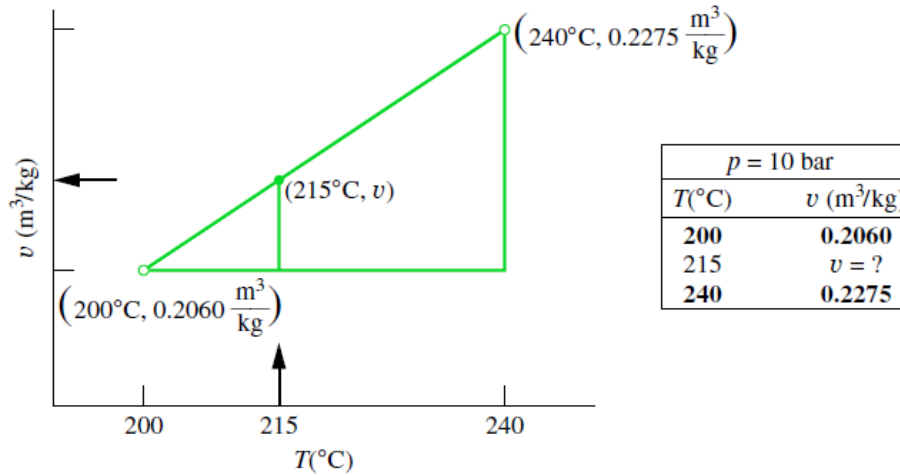$$v = \left(\frac{m_{\text{liq}}}{m}\right) v_{\text{f}} + \left(\frac{m_{\text{vap}}}{m}\right) v_{\text{g}}$$

$$v = (1 - x) v_{\text{f}} + x v_{\text{g}} = v_{\text{f}} + x(v_{\text{g}} - v_{\text{f}})$$

$$= v_f + x v_{fg}$$

Linear interpolation

For example. Determine the specific volume of water vapor at a state where p = 10 bar and $T = 215^0C$.

p = 10 bar	
$T(°C)$	v (m³/kg)
200	0.2060
215	v = ?
240	0.2275

$$slope = \frac{(0.2275 - 0.2060) \text{ m}^3/\text{kg}}{(240 - 200)°C} = \frac{(v - 0.2060) \text{ m}^3/\text{kg}}{(215 - 200)°C}$$

$$v = 0.2141 \text{ m}^3/\text{kg}.$$

Q_1: A closed, rigid container of volume 0.5 m³ is placed on a hot plate. Initially, the container holds a two-phase mixture of saturated liquid water and saturated water vapor at p_1 = 1 bar with a quality of 0.5. After heating, the pressure in the container is p_2 = 1.5 bar. Indicate the initial and final states on a T–v diagram, and determine

(a) The temperature, in ^0C, at each state.

(b) The mass of vapor present at each state, in kg.

(c) If heating continues, determine the pressure, in bar, when the container holds only saturated vapor.

Q2: A vertical piston–cylinder assembly containing 0.05 kg of ammonia, initially a saturated vapor, is placed on a hot plate. Due to the weight of the piston and the surrounding atmospheric pressure, the pressure of the ammonia is 1.5 bars. Heating occurs slowly, and the ammonia expands at constant pressure until the final temperature is 25^0C. Show the initial and final states on T–v and p–v diagrams, and determine the volume occupied by the ammonia at each state, in m³.

EXAMPLE: Determine the volume change when 1 kg of saturated water is completely vaporized at a pressure of (a) 1 kPa, (b) 100 kPa, and (c) 10000 kPa.

Table B.1.2.SI, Provides the necessary values. The quantity being sought is v_{fg} or v_g - v_f

(**a**) 1 kPa. Thus, v_{fg} = 129.2 - 0.001 = 129.2 m³/kg.

(*b*) 100 kPa = 0.1 MPa. Again, v_{fg} = 1.694 - 0.001 = 1.693 m^3/kg.

(*c*) 10000 kPa = 10 MPa. Finally, v_{fg} = 0.01803 - 0.00145 = 0.01658 m3/kg.

EXAMPLE: A rigid tank contains 50 kg of saturated liquid water at 90°C. Determine the pressure in the tank and the volume of the tank.

From table B.1.1.SI, at T= 90 ^{o}C

P = Psat = 70.14 kPa

v = v_f = 0.001036 m^3/kg

V = mv = (150 kg)(10.001036 m^3/kg) = 0.0518 m3

EXAMPLE: 4 kg of water is placed in an enclosed volume of 1m^3. Heat is added until the temperature is 150°C. Find (*a*) the pressure, (*b*) the mass of vapor, and (*c*) the volume of the vapor.

From table B.1.1.SI, at T= 150 ^{o}C the specific volume of 4 kg of saturated vapor is 0.3928 m^3/kg > 0.25 m^3/kg Since the given volume is quality region.

(*a*) In the quality region the pressure is given as *P* = 475.8 kPa.

(*b*) To find the mass of the vapor we must determine the quality

0.25 = 0.00109 + x (0.3928- 0.00109)

x= 0.2489/0.3917 = 0.6354.

The mass vapor is m_g = mx = (4)(0.6354) = 2.542 kg

(*c*) The volume of the vapor is V_g= $v_g m_g$= (0.3928) (2.542) = 0.9985 m^3

EXAMPLE: 4 kg of water is heated at a pressure of 220 kPa to produce a mixture with quality *x* = 0.8. Determine the final volume occupied by the mixture.

From table B.1.2.SI, at P= 220 kPa , interpolate between 200 kpa and
225 kpa

v_g =($\frac{220-200}{225-200}$)(0.79325-0.88573) + 0.88573 = 0,811746 m^3/kg

v_f = 0,0010616 m^3/kg

v = v_f + xv_{fg} =0,0010616 +0.8(0,811746 - 0,0010616) = 0,64960912 m^3/kg

The total volume occupied by 4 kg is V = m v = (4 kg) (0,649 m^3/kg) = 2,598 m^3.

EXAMPLE: An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (*a*) the temperature, (*b*) the quality, (*c*) the volume occupied by the vapor phase.

(*a*) We do not know whether the refrigerant is in the compressed liquid, superheated vapor, or saturated mixture region. This can be determined by comparing a suitable property to the saturated liquid and saturated vapor values.

$$\text{Specific volume} \quad v = \frac{V}{m} = \frac{0.080 \text{ m}^3}{4 \text{ kg}} = 0.02 \text{ m}^3/\text{kg}$$

From table B.5.1.SI, at P= 160 kPa , by interpolation
$$v_f = 0.0007437 \text{ m}^3/\text{kg} \quad ; \quad v_g = 0.12348 \text{ m}^3/\text{kg}$$

Obviously, $v_f < v < v_g$, and, the refrigerant is in the saturated mixture region. Thus, the temperature must be the saturation temperature at the specified pressure: (by interpolation)
$$T = T_{\text{sat}} = \textbf{-15.60°C}$$

(*b*) Quality can be determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007437}{0.12348 - 0.0007437} = \quad \textbf{0.157}$$

(*c*) The mass of the vapor is

$$m_g = xm = (10.1572)(4 \text{ kg}) = 0.628 \text{ kg}$$

And the volume occupied by the vapor phase is
$$V_g = m_g v_g = (0.628 \text{ kg}) (0.12348 \text{ m}^3/\text{kg}) = \textbf{0.0775 m}^3 \text{ (or 77.5 L)}$$

The rest of the volume (2.5 L) is occupied by the liquid.

The ideal-gas equation of state

An ideal gas is an *imaginary* substance that obeys the relation $Pv = RT$. At low pressures and high temperatures, the density of a gas decreases, and the gas behaves as an ideal gas under these conditions.

Any equation that relates the pressure, temperature, and specific volume of a substance is called an **equation of state.** There are several equations of state, some simple and others very complex. The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the *P-v-T* behavior of a gas quite accurately within some properly selected region.
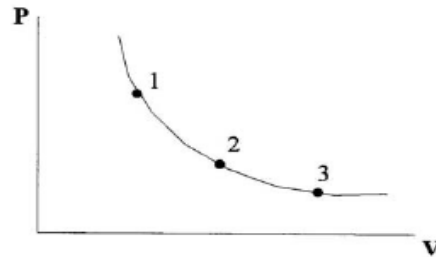
Many familiar gases such as air, nitrogen, oxygen, hydrogen, helium, argon, neon, krypton, and even heavier gases such as carbon dioxide can be treated as ideal gases. Dense gases such as water vapor in steam power plants and refrigerant vapor in refrigerators, however, should not be treated as ideal gases. Instead, the property tables should be used for these substances.

Boyle's Law (T= C)

The pressure of gases is inversely proportional to their volume.

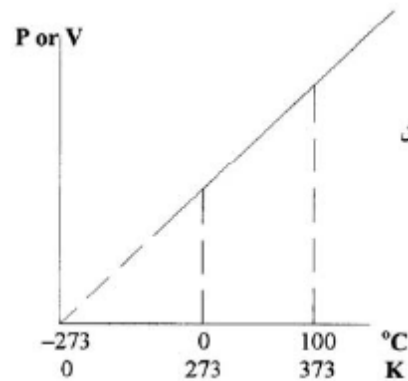$$P_1V_1 = P_2V_2 = P_3V_3 = PV = Const.$$

Charle's Law and Absoulte Temperature (Gay-Lussac)

At low pressures the volume of a gas is proportional to its temperature.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V}{T} = Const.$$

$$\frac{P}{T} = Const$$

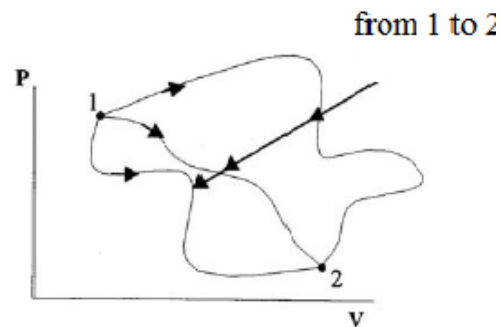## The General Equation of Perfect Gas (Equation of State)

From 1 to A
$$P_1V_1 = P_A V_A = P_2V_A$$

$$V_A = \frac{P_1V_1}{P_2} \quad \text{---} \quad 1$$

from 1 to 2

From A to 2

$$\frac{V_A}{T_A} = \frac{V_2}{T_2} = \frac{V_A}{T_1}$$

$$\therefore V_A = \frac{V_2T_1}{T_2} \quad \text{---} \quad 2$$

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From eq. 1 and 2

$$\frac{P_1 V_1}{P_2} = \frac{V_2 T_1}{T_2}$$

Or

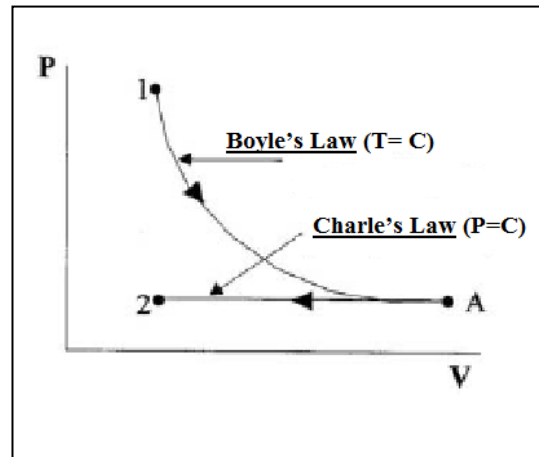$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} = \frac{PV}{T} = Const$$

For 1 kg

$$\frac{P v}{T} = R$$

Or

$$\boxed{PV = m\,R\,T}$$ Equation of State

The gas constant R is different for each gas and is determined from

$$R = \frac{R_u}{M} \quad (KJ/kg.\ K)$$

Where R_u is the **universal gas constant** (8.31447 KJ/kg. K) and M is the *molecular weight* (molar mass).

The mass of a system is equal to the product of its molar mass M and the mole number N:
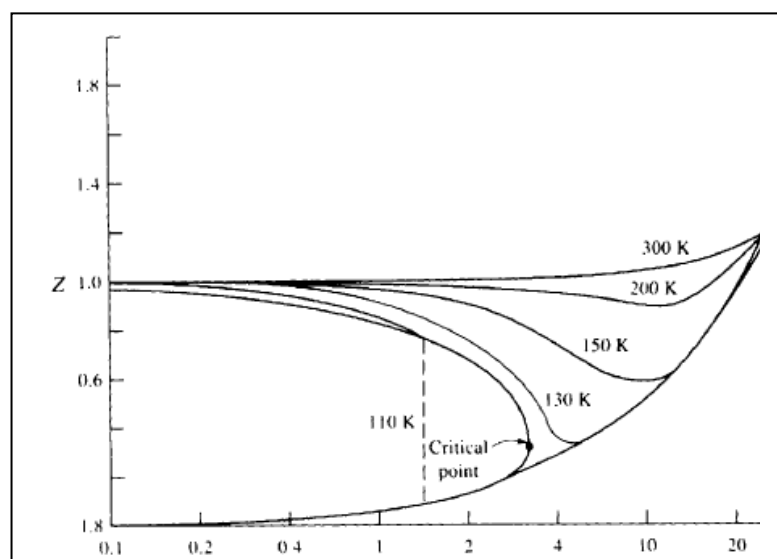
$$m = MN \quad (kg)$$

Compressibility factor

The *compressibility factor* Z helps us in determining whether or not the ideal-gas equation should be used. It is defined as

$$Z = \frac{P v}{RT}$$

The compressibility factor can be determined for any

gas by using a generalized compressibility chart. In the generalized chart the **reduced pressure P_R** and **reduced temperature T_R** must be used. They are calculated from

Where P_c and T_c are critical-point pressure and temperature, respectively.

Other equations of state
Van der waals equation of state

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

beattie- bridgeman equation of state

$$P = \frac{RT'(1 - E)}{v^2}(v + B) - \frac{A}{v^2}$$

EXAMPLE: Determine the mass of the air in a room whose dimensions are 4 m * 5 m* 6 m at 100 kPa and 25°C.

From table A.5
The gas constant of air is $R = 0.287$ kPa · m³/kg · K,

$$V = 4 \text{ m}* 5 \text{ m}* 6 \text{ m} = 120 \text{ m}^3$$

$$m = \frac{PV}{RT} = \frac{(100 \text{ kPa})(120 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(298 \text{ K})} = \textbf{140.3 kg}$$

EX: A spherical helium balloon of 10 m in diameter is at ambient T and P, 15°C and 100 kPa. How much helium does it contain? It can lift a total mass that equals the mass of displaced atmospheric air. How much mass of the balloon fabric and cage can then be lifted?

$$V = \frac{\pi}{6} D^3 = \frac{\pi}{6} 10^3 = 523.6 \text{ m}^3$$

$$m_{He} = \rho V = \frac{V}{v} = \frac{PV}{RT}$$

$$= \frac{100 \times 523.6}{2.0771 \times 288} = 87.5 \text{ kg}$$

$$m_{air} = \frac{PV}{RT} = \frac{100 \times 523.6}{0.287 \times 288} = 633 \text{ kg}$$

$$m_{lift} = m_{air} - m_{He} = 633\text{-}87.5 = \textbf{545.5 kg}$$

EX: A rigid tank of 1 m³ contains nitrogen gas at 600 kPa, 400 K. By mistake someone lets 0.5 kg flow out. If the final temperature is 375 K what is then the final pressure?

$$m = \frac{PV}{RT} = \frac{600 \times 1}{0.2968 \times 400} = 5.054 \text{ kg}$$

$$m_2 = m - 0.5 = 4.554 \text{ kg}$$

$$P_2 = \frac{m_2 RT_2}{V} = \frac{4.554 \times 0.2968 \times 375}{1} = 506.9 \text{ kPa}$$

EX: A cylindrical gas tank 1 m long, inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 25°C. To what pressure should it be charged if there should be 1.2 kg of carbon dioxide?

Assume CO_2 is an ideal gas, table A.5:   R = 0.1889 kJ/kg K

$$V_{cyl} = A \times L = \frac{\pi}{4}(0.2)^2 \times 1 = 0.031416 \text{ m}^3$$

$$P V = mRT \qquad => \qquad P = \frac{mRT}{V}$$

$$\Rightarrow P = \frac{1.2 \text{ kg} \times 0.1889 \text{ kJ/kg K} \times (273.15 + 25) \text{ K}}{0.031416 \text{ m}^3} = 2152 \text{ kPa}$$

EX: Is it reasonable to assume that at the given states the substance behaves as an ideal gas?

a) Oxygen, O_2 at 30°C, 3 MPa   **Ideal Gas** (T » Tc = 155 K from A.2)
b) Methane, CH_4 at 30°C, 3 MPa   **Ideal Gas** (T » Tc = 190 K from A.2)
c) Water, H_2O at 30°C, 3 MPa   **NO** compressed liquid P > Psat (B.1.1)
d) R-134a at 30°C, 3 MPa   **NO** compressed liquid P > Psat (B.5.1)
e) R-134a at 30°C, 100 kPa   **Ideal Gas** P is low < Psat (B.5.1)

EX : A cylinder fitted with a frictionless piston contains butane at 25°C, 500 kPa. Can the butane reasonably be assumed to behave as an ideal gas at this state ?

Butane 25°C, 500 kPa, Table A.2: $T_c = 425$ K; $P_c = 3.8$ MPa

$$T_r = \frac{25 + 273}{425} = 0.701; \qquad P_r = \frac{0.5}{3.8} = 0.13$$

Look at generalized chart in Figure D.1

Actual $P_r > P_{r, sat} = 0.1$ =>   **liquid!! not a gas**

The pressure should be less than 380 kPa to have a gas at that T.

EX: How close to ideal gas behavior (find Z) is ammonia at saturated vapor, 100 kPa? How about saturated vapor at 2000 kPa?

Table B.2.2: $\quad v_1 = 1.1381 \ m^3/kg, \ T_1 = -33.6^oC, \ P_1 = 100 \ kPa$
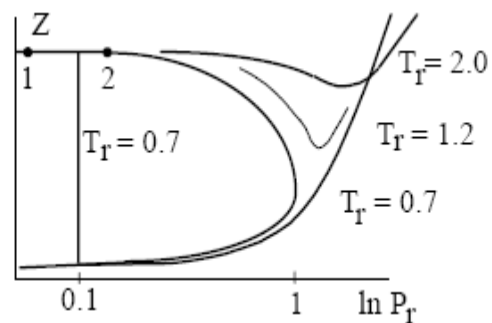$v_2 = 0.06444 \ m^3/kg, \ T_2 = 49.37^oC, \ P_2 = 2000 \ kPa$
Table A.5: $\quad R = 0.4882 \ kJ/kg \ K$

Extended gas law: Pv = ZRT so we can calculate Z from this

$$Z_1 = \frac{P_1 v_1}{RT_1} = \frac{100 \times 1.1381}{0.4882 \times (273.15 - 33.6)} = 0.973$$

$$Z_2 = \frac{P_2 v_2}{RT_2} = \frac{2000 \times 0.06444}{0.4882 \times (273.15 + 49.37)} = 0.8185$$

So state 1 is close to ideal gas and state 2 is not so close

EX: Find the volume of 2 kg of ethylene at 270 K, 2500 kPa using Z from Fig. D.1

Ethylene Table A.2: $\quad$ Tc = 282.4 K, Pc = 5.04 MPa
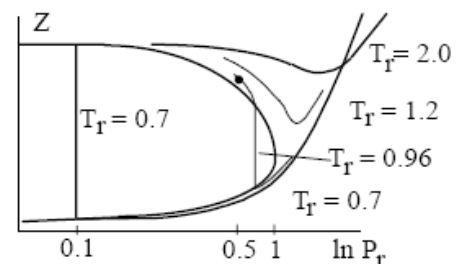Table A.5: $\quad$ R = 0.2964 kJ/kg K

The reduced temperature and pressure are

$$T_r = \frac{T}{T_c} = \frac{270}{282.4} = 0.956, \quad P_r = \frac{P}{P_c} = \frac{2.5}{5.04} = 0.496$$

Enter the chart with these coordinates and read:
Z = 0.76

$$V = \frac{mZRT}{P} = \frac{2 \times 0.76 \times 0.2964 \times 270}{2500} = 0.0487 \ m^3$$

EX: Give the phase for the following states.

a. CO2 $\quad$ T = 267°C $\quad\quad$ P = 0.5 MPa Table A.2
$\quad\quad\quad\quad$ **Superheated vapor** assume ideal gas Table A.5
b. Air $\quad$ T = 20°C $\quad\quad$ P = 200 kPa Table A.2
$\quad\quad\quad\quad$ **Superheated vapor** assume ideal gas Table A.5
c. NH3 $\quad$ T = 170°C $\quad\quad$ P = 600 kPa Table B.2.2 or A.2

T > Tc => **superheated vapor**

EX: Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.

    a.   P = 10 MPa, v = 0.003 m³/kg   b. 1 MPa, 190°C

    c. 200°C, 0.1 m3/kg   d. 10 kPa, 10°C

For all states start search in table B.1.1 (if T given) or B.1.2 (if P given)
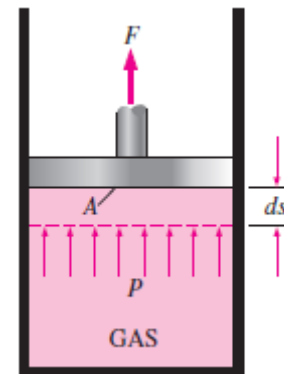
a. P = 10 MPa, v = 0.003 m³/kg so look in B.1.2 at 10 MPa

           vf = 0.001452; vg = 0.01803 m³/kg,

           => vf < v < vg => so mixture of liquid and vapor.

b. 1 MPa, 190°C : Only one of the two look-ups is needed

           B.1.1: P < Psat = 1254.4 kPa so it is superheated vapor

           B.1.2: T > Tsat = 179.91°C so it is superheated vapor

c. 200°C, 0.1 m3/kg: look in B.1.1

           vf = 0.001156 m³/kg ; vg = 0.12736 m³/kg,

           => vf < v < vg => so mixture of liquid and vapor.

d. 10 kPa, 10°C : Only one of the two look-ups is needed

           From B.1.1: P > Pg = 1.2276 kPa so compressed liquid

           From B.1.2: T < Tsat = 45.8 °C so compressed liquid

Work and Heat

Work, designated *W,* is often defined as the product of a force and the distance moved in the direction of the force: in the SI system, Newton-meters (N. **m)** or joules (J). This is a mechanical definition of work. **A** more general definition of work is the thermodynamic definition: ***Work,*** an interaction between a system and its surroundings.

Work due to a moving boundary

Consider the piston-cylinder arrangement shown in Figure. The initial pressure of the gas is *P*, the total volume is *V*, and the cross sectional area of the piston is *A*. If the piston is allowed to move a distance *ds*, the differential work done during this process is
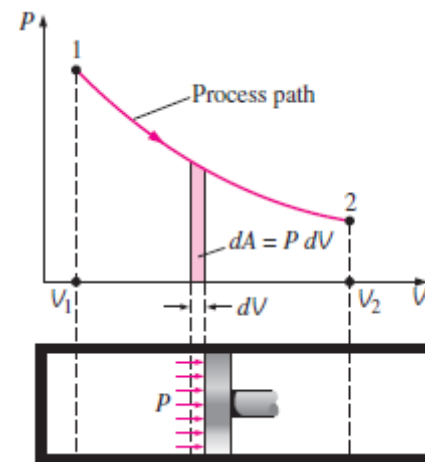
$$dW_b = F\ ds = PA\ ds = PdV$$

$$W_{1-2} = \int_{V_1}^{V_2} P\,dV$$

This integral can be evaluated only if we know the functional relationship between *P* and *V* during the process. That is, $P = f(V)$ should be available. Note that $P = f(V)$ is simply the equation of the process path on a *P-V* diagram.

If the relationship between *P* and *V* during an expansion or a compression process is given in terms of experimental data instead of in a functional form, obviously we cannot perform the integration analytically. But we can always plot the *P-V* diagram of the process, using these data points, and calculate the area underneath graphically to determine the work done.
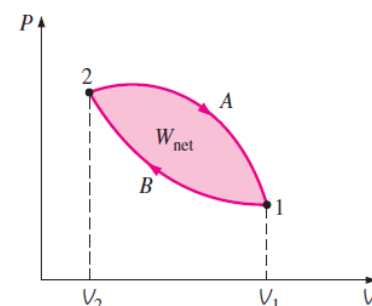
The cycle shown in Figure Produces a net work output because the work done by the system during the expansion process (area under path *A*) is greater than the work done on the system during the compression part of the cycle (area under path *B*), and the difference between these two is the net work done during the cycle.

The work associated with a unit mass will be designated *w:*
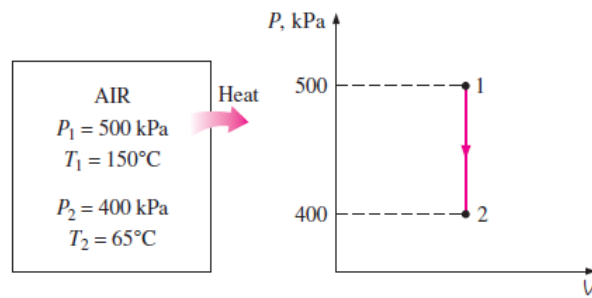
$$w = \frac{W}{m}$$

The rate of doing work, designated $\dot{W}$ is called ***power.*** In the **SI** system, power has units joules per second **(J/s),** or watts **(W)**

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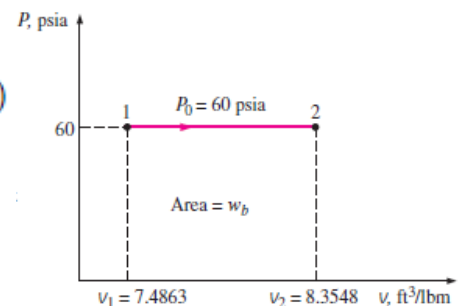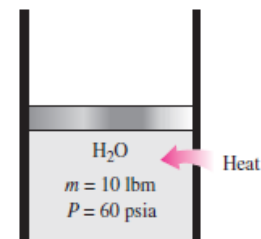
1-Boundary Work for a Constant-Volume Process

EX: A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

$$W_b = \int_1^2 P \, dV^{0} = 0$$

2-Boundary Work for a Constant-Pressure Process

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

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

Or

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

Since $V = mv$. From the superheated vapor table (Table C.8.2 ENG), the specific volumes are determined to be $v_1 = 7.4863$ ft³/lbm at state 1 (60 psia, 320°F) and $v_2 = 8.3548$ ft³/lbm at state 2 (60 psia, 400°F). Substituting these values yields

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

$$= 96.4 \text{ Btu}$$

3-Isothermal Compression of an Ideal Gas

EX: 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

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cylinder remains constant. Determine the work done during this process.

For an ideal gas at constant temperature T_0,

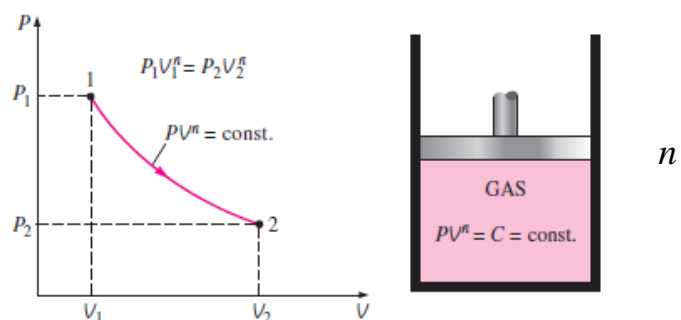$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

We have

$$W_b = \int_1^2 P\,dV = \int_1^2 \frac{C}{V}\,dV = C\int_1^2 \frac{dV}{V} = C \ln \frac{V_2}{V_1} = P_1 V_1 \ln \frac{V_2}{V_1}$$

$P_1 V_1$ can be replaced by $P_2 V_2$ or mRT_0. Also, V_2/V_1 can be replaced by P_1/P_2 for this case since $P_1 V_1 = P_2 V_2$.

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

4-Polytropic Process

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

n

The pressure for a polytropic process can be expressed as

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

We obtain

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

Since $C = P_1 V_1^n = P_2 V_2^n$. For an ideal gas ($PV = mRT$), this equation can also be written as
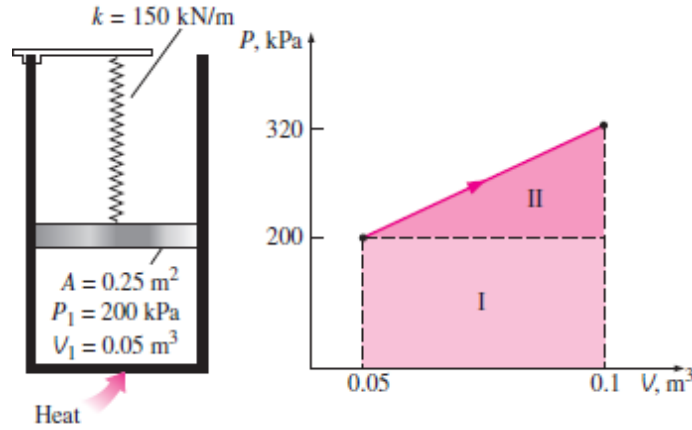
$$W_b = \frac{mR(T_2 - T_1)}{1-n} \qquad n \neq 1$$

For the special case of $n = 1$ the boundary work becomes

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = PV \ln\left(\frac{V_2}{V_1}\right)$$

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Expansion of a Gas against a spring

EX: A piston–cylinder device contains 0.05 m^3 of a gas initially at 200 kPa. At this state, a linear spring that has a spring constant of 150 kN/m is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m^2, determine (*a*) the final pressure inside the cylinder, (*b*) the total work done by the gas, and (*c*) the fraction of this work done against the spring to compress it.

(*a*) $$V_2 = 2V_1 = (2)\,(0.05\ \text{m}^3) = 0.1\ \text{m}^3$$

$$x = \frac{\Delta V}{A} = \frac{(0.1 - 0.05)\ \text{m}^3}{0.25\ \text{m}^2} = 0.2\ \text{m} \qquad \text{Displacement of the piston}$$

The force applied by the linear spring
$$F = kx = (150\ \text{kN/m})\,(0.2\ \text{m}) = 30\ \text{kN}$$
The additional pressure applied by the spring on the gas

$$P = \frac{F}{A} = \frac{30\ \text{kN}}{0.25\ \text{m}^2} = 120\ \text{kPa}$$

At the final state $200 + 120 = 320\ \text{kPa}$

(*b*) The area under the process curve

$$W = \text{area} = \frac{(200 + 320)\ \text{kPa}}{2}\,[(0.1 - 0.05)\ \text{m}^3]\left(\frac{1\ \text{kJ}}{1\ \text{kPa} \cdot \text{m}^3}\right)$$

$$= 13\ \text{kJ}$$

(*c*) The work represented by the rectangular area (region I) is done against the piston and the atmosphere, and the work represented by the triangular area (region II) is done against the spring. Thus,

$$W_{\text{spring}} = 1/2((320 - 200)\ \text{kPa})\,(0.05\ \text{m}^3) = 3\ \text{kJ}$$

This result could also be obtained from

$$W = \int_{x_1}^{x_2} F\,dx = \int_{x_1}^{x_2} Kx\,dx = \tfrac{1}{2}K\left(x_2^2 - x_1^2\right)$$

$$W_{spring} = \tfrac{1}{2}k(x_2^2 - x_1^2) = \tfrac{1}{2}(150\ \text{kN/m})\left[(0.2\ \text{m})^2 - 0^2\right]$$
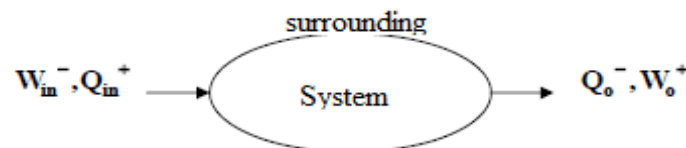
$$= 3\ \text{kJ}$$

HEAT

Heat, designated Q, is energy transferred across the boundary of a system due to a difference in temperature between the system and the surroundings of the system. A system does not contain heat, it contains energy, and heat is energy in transit. Heat, like work, is something that *crosses a boundary*. Because a system does not *contain* heat, heat is not a property.

The *rate* of heat transfer will be denoted by $\dot{Q}$.
Heat transfer per unit mass will be designated q and defined by

$$q = \frac{Q}{m}$$

By convention, if heat is transferred *to* a system it is considered positive. If it is transferred *from* a system it is negative. This is opposite from the convention chosen for work; if a system performs work on the surroundings it is positive. Positive heat transfer adds energy to a system, whereas positive work subtracts energy from a system. **A process in which there is zero heat transfer is called an *adiabatic process.***

Heat can be transferred in three different ways: ***conduction, convection***, and ***radiation.*** All modes of heat transfer require the existence of a temperature difference, and all modes of heat transfer are from the high-temperature medium to a lower temperature one.

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.
It is observed that the rate of heat conduction $\dot{Q}_{cond}$ through a layer of constant thickness dx is proportional to the temperature difference dT across the layer and the area A normal to the direction of heat transfer, and is inversely proportional to the thickness of the layer.

$$\dot{Q}_{cond} = -k_t A \frac{dT}{dx} \quad (W)$$

Fourier's law of heat conduction & k_t is the **thermal conductivity**

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion*.

The rate of heat transfer by convection is determined from **Newton's law of cooling,** expressed as

$$\dot{Q}_{conv} = hA(T_s - T_f) \quad (W)$$

Where h is the **convection heat transfer coefficient,** A is the surface area through which heat transfer takes place, T_s is the surface temperature, and T_f is bulk fluid temperature away from the surface

Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules. All bodies at a temperature above absolute zero emit thermal radiation and all solids, liquids, and gases emit, absorb, or transmit radiation of varying degrees.

The maximum rate of radiation that can be emitted from a surface at an *absolute* temperature T_s is given by the *Stefan–Boltzmann law* as

$$\dot{Q}_{emit,max} = \sigma A T_s^4 \quad (W)$$

Where A is the surface area and $\sigma = 5.67 * 10^{-8}$ W/m^2 .

The radiation emitted by all *real* surfaces is less than the radiation emitted by a blackbody (The idealized surface that emits radiation at this maximum rate) at the same temperatures and is expressed as

$$\dot{Q}_{emit,} = \varepsilon \sigma A T_s^4 \quad (W)$$

Where ε is the **emissivity** of the surface. The property emissivity, whose value is in the range $0 \le \varepsilon \le 1$, is a measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$.

EX: You drive a car on a winter day with the atmospheric air at $-15°C$ and you keep the outside front windshield surface temperature at $+2°C$ by blowing hot air on the inside surface. If the windshield is 0.5 m^2 and the outside convection coefficient is 250 W/m^{2}K find the rate of energy loss through the front windshield. For that heat transfer rate and a 5 mm thick glass with k = 1.25 W/m K what is then the inside windshield surface temperature?

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$$\dot{Q}_{conv} = h\ A\ \Delta T = 250 \times 0.5 \times [2 - (-15)]$$
$$= 250 \times 0.5 \times 17 = \mathbf{2125\ W}$$

$$\dot{Q}_{cond} = K\ A \frac{\Delta T}{\Delta X} \qquad \Delta T = \frac{Q}{KA} \Delta X$$

$$\Delta T = \frac{2125\ W}{1.25 W/mK * 0.5 m^2}\ 0.005\ m = 17\ K$$

$$T_{in} = T_{out} + \Delta T = 2 + 17 = 19°C$$

EX: A steam radiator in a room at 25°C has saturated water vapor at 110 kPa flowing through it, when the inlet and exit valves are closed. What is the pressure and the quality of the water, when it has cooled to 25°C? How much work is done?

After the valve is closed no more flow, constant volume and mass.
1: $x_1 = 1$, $P_1 = 110$ kPa $\Rightarrow v_1 = vg = 1.566$ m3/kg from Table B.1.2
2: $T_2 = 25°C$,   ?
Process: $v_2 = v_1 = 1.566$ m³/kg $= [0.001003 + x_2 \times 43.359]$ m³/kg
$\quad\quad x_2 = 1.566 - 0.001003/43.359 = \mathbf{0.0361}$

State 2: T_2 , x_2 From Table B.1.1 $\mathbf{P_2 = Psat = 3.169\ kPa}$
$$_1\mathbf{W_2} = \int PdV = \mathbf{0}$$

EX: Saturated water vapor at 200 kPa is in a constant pressure piston cylinder. At this state the piston is 0.1 m from the cylinder bottom and cylinder area is 0.25 m². The temperature is then changed to 200°C. Find the work in the process.

State 1   from B.1.2 (P, x): $v_1 = vg = 0.8857$ m³/kg (also in B.1.3)
State 2   from B.1.3 (P, T): $v_2 = 1.0803$ m³/kg
Since the mass and the cross sectional area is the same we get

$$h_2 = \frac{v_2}{v_1} \times h_1 = \frac{1.0803}{0.8857} \times 0.1 = 0.122\ m$$

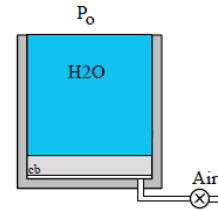Process: P = C so the work integral is
$$W = \int PdV = P\ (V_2 - V_1) = PA\ (h_2 - h_1)$$
$$W = 200\ kPa \times 0.25\ m^2 \times (0.122 - 0.1)\ m = \mathbf{1.1\ kJ}$$

4.38: A piston/cylinder has 5 m of liquid 20°C water on top of the piston (m = 0) with cross-sectional area of 0.1 m^2, see Figure. Air is let in under the piston that rises and pushes the water out over the top edge. Find the necessary work to push all the water out and plot the process in a P-V diagram.
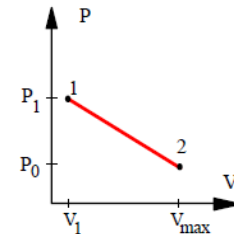
P1 = Po + ρgH

$\quad$ = 101.32 + 997 $\times$ 9.807 $\times$ 5 / 1000 = 150.2 kPa

ΔV = H $\times$ A = 5 $\times$ 0.1 = 0.5 m^3

$_1W_2$ = AREA = $\int$ P dV = ½ (P1 + Po) (Vmax -V1)

$\quad$ = ½ (150.2 + 101.32) kPa $\times$ 0.5 m^3

$\quad$ **= 62.88 kJ**

4.51: Air goes through a polytropic process from 125 kPa, 325 K to 300 kPa and 500 K. Find the polytropic exponent n and the specific work in the process.

Process: Pv^n = Const = $P_1v_1^n$ = $P_2 v_2^n$

Ideal gas Pv = RT so

$$v_1 = RT/P = \frac{0.287 \times 325}{125} = 0.7462 \text{ m}^3/\text{kg}$$

$$v_2 = RT/P = \frac{0.287 \times 500}{300} = 0.47833 \text{ m}^3/\text{kg}$$

From the process equation

$$(P_2/ P_1) = (v_1/ v_2)^n => \ln(P_2/ P_1) = n \ln(v_1/ v_2)$$

$$n = \ln(P_2/ P_1) / \ln(v_1/ v_2) = \frac{\ln 2.4}{\ln 1.56} = \textbf{1.969}$$

The work per unit mass is

$$_1W_2 = \frac{P_2v_2 - P_1v_1}{1-n} = \frac{R(T_2 - T_1)}{1-n} = \frac{0.287(500 - 325)}{1-1.969} = \textbf{-51.8 kJ/kg}$$

4.52 A piston cylinder contains 0.1 kg air at 100 kPa, 400 K which goes through a polytropic compression process with n = 1.3 to a pressure of 300 kPa. How much work has the air done in the process?

Process: Pv^n = Const.

$T_2 = T_1 (P_2 V_2 / P_1V_1) = T_1 (P_2 / P_1)(P_1 / P_2)^{1/n}$

$\quad = 400 \times (300/100)^{(1 - 1/1.3)} = 515.4$ K

$$_1W_2 = \frac{1}{1-n} (P_2 V_2 - P_1V_1) = \frac{mR}{1-n} (T_2 - T_1)$$

$$= \frac{0.2 \times 0.287}{1-1.3} \times (515.4\text{-}400) = \textbf{-477 kJ}$$

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4.55 Consider a piston cylinder with 0.5 kg of R-134a as saturated vapor at -10°C. It is now compressed to a pressure of 500 kPa in a polytropic process with n = 1.5. Find the final volume and temperature, and determine the work done during the process.

1: (T, x) $v_1 = 0.09921$ m³/kg, P = Psat = 201.7 kPa   from Table B.5.1

2: (P, process) $v_2 = v_1 (P_1/P_2)^{(1/1.5)} = 0.09921 \times (201.7/500)^{2/3} = $ **0.05416**

Given (P, v) at state 2 from B.5.2 it is superheated vapor at $T_2 = 79°C$
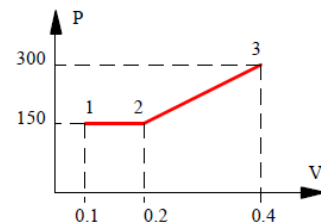
$$_1W_2 = \int P \, dV = \frac{m}{1-1.5} (P_2v_2 - P_1v_1)$$
$$= \frac{2}{-0.5} \times (500 \times 0.05416 - 201.7 \times 0.09921) = \textbf{-7.07 kJ}$$

4.59 Consider a two-part process with an expansion from 0.1 to 0.2 m³ at a constant pressure of 150 kPa followed by an expansion from 0.2 to 0.4 m³ with a linearly rising pressure from 150 kPa ending at 300 kPa. Show the process in a P-V diagram and find the boundary work.
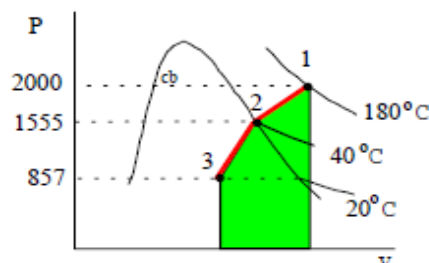

$$_1W_3 = {}_1W_2 + {}_2W_3 = \int_1^2 PdV + \int_2^3 PdV$$
$$= P_1 (V_2 - V_1) + 1/2 (P_2 + P_3)(V_3-V_2)$$
$$= 150 (0.2-1.0) + 1/2 (150 + 300)(0.4 -$$

0.2) = 15 + 45 = **60 kJ**

4.60 A cylinder containing 1 kg of ammonia has an externally loaded piston. Initially the ammonia is at 2 MPa, 180°C and is now cooled to saturated vapor at 40°C, and then further cooled to 20°C, at which point the quality is 50%. Find the total work for the process, assuming a piecewise linear variation of P versus V.

State 1: (T, P) Table B.2.2
$$v_1 = 0.10571 \text{ m}^3/\text{kg}$$
State 2: (T, x) Table B.2.1 sat. vap.
$$P_2 = 1555 \text{ kPa},$$
$$v_2 = 0.08313 \text{ m}^3/\text{kg}$$

State 3: (T, x) $P_3 = 857$ kPa, $v_3 = (0.001638 + 0.14922)/2 = 0.07543$ m³/kg
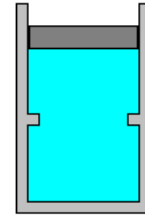
Sum the the work as two integrals each evaluated by the area in the P-v diagram.

$$_1W_3 = \int_1^3 PdV \approx (\frac{P_1 + P_2}{2}) m(v_2 - v_1) + (\frac{P_2 + P_3}{2}) m(v_3 - v_2)$$

$$= \frac{2000 + 1555}{2} 1(0.08313 - 0.10571) + \frac{1555 + 857}{2} 1(0.07543 - 0.08313)$$
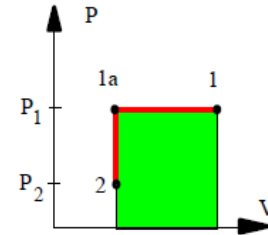
$$= -49.4 \text{ kJ}$$

4.61 A piston/cylinder arrangement shown in Figure initially contains air at 150 kPa, 400°C. The setup is allowed to cool to the ambient temperature of 20°C.

    a. Is the piston resting on the stops in the final state? What is the final pressure in the cylinder?

    b. What is the specific work done by the air during this process?

State 1: $P_1 = 150$ kPa, $T_1 = 400°C = 673.2$ K
State 2: $T_2 = T_0 = 20°C = 293.2$ K

a) If piston at stops at 2, $V_2 = V_1/2$ and pressure less than $P_{lift} = P_1$

$$\Rightarrow P_2 = P_1 \times \frac{V_1}{V_2} \times \frac{T_2}{T_1} = 150 \times 2 \times \frac{293.2}{673.2} = 130.7 \text{ kPa} < P_1$$

$\Rightarrow$ Piston is resting on stops at state 2.

b) Work done while piston is moving at constant $P_{ext} = P_1$.

$$_1W_2 = \int P_{ext} \, dV = P_1 (V_2 - V_1) ; \quad V_2 = \frac{1}{2} V_1 = \frac{1}{2} m \, RT_1/P_1$$

$$_1w_2 = {_1W_2}/m = RT_1 \left(\frac{1}{2} - 1\right) = -\frac{1}{2} \times 0.287 \times 673.2 = \textbf{-96.6 kJ/kg}$$

4.62 A piston cylinder has 1.5 kg of air at 300 K and 150 kPa. It is now heated up in a two step process. First constant volume to 1000 K (state 2) then followed by a constant pressure process to 1500 K, state 3. Find the final volume and the work in the process.

The two processes are:
1 => 2: Constant volume $V_2 = V_1$
2 => 3: Constant pressure $P_3 = P_2$

State 1:   T, P => $V_1 = mRT_1/P_1 = 1.5 \times 0.287 \times 300/150 = 0.861$ m^3
State 2: $V_2 = V_1 =>$ $P_2 = P_1 (T_2/T_1) = 150 \times 1000/300 = 500$ kPa
State 3: $P_3 = P_2 =>$ $V_3 = V_2 (T_3/T_2) = 0.861 \times 1500/1000 = \textbf{1.2915 m}^3$

We find the work by summing along the process path.

$$_1W_3 = {_1W_2} + {_2W_3} = {_2W_3} = P_3(V_3 - V_2)$$
$$= 500(1.2915 - 0.861) = \textbf{215.3 kJ}$$

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Energy balance for closed systems (the first law of thermodynamics)

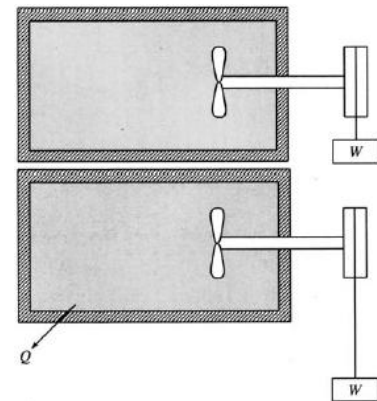The first law of thermodynamics is commonly called the law of conservation of energy. In elementary physics courses, the study of conservation of energy emphasizes changes in kinetic and potential energy and their relationship to work. A more general form of conservation of energy includes the effects of heat transfer and internal energy changes. This more general form is usually called the first law of thermodynamics. Other forms of energy may also be included, such as electrostatic, magnetic, strain, and surface energy. We will present the first law for a system and then for a control volume.

The first law applied to a process

The net heat transfer is equal to the net work done for a system undergoing a cycle. This is expressed in equation form by

$$\sum W = \sum Q$$

Let a weight be attached to a pulley-paddle-wheel setup, such as that shown in Figure. Let the weight fall a certain distance thereby doing work on the system. The temperature of the system (the fluid in the tank) will immediately rise an amount ΔT. Now, the system is returned to its initial state by transferring heat to the surroundings. This reduces the temperature of the system to its initial temperature. The first law states that this heat transfer will be exactly equal to the work which was done by the falling weight.

Cycle results when a system undergoes several processes and returns to the initial state, we could consider a cycle composed of the two processes represented by *A* and *B* in Figure. Using the first law, we can show

$$Q_{1-2} - W_{1-2} = E_2 - E_1$$

Where Q_{1-2} is the heat transferred to the system during the process from state 1 to state 2, W_{1-2} is the work done by the system on the surroundings during the process, and E_1 and E_2 are the values of the energy of the system.

The property E represents all of the energy: kinetic energy *KE*, potential energy *PE*, and internal energy *U* (includes chemical energy and the energy associated with the atom). Any other form of energy is also included in the total energy E.

The first law of thermodynamics then takes the form

$$Q_{l-2} - W_{1-2} = KE_2 - KE_1 + PE_2 - PE_1 + U_2 - U_1$$
$$= \frac{m}{2}(V_2^2 - V_1^2) + mg\,(z_2 - z_1) + U_2 - U_1$$

The internal energy U is an extensive property. Its associated intensive property is the specific internal energy u; that is, $u = U/m$. the value for a particular quality would be

$$u = u_f + x\,(u_g - u_f)$$

EX: A 5-hp fan is used in a large room to provide for air circulation. Assuming a well-insulated, sealed room determines the internal energy increase after 1 h of operation.

By assumption, $Q = 0$. With $\Delta PE = \Delta KE = 0$ the first law becomes $-W = \Delta U$. The work input is

$W = (-5\ hp)\,(1\ h)\,(746\ W/hp)\,(3600s/h) = -1.343 \times 10^7\ J$

$\Delta U = -(-1.343 \times 10^7) = 1.343 \times 10^7\ J$

5.14 Two kg water at 120°C with a quality of 25% has its temperature raised 20°C in a constant volume process. What are the new quality and specific internal energy?

State 1 from Table B.1.1 at 120°C

$v = v_f + x\,v_{fg} = 0.001060 + 0.25 \times 0.8908 = 0.22376\ m^3/kg$

State 2 has same v at 140°C also from Table B.1.1

$X = \dfrac{v - vf}{vfg} = \dfrac{0.22376 - 0.00108}{0.50777} = \mathbf{0.4385}$

$u = u_f + x\,u_{fg} = 588.72 + 0.4385 \times 1961.3 = \mathbf{1448.8\ kJ/kg}$

5.36 A rigid container has 0.75 kg water at 300°C, 1200 kPa. The water is now cooled to a final pressure of 300 kPa. Find the final temperature, the work and the heat transfer in the process.

State 1: 300°C, 1200 kPa => superheated vapor Table B.1.3 v = 0.21382 m³/kg, u = 2789.22 kJ/kg

State 2: 300 kPa and $v_2 = v_1$ from Table B.1.2 $v_2 < v_g$ two-phase $T_2 = T_{sat} = \mathbf{133.55^{o}C}$

$x_2 = \dfrac{v2 - vf}{vfg} = \dfrac{0.21382 - 0.001073}{0.60475} = 0.35179$

$u_2 = u_f + x_2\,u_{fg} = 561.13 + x_2\,1982.43 = 1258.5\ kJ/kg$

$_1Q_2 = m(u_2 - u_1) + {_1}W_2 = m(u_2 - u_1) = 0.75\,(1258.5 - 2789.22) = \mathbf{-1148\ kJ}$

Enthalpy

In the solution of problems involving systems, certain products or sums of properties occur with regularity. One such combination of properties can be demonstrated by considering the addition of heat to the constant-pressure situation. If the kinetic energy changes and potential energy changes of the system are neglected and all other work modes are absent, the first law of thermodynamics requires that.

$$Q - W = U_2 - U_1$$

The work done for the constant-pressure process is given by

$$W = P (V_2 - V_1)$$

The first law can then be written as

$$Q = (U + PV)_2 - (U + P V)_1$$

The quantity in parentheses is a combination of properties and is thus a property itself. It is called the *enthalpy H* of the system; that is,

$$H = U + P V$$

The specific enthalpy *h* is found by dividing by the mass. It is

$$h = u + P v$$

Enthalpy is a property of a system and is also found in the steam tables. The energy equation can now be written for a constant-pressure equilibrium process as

$$Q_{1-2} = H_2 - H_1$$

EX: A frictionless piston is used to provide a constant pressure of 400 kPa in a cylinder containing steam originally at 200°C with a volume of 2 m^3. Calculate the final temperature if 3500 kJ of heat is added.

From table B1.3 at T= 200 ^{o}C & P = 400 kpa; $v_1 = 0.534$ m^3/kg, $h_1 = 2860$ kJ/kg

$$Q = H_2 - H_1 \qquad or \qquad 3500 = (h_2 - 2860)\ m$$

$$m = \frac{V}{v} = \frac{2}{0.534} = 3.744 \text{ kg}$$

$$h_2 = \frac{3500}{3.744} + 2860 = 3795 \text{ kJ/kg}$$

From table B1.3 at P = 400 kpa & h_2= 3795 kJ/kg by interpolates

$$T_2 = 600 + (\frac{9.26}{224})\ (100) = \textbf{641°C}$$

5.37 A cylinder fitted with a frictionless piston contains 2 kg of superheated refrigerant R-134a vapor at 350 kPa, 100°C. The cylinder is now cooled so the R-134a remains at constant pressure until it reaches a quality of 75%. Calculate the heat transfer in the process.

State 1: Table B.5.2 $h_1 = (490.48 + 489.52)/2 = 490$ kJ/kg

State 2: Table B.5.1 $h_2 = 206.75 + 0.75 \times 194.57 = 352.7$ kJ/kg (350.9 kPa)

$_1Q_2 = m (u_2 - u_1) + {}_1W_2 = m (u_2 - u_1) + Pm (v_2 - v_1) = m (h_2 - h_1)$

$_1Q_2 = 2 \times (352.7 - 490) =$ **-274.6 kJ**

Latent heat

It is the amount of energy that must be transferred in the form of heat to a substance held at constant pressure in order that a phase change; it is equal to $h_{fg} = h_g - h_f.$

Specific heats

We can consider the specific internal energy to be a function of temperature and specific volume; that is,

$$U = u (T, v)$$

By using the chain rule

$$du = \frac{\partial u}{\partial T} \bigg|_v \ dT + \frac{\partial u}{\partial v} \bigg|_T dv$$

Since *u, v,* and *T* are all properties, the partial derivative is also a property and is called the *constant-volume specific heat c_v*; that is,

$$c_v = \frac{\partial u}{\partial T} \bigg|_v$$

For such a gas, which behaves as an ideal gas, we have

$$\frac{\partial u}{\partial v} \bigg|_T = 0$$

So $du = c_v \ dT$

This can be integrated to give

$$u_2 - u_1 = \int_{T_1}^{T_2} c_v dT$$

Likewise, considering specific enthalpy to be dependent on the two variables *T* and *P,* we have

$$dh = \frac{\partial h}{\partial T} \bigg|_p \ dT + \frac{\partial h}{\partial p} \bigg|_T \ dp$$

The *constant-pressure specific heat c,* is defined as

$$C_p = \frac{\partial h}{\partial T} \bigg|_p$$

For an ideal gas we have, returning to the definition of enthalpy,

$$h = u + P v = u + R T$$

Where we have used the ideal-gas equation of state. Since *u* is only a function of *T,* we see that h is also only a function of *T* for an ideal gas. Hence, for an ideal gas

$$\frac{\partial h}{\partial p} \bigg|_T = 0$$

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And we have, from $$dh = c_p\, dT$$

Over the temperature range T_1 to T_2 this is integrated to give

$$h_2 - h_1 = \int_{T_1}^{T_2} c_p\, dT$$

For an ideal gas.

It is often convenient to specify specific heats on a per-mole, rather than a per-unit-mass, basis; these **molar specific heats** are notated $\bar{c}_v$, and $\bar{c}_p$. Clearly, we have the relations

$\bar{c}_v = Mc_v$ and $\bar{c}_p = Mc_p$ where M is the molar mass.

Specific Heat Relations of Ideal Gases

The equation for enthalpy can be used to relate, for an ideal gas, the specific heats and the gas constant. In differential form takes the form

$$dh = du + \bar{d}(\,P\,v\,)$$

Introducing the specific heat relations and the ideal-gas equation, we have

$$c_p\, dT = c_v\, dT + RdT$$

Which, after dividing by dT, gives

$$c_p = c_v + R$$

Note that the difference between c_p and c_v for an ideal gas is always a constant, even though both are functions of temperature.

The **specific heat ratio k** is also a property of particular interest; it is defined as $\mathbf{k} = \dfrac{c_p}{c_v}$

And we have, from

$$c_p = R\,\frac{k}{k-1}$$

Or

$$c_v = \frac{R}{k-1}$$

For *incompressible substances* (liquids and solids), both the constant-pressure and constant-volume specific heats are identical and denoted by c:

$$C_p = C_v = C \qquad (kJ/kg.k)$$

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The first law applied to various processes

1-The Constant-Volume Process

The work for a constant-volume process is zero, since dV is zero. For such a process the first law becomes

$$Q = \Delta U$$

If tabulated values are available for a substance, we may directly determine ΔU. For a gas, approximated by an ideal gas, we would have

$$Q = m \int_{T_1}^{T_2} C_v \, dT$$

Or, for a process for which c_v is essentially constant,

$$Q = m \, c_v \, \Delta T$$

2-The Constant-Pressure Process

The first law, for a constant-pressure process, to be

$$Q = \Delta H$$

For a gas that behaves as an ideal gas, we have

$$Q = m \int_{T_1}^{T_2} C_p \, dT$$

For a process involving an ideal gas for which cp is constant there results

$$Q = mc_p \, \Delta T$$

3-The Constant-Temperature Process

Energy equation is

$$Q - W = \Delta U$$

For a gas that approximates an ideal gas, the internal energy depends only on the temperature and thus $\Delta U = 0$ for an isothermal process; for such a process

$$Q = W$$

Using the ideal-gas equation $PV = mRT$, the work can be found by

$$W = \int_{V_1}^{V_2} PdV = mRT\int_{V_1}^{V_2} \frac{dV}{V} = mRT \ln \frac{V_2}{V_1} = mRT \ln\frac{P_1}{P_2}$$

4-The Polytropic Process ($PV^{\,n}$ = const)

Energy equation is

$$Q - W = \Delta U$$

The work is calculated

$$W = \int_{V_1}^{V_2} PdV = P_1 V_1^n \int_{V_1}^{V_2} V^{-n} \, dV = \frac{P_2V_2 - P_1V_1}{1-n}$$

5- The Adiabatic Process (Q= 0)

The form of the first law for the adiabatic process is

$$- dw = du$$

By using $dw = Pdv$

$$du + Pdv = 0$$

For an ideal gas with constant specific heats.

$$C_v \, dT + \frac{RT}{v} \, dv = 0$$

Rearranging, we have

$$\frac{C_v}{R} \frac{dT}{T} = - \frac{dv}{v}$$

This is integrated, assuming constant c_u between states 1 and 2 to give

$$\frac{C_v}{R} In \frac{T_2}{T_1} = -In \frac{v_2}{v_1}$$

This can be put in the form,

$$\frac{T_2}{T_1} = (\frac{v_1}{v_2})^{R/C_v} = (\frac{v_1}{v_2})^{k-1}$$
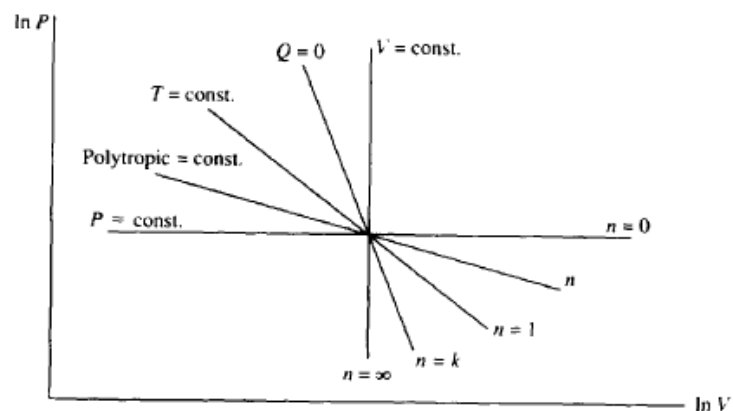
Using the ideal-gas law, this can be written as

$$\frac{T_2}{T_1} = (\frac{P_2}{P_1})^{(k-1)/k} = (\frac{v_1}{v_2})^{k-1} \quad ; \quad \frac{P_2}{P_1} = (\frac{v_1}{v_2})^k$$

Finally, the above three relations can be put in general forms, without reference to particular points.

$$Tv^{k-1} = const \qquad TP^{(1-k)/k} = const \qquad P \, v^k = const$$

Each process is associated with a particular value for **n** as follows:

Isothermal: **n = l**

Constant -volume: **n = ∞**

Constant-pressure: **n = 0**

Adiabatic: **n = k**

Polytropic exponents for various processes

5.75 A house is being designed to use a thick concrete floor mass as thermal storage material for solar energy heating. The concrete is 30 cm thick and the area exposed to the sun during the daytime is 4 m × 6 m. It is expected that this

mass will undergo an average temperature rise of about 3°C during the day. How much energy will be available for heating during the nighttime hours?

C.V. The mass of concrete.

Concrete is a solid with some properties listed in Table A.3

$V = 4 \times 6 \times 0.3 = 7.2 \text{ m}^3$;
$m = \rho V = 2200 \text{ kg/m}^3 \times 7.2 \text{ m}^3 = 15\,840 \text{ kg}$

From table A.3
$\Delta U = m \, C \, \Delta T = 15840 \text{ kg} \times 0.88 \text{ kJ/kg K} \times 3 \text{ K} = 41818 \text{ kJ} = \textbf{41.82 MJ}$

5.76 A copper block of volume 1 L is heat treated at 500°C and now cooled in a 200-L oil bath initially at 20°C. Assuming no heat transfers with the surroundings, what is the final temperature?

Properties from Table A.3 and A.4

$m_{met} = V\rho = 0.001 \text{ m}^3 \times 8300 \text{ kg/m}^3 = 8.3 \text{ kg}$,
$m_{oil} = V\rho = 0.2 \text{ m}^3 \times 910 \text{ kg/m}^3 = 182 \text{ kg}$

For Solid and liquid: $\Delta u \cong C_v \, \Delta T$,

Table A.3 and A.4: $C_{v\,met} = 0.42 \text{ kJ/kg K}$, $C_{v\,oil} = 1.8 \text{ kJ/kg K}$

The energy equation for the C.V. becomes

$m_{met}C_{v\,met}(T_2 - T_{1,met}) + m_{oil}C_{v\,oil}(T_2 - T_{1,oil}) = 0$
$8.3 \times 0.42(T_2 - 500) + 182 \times 1.8 \, (T_2 - 20) = 0$
$331.09 \, T_2 - 1743 - 6552 = 0$
$\Rightarrow T_2 = \textbf{25 °C}$

5.79 Saturated, x=1%, water at 25°C is contained in a hollow spherical aluminum vessel with inside diameter of 0.5 m and a 1-cm thick wall. The vessel is heated until the water inside is saturated vapor. Considering the vessel and water together as a control mass, calculate the heat transfer for the process.

State 1: $v_1 = 0.001003 + 0.01 \times 43.359 = 0.4346 \text{ m}^3/\text{kg}$
$u_1 = 104.88 + 0.01 \times 2304.9 = 127.9 \text{ kJ/kg}$

State 2: $x_2 = 1$ and constant volume so $v2 = v1 = V/m$
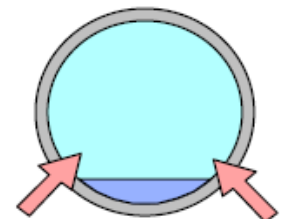
$v_{g\,T2} = v_1 = 0.4346 \Rightarrow T_2 = 146.1°C$; $u_2 = u_{G2} = 2555.9$

$V_{INSIDE} = \pi/6 \, (0.5)^3 = 0.06545 \text{ m}^3$; $m_{H2O} = 0.06545/0.4346 = 0.1506 \text{ kg}$

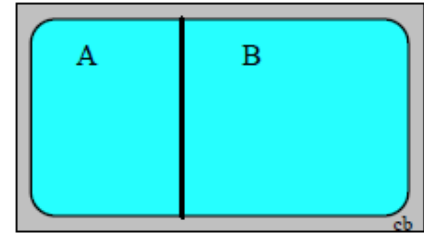$V_{alu} = \pi/6(\, (0.52)^3 - (0.5)^3) = 0.00817 \text{ m}^3$
$m_{alu} = \rho_{alu}V_{alu} = 2700 \times 0.00817 = 22.065 \text{ kg}$

From the energy equation

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$_1Q_2 = U_2 - U_1 = m_{H2O}(u_2 - u_1)_{H2O} + m_{alu}C_{v\,alu}(T_2 - T_1)$

$= 0.1506(2555.9 - 127.9) + 22.065 \times 0.9(146.1 - 25)$

$= $ **2770.6 kJ**

5.90 A rigid insulated tank is separated into two rooms by a stiff plate. Room A of 0.5 m3 contains air at 250 kPa, 300 K and room B of 1 m3 has air at 150 kPa, 1000 K. The plate is removed and the air comes to a uniform state without any heat transfer. Find the final pressure and temperature.

Ideal gas at 1: $m_A = P_{A1}V_A/RT_{A1} = 250 \times 0.5/(0.287 \times 300) = 1.452$ kg

$u_{A1} = 214.364$ kJ/kg from Table A.7

Ideal gas at 2: $m_B = P_{B1}V_B/RT_{B1} = 150 \times 1/(0.287 \times 1000) = 0.523$ kg

$u_{B1} = 759.189$ kJ/kg from Table A.7

$m_2 = m_A + m_B = 1.975$ kg

$U_2 - U_1 = m_2 u_2 - m_A u_{A1} - m_B u_{B1} = Q - W = 0$

$u_2 = m_A u_{A1} + m_B u_{B1} / m_2 = 1.452 \times 214.364 + 0.523 \times 759.189 / 1.975 = 358.64$ kJ/kg

$\Rightarrow$ Table A.7.1: **$T_2 = 498.4$ K**

$P_2 = m_2 RT_2 /V = 1.975 \times 0.287 \times 498.4/1.5 = $ **188.3 kPa**

5.93 A 10-m high cylinder, cross-sectional area 0.1 m^2, has a massless piston at the bottom with water at 20°C on top of it, shown in Figure. Air at 300 K, volume 0.3 m^3, under the piston is heated so that the piston moves up, spilling the water out over the side. Find the total heat transfer to the air when all the water has been pushed out.

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The water on top is compressed liquid and has volume and mass

$$V_{H_2O} = V_{tot} - V_{air} = 10 \times 0.1 - 0.3 = 0.7 \ m^3$$

$$m_{H_2O} = V_{H_2O}/v_f = 0.7 / 0.001002 = 698.6 \ kg$$

The initial air pressure is then

$$P_1 = P_0 + m_{H_2O}g/A = 101.325 + \frac{698.6 \times 9.807}{0.1 \times 1000} = 169.84 \ kPa$$

and then $m_{air} = PV/RT = \dfrac{169.84 \times 0.3}{0.287 \times 300} = 0.592 \ kg$

State 2: No liquid water over the piston so

$$P_2 = P_0 + 0 = 101.325 \ kPa, \quad V_2 = 10 \times 0.1 = 1 \ m^3$$

State 2: $P_2, V_2 \quad \Rightarrow \quad T_2 = \dfrac{T_1 P_2 V_2}{P_1 V_1} = \dfrac{300 \times 101.325 \times 1}{169.84 \times 0.3} = 596.59 \ K$

The process line shows the work as an area

$$_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{1}{2}(169.84 + 101.325)(1 - 0.3) = 94.91 \ kJ$$

The energy equation solved for the heat transfer becomes

$$_1Q_2 = m(u_2 - u_1) + {_1}W_2 \cong mC_v(T_2 - T_1) + {_1}W_2$$

$$= 0.592 \times 0.717 \times (596.59 - 300) + 94.91 = \mathbf{220.7 \ kJ}$$

Remark: we could have used u values from Table A.7:
$u_2 - u_1 = 432.5 - 214.36 = 218.14 \ kJ/kg$ versus $212.5 \ kJ/kg$ with Cv.

Mass and energy analysis of control volumes
1-Conservation of mass

For *closed systems*, the conservation of mass principle is implicitly used by requiring that the mass of the system remain constant during a process. For *control volumes (open system)*, however, mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.

Mass and volume flow rates

The amount of mass flowing through a cross section per unit time is called the **mass flow rate** and is denoted by ṁ. The dot over a symbol is used to indicate *time rate of change*.

$$\dot{m} = \rho A V \qquad \text{kg/s (where V = velocity)}$$

The mass and volume flow rates are related by

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$

Where *v* is the specific volume. This relation is similar to $m = \rho V = V/v$, which is the relation between the mass and the volume of a fluid in a container.

Conservation of mass principle

The **conservation of mass principle** for a control volume can be expressed as: *The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt.* That is,

$$\begin{pmatrix} \text{Total mass entering} \\ \text{the CV during } \Delta t \end{pmatrix} - \begin{pmatrix} \text{Total mass leaving} \\ \text{the CV during } \Delta t \end{pmatrix} = \begin{pmatrix} \text{Net change in mass} \\ \text{within the CV during } \Delta t \end{pmatrix}$$

$$m_{in} - m_{out} = \Delta m_{CV} \qquad \text{kg}$$

It can also be expressed in *rate form* as

$$\dot{m}_{in} - \dot{m}_{out} = dm_{cv}/dt \qquad \text{Kg/s}$$

Or

$$\frac{dm_{cv}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m} \qquad \text{Kg/s}$$

Where $\dot{m}_{in}$ and $\dot{m}_{out}$ are the total rates of mass flow into and out of the control volume, and dm_{CV}/dt is the time rate of change of mass within the control volume boundaries.

Mass balance for steady-flow processes

During a steady-flow process, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant). Then the conservation of mass principle requires that the total amount of mass entering a control volume equal the total amount of mass leaving it.

When dealing with steady-flow processes, we are not interested in the amount of mass that flows in or out of a device over time; instead, we are interested in the amount of mass flowing per unit time, that is, *the mass flow rate* $\dot{m}$.

$$\text{Steady flow}: \qquad \sum_{in}\dot{m} = \sum_{out}\dot{m} \quad \text{Kg/s}$$

Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet). For *single-stream steady-flow systems*, to
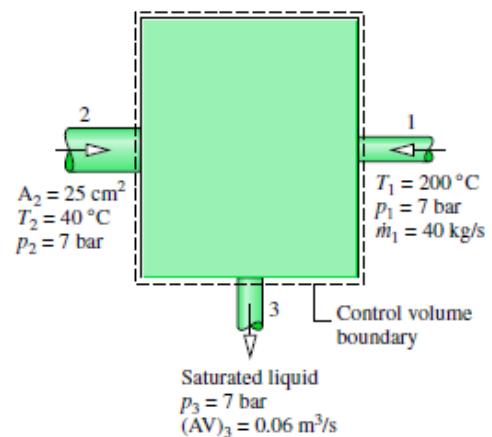
$$\text{Steady flow (single stream)}: \quad \dot{m}_1 = \dot{m}_2 \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

The conservation of mass relations can be simplified even further when the fluid is incompressible, which is usually the case for liquids. Canceling the density from both sides of the general steady-flow relation gives:

Steady, incompressible flow: $\qquad \sum_{in}\dot{V} = \sum_{out}\dot{V} \quad \text{m}^3/\text{s}$

Steady, incompressible flow (single stream): $\dot{V}_1 = \dot{V}_2 \rightarrow V_1 A_1 = V_2 A_2$

Ex: A feedwater heater operating at steady state has two inlets and one exit. At inlet 1, water vapor enters at $p_1 = 7$ bar, $T_1 = 200°C$ with a mass flow rate of 40 kg/s. At inlet 2, liquid water at $p_2 = 7$ bar, $T_2 = 40°C$ enters through an area $A_2 = 25$ cm². Saturated liquid at 7 bar exits at 3 with a volumetric flow rate of 0.06 m³/s. Determine the amass flow rates at inlet 2 and at the exit, in kg/s, and the velocity at inlet 2, in m/s.

From table

$v_2 = 1.0078 * 10^{-3}$ m³/kg

$v_3 = 1.108 * 10^{-3}$ m³/kg

$$dm_{cv}/dt = \dot{m}_{in} - \dot{m}_{out} = \dot{m}_1 + \dot{m}_2 - \dot{m}_3$$

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1$$

$$\dot{m}_3 = \frac{(AV)_3}{v_3} = \frac{0{,}06 \text{ m}^3/\text{s}}{1.108 * 10^{-3} \text{ m}^3/\text{kg}} = 54.15 \; kg/s$$

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1 = 54.15 - 40 = 14.15 \text{ kg /s}$$

$$V_2 = \dot{m}_2 v_2/A_2$$

$$V_2 = \frac{14.15 \text{ kg/s} * 1.0078 * 10^{-3} \text{ m}^3/\text{kg}}{25 * 10^{-4} \text{ m}} = 5.7 \; m/s$$
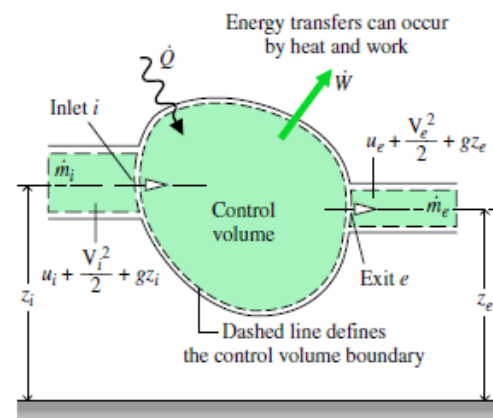
2- Conservation of Energy for a Control Volume

The *conservation of energy* principle applied to a control volume states:

$$
\begin{bmatrix} \text{time } rate\ of\ change \\ \text{of the energy} \\ \text{contained within} \\ \text{the control volume } at \\ time\ t \end{bmatrix} = \begin{bmatrix} \text{net } rate\ \text{at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \text{at time } t \end{bmatrix} - \begin{bmatrix} \text{net } rate\ \text{at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work } at \\ time\ t \end{bmatrix} + \begin{bmatrix} net\ \text{rate of energy} \\ \text{transfer } into\ \text{the} \\ \text{control volume} \\ \text{accompanying} \\ \text{mass flow} \end{bmatrix}
$$

For the one-inlet one-exit control volume with one-dimensional flow the energy rate balance is

$$
\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \dot{m}_i\left(u_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(u_e + \frac{V_e^2}{2} + gz_e\right)
$$

Where E_{cv} denotes the energy of the control volume at time t. The terms and account, respectively, for the net rate of energy transfer by heat and work across the boundary of the control volume at t.

Evaluating work for a control volume

Because work is always done on or by a control volume where matter flows across the boundary, it is convenient to separate the work term $\dot{W}$ into *two contributions:* One contribution is the work associated with the fluid pressure as mass is introduced at inlets and removed at exits. The other contribution, denoted by includes *all other* work effects, such as those associated with rotating shafts, displacement of the boundary, and electrical effects

The *rate* at which work is done at the exit by the normal force (normal to the exit area in the direction of flow) due to pressure is the product of the normal force, $p_e A_e$, and the fluid velocity, V_e. That is

$$\begin{bmatrix} \text{time rate of energy transfer} \\ \text{by work } \textit{from} \text{ the control} \\ \text{volume at exit } e \end{bmatrix} = (p_e A_e) V_e$$

Where p_e is the pressure, A_e is the area, and V_e is the velocity at exit e, respectively. A similar expression can be written for the rate of energy transfer by work into the control volume at inlet i.

The work term $\dot{W}$ of the energy rate can be written as.

$$\dot{W} = \dot{W}_{cv} + (p_e A_e) V_e - (p_i A_i) V_i$$

$$\dot{W} = \dot{W}_{cv} + \dot{m}_e (p_e v_e) - \dot{m}_i (p_i v_i)$$

Forms of the Control Volume Energy Rate Balance

Collecting all terms referring to the inlet and the exit into separate expressions, the following form of the control volume energy rate balance results.

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i \left(u_i + p_i v_i + \frac{V_i^2}{2} + g z_i \right) - \dot{m}_e \left(u_e + p_e v_e + \frac{V_e^2}{2} + g z_e \right)$$

With $h = u + pv$, the energy rate balance becomes

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g z_i \right) - \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e \right)$$

In practice there may be several locations on the boundary through which mass enters or exits. This can be accounted for by introducing summations as in the mass balance. Accordingly, the *energy rate balance* is

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e \right)$$

Steady-State Forms of the Mass and Energy Rate Balances

For a control volume at steady state, the conditions of the mass within the control volume and at the boundary do not vary with time. The mass flow rates and the rates of energy transfer by heat and work are also constant with time. There can be no accumulation of mass within the control volume, so $dm_{cv}/dt = 0$ and the mass rate balance, takes the form

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e$$

(mass rate in)   (mass rate out)

Furthermore, at steady state $dE_{cv}/dt = 0$, so energy Eq. can be written as

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

Or

$$\dot{Q}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{W}_{cv} + \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

(energy rate in)   (energy rate out)

Many important applications involve one-inlet, one-exit control volumes at steady state. It is instructive to apply the mass and energy rate balances to this special case. The mass rate balance reduces simply to $\dot{m}_1 = \dot{m}_2$ .The common mass flow rate is designated simply by $\dot{m}_2$. Next, applying the energy rate balance and factoring the mass flow rate gives

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$$

If the kinetic energy and potential energy changes are negligible, the first law then takes the simplified form

$$\dot{Q} - \dot{W}_s = \dot{m}(h_2 - h_1)$$

$$q - w_s = h_2 - h_1$$

Where $q = \dot{Q} / \dot{m}$ and $w_s = \dot{W}_s/\dot{m}$. This simplified form of the energy equation has a surprisingly large number of applications.

Some steady-flow engineering devices
1 - Nozzles and diffusers

A **nozzle** is a device that *increases the velocity of a fluid* at the expense of pressure. A **diffuser** is a device that *increases the pressure of a fluid* by slowing it down. That is, nozzles and diffusers perform opposite tasks.

The rate of heat transfer between the fluid flowing through a nozzle or a diffuser and the surroundings is usually very small ($\dot{Q} = 0$). Nozzles and diffusers typically involve no work ($\dot{W} = 0$) and any change in potential energy is negligible ($\Delta pe = 0$). Energy equation takes the form

$$0 = \frac{V_2^2}{2} - \frac{V_1^2}{2} + h_2 - h_1$$

6.31 A nozzle receives 0.1 kg/s steam at 1 MPa, 400°C with negligible kinetic energy. The exit is at 500 kPa, 350°C and the flow is adiabatic. Find the nozzle exit velocity and the exit area.

Energy Eq.6.13: $h_1 + \frac{1}{2}V_1^2 + gZ_1 = h_2 + \frac{1}{2}V_2^2 + gZ_2$

Process: $Z_1 = Z_2$

State 1: $V_1 = 0$, Table B.1.3 $h_1 = 3263.88$ kJ/kg

State 2: Table B.1.3 $h_2 = 3167.65$ kJ/kg
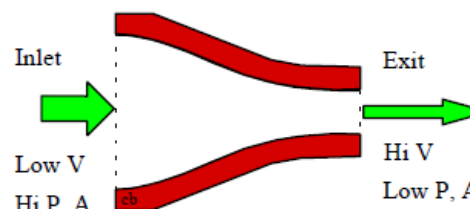
Then from the energy equation

$$\frac{1}{2}V_2^2 = h_1 - h_2 = 3263.88 - 3167.65 = 96.23 \text{ kJ/kg}$$

$$V_2 = \sqrt{2(h_1 - h_2)} = \sqrt{2 \times 96.23 \times 1000} = 438.7 \text{ m/s}$$

The mass flow rate from Eq.6.3

$$\dot{m} = \rho AV = AV/v$$

$$A = \dot{m}v/V = 0.1 \times 0.57012 / 438.7 = 0.00013 \text{ m}^2 = 1.3 \text{ cm}^2$$

6.36 A diffuser, shown in Figure, has air entering at 100 kPa, 300 K, with a velocity of 200 m/s. The inlet cross-sectional area of the diffuser is 100 mm². At the exit, the area is 860 mm², and the exit velocity is 20 m/s. Determine the exit pressure and temperature of the air.

Continuity Eq.6.3: $\dot{m}_i = A_i V_i / v_i = \dot{m}_e = A_e V_e / v_e$,

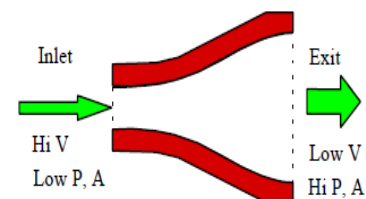Energy Eq.(per unit mass flow)6.13: $h_i + \frac{1}{2}V_i^2 = h_e + \frac{1}{2}V_e^2$

$$h_e - h_i = \frac{1}{2} \times 200^2/1000 - \frac{1}{2} \times 20^2/1000 = 19.8 \text{ kJ/kg}$$

$$T_e = T_i + (h_e - h_i)/C_p = 300 + 19.8/1.004 = 319.72 \text{ K}$$

Now use the continuity equation and the ideal gas law

$$v_e = v_i \left(\frac{A_e V_e}{A_i V_i}\right) = (RT_i/P_i)\left(\frac{A_e V_e}{A_i V_i}\right) = RT_e/P_e$$

$$P_e = P_i \left(\frac{T_e}{T_i}\right)\left(\frac{A_i V_i}{A_e V_e}\right) = 100 \left(\frac{319.72}{300}\right)\left(\frac{100 \times 200}{860 \times 20}\right) = 123.92 \text{ kPa}$$

2 -Turbines and Compressors

As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft. As a result, the shaft rotates, and the turbine produces work.

Compressors, as well as pumps and fans, are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft. Therefore, compressors involve work inputs. Even though these three devices function similarly, they do differ in the tasks they perform. A *fan* increases the pressure of a gas slightly and is mainly used to mobilize a gas. A *compressor* is capable of compressing the gas to very high pressures. *Pumps* work very much like compressors except that they handle liquids instead of gases. Note that turbines produce power output whereas compressors, pumps, and fans require power input.

Heat transfer from turbines is usually negligible ($\dot{Q} = 0$) since they are typically well insulated. Heat transfer is also negligible for compressors unless there is intentional cooling. Potential energy changes are negligible for all of these devices (pe = 0). The velocities involved in these devices, with the exception of turbines and fans, are usually too low to cause any significant change in the kinetic energy (ke = 0). The fluid velocities encountered in most turbines are very high, and the fluid experiences a significant change in its kinetic energy. However, this change is usually very small relative to the change in enthalpy, and thus it is often disregarded.

6.48: A steam turbine has an inlet of 2 kg/s water at 1000 kPa, 350°C and velocity of 15 m/s. The exit is at 100 kPa, x = 1 and very low velocity. Find the specific work and the power produced.
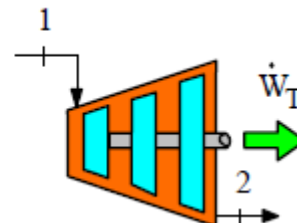
Energy Eq.6.13: $h_1 + \frac{1}{2}V_1^2 + gZ_1 = h_2 + \frac{1}{2}V_2^2 + gZ_2 + w_T$

Process: $Z_1 = Z_2$ and $V_2 = 0$

Table B.1.3: $h_1 = 3157.65 \text{ kJ/kg}$, $h_2 = 2675.46 \text{ kJ/kg}$

$$w_T = h_1 + \frac{1}{2}V_1^2 - h_2 = 3157.65 + 15^2 / 2000 - 2675.46 = \textbf{482.3 kJ/kg}$$

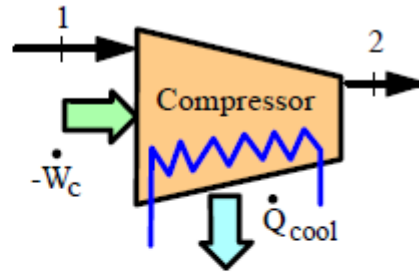$$\dot{W}_T = \dot{m} \times w_T = 2 \times 482.3 = \textbf{964.6 kW}$$

6.57: A compressor brings R-134a from 150 kPa, -10°C to 1200 kPa, 50°C. It is water cooled with a heat loss estimated as 40 kW and the shaft work input is measured to be 150 kW. How much is the mass flow rate through the compressor?

C.V Compressor. Steady flow.
Neglect kinetic and potential energies.

Energy : $\dot{m}\, h_i + \dot{Q} = \dot{m} h_e + \dot{W}$

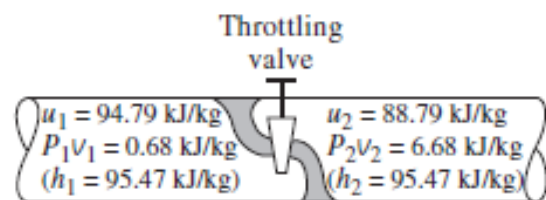$\dot{m} = (\dot{Q} - \dot{W})/(h_e - h_i)$

Look in table B.5.2

$h_i = 393.84$ kJ/kg, $h_e = 426.84$ kJ/kg

$\dot{m} = \dfrac{-40 - (-150)}{426.84 - 393.84} = 3.333$ kg/s

3 - Throttling Valves

Throttling valves are *any kind of flow-restricting devices* that cause a significant pressure drop in the fluid. The pressure drop in the fluid is often accompanied by a *large drop in temperature*, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications. The sudden drop in pressure causes a change in phase of the working substance.

Throttling valves are usually small devices, and the flow through them may be assumed to be adiabatic ($q = 0$) since there is neither sufficient time nor large enough area for any effective heat transfer to take place. Also, there is no work done ($w = 0$), and the change in potential energy, if any, is very small (pe $= 0$). Even though the exit velocity is often considerably higher than the inlet velocity, in many cases, the increase in kinetic energy is insignificant (ke $= 0$). Then the conservation of energy equation for this single-stream steady-flow device reduces to

$$h_2 = h_1 \qquad \text{(kJ/kg)}$$

6.46 R-134a is throttled in a line flowing at 25°C, 750 kPa with negligible kinetic energy to a pressure of 165 kPa. Find the exit temperature and the ratio of exit pipe diameter to that of the inlet pipe (D_{ex}/D_{in}) so the velocity stays constant.

Energy Eq.6.13: $h_1 + \frac{1}{2} V_1^2 + gZ_1 = h_2 + \frac{1}{2} V_2^2 + gZ_2$

Process: $Z_1 = Z_2$ and $V_2 = V_1$

State 1, Table B.5.1: $h_1 = 234.59$ kJ/kg, $v_1 = v_f = 0.000829$ m^3/kg

Use energy eq.: $\Rightarrow$ $h_2 = h_1 = 234.59$ kJ/kg

State 2: P_2 & h_2 $\Rightarrow$ 2 – phase and $T_2 = T_{sat}$ (165 kPa) = -15°C

$h_2 = h_f + x_2 \, h_{fg}$ = 234.59 kJ/kg

$x_2 = (h_2 - h_f) / h_{fg} = (234.59 - 180.19) / 209 = 0.2603$

$v_2 = v_f + x_2 \times v_{fg} = 0.000746 + 0.2603 \times 0.11932 = 0.0318$ m³/kg

Now the continuity equation with $V_2 = V_1$ gives, from Eq.6.3,

$$\dot{m} = \rho AV = AV/v = A_1 V_1 / v_1 = (A_2 \, V_1) / v_2$$
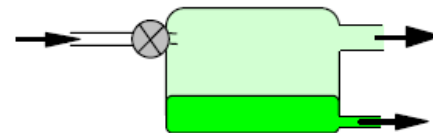
$$(A_2 / A_1) = v_2 / v_1 = (D_2 / D_1)^2$$

$$(D_2/D_1) = (v_2 / v_1)^{0.5} = (0.0318 / 0.000829)^{0.5} = 6.19$$

6.44 Liquid water at 180°C, 2000 kPa is throttled into a flash evaporator chamber having a pressure of 500 kPa. Neglect any change in the kinetic energy. What is the fraction of liquid and vapor in the chamber?

Energy Eq.6.13: $h_1 + \frac{1}{2} V_1^2 + gZ_1 = h_2 + \frac{1}{2} V_2^2 + gZ_2$

Process: $Z_1 = Z_2$ and $V_2 = V_1$

$\Rightarrow$ $h_2 = h_1$ = 763.71 kJ/kg from Table B.1.4

State 2: P_2 & h_2 $\Rightarrow$ 2 – phase

$h_2 = h_f + x_2 \, h_{fg}$

$x_2 = (h_2 - h_f) / h_{fg} = \dfrac{763.71 - 640.21}{2108.47} = 0.0586$

Two-phase out of the valve. The liquid drops to the bottom.

Fraction of Vapor: x_2 = 0.0586   (5.86 %)

Liquid: 1 - x_2 = 0.941   (94.1 %)

4- Heat Exchangers

As the name implies, **heat exchangers** are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries, and they come in various designs.

The simplest form of a heat exchanger is a *double-tube heat exchanger*, shown in Figure. It is composed of two concentric pipes of different diameters. One fluid flows in the inner pipe, and the other in the annular space between the two pipes. Heat is transferred from the hot fluid to the cold one through the wall separating them. Sometimes the

inner tube makes a couple of turns inside the shell to increase the heat transfer area, and thus the rate of heat transfer.

The conservation of mass principle for a heat exchanger in steady operation requires that the sum of the inbound mass flow rates equal the sum of the outbound mass flow rates. This principle can also be expressed as follows: *Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.*

Heat exchangers typically involve no work interactions ($w = 0$) and negligible kinetic and potential energy changes ($\Delta ke = 0$, $\Delta pe = 0$) for each fluid stream. The heat transfer rate associated with heat exchangers depends on how the control volume is selected. Heat exchangers are intended for heat transfer between two fluids *within* the device, and the outer shell is usually well insulated to prevent any heat loss to the surrounding medium.

6.84 A condenser (heat exchanger) brings 1 kg/s water flow at 10 kPa from 300°C to saturated liquid at 10 kPa, as shown in Fig. P6.84. the cooling is done by lake water at 20°C that returns to the lake at 30°C. For an insulated condenser, find the flow rate of cooling water.

C.V. Heat exchanger

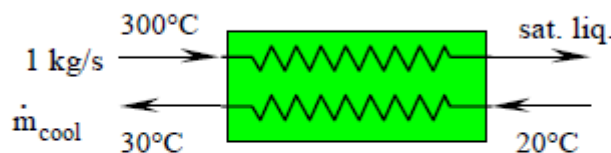Energy Eq.6.10: $\dot{m}_{cool}h_{20} + \dot{m}_{H_2O}h_{300} = \dot{m}_{cool}h_{30} + \dot{m}_{H_2O}h_{f,\,10\,kPa}$

Table B.1.1: $h_{20} = 83.96$ kJ/kg , $h_{30} = 125.79$ kJ/kg

Table B.1.3: $h_{300,\,10kPa} = 3076.5$ kJ/kg, B.1.2: $h_{f,\,10\,kPa} = 191.83$ kJ/kg

$$\dot{m}_{cool} = \dot{m}_{H_2O}\frac{h_{300} - h_{f,\,10kPa}}{h_{30} - h_{20}} = 1 \times \frac{3076.5 - 191.83}{125.79 - 83.96} = 69 \text{ kg/s}$$

6.90 A copper wire has been heat treated to 1000 K and is now pulled into a cooling chamber that has 1.5 kg/s air coming in at 20°C; the air leaves the other end at 60°C. If the wire moves 0.25 kg/s copper, how hot is the copper as it comes out?

C.V. Total chamber, no external heat transfer

Energy eq.:
$$\dot{m}_{cu}\, h_{i\,cu} + \dot{m}_{air}\, h_{i\,air} = \dot{m}_{cu}\, h_{e\,cu} + \dot{m}_{air}\, h_{e\,air}$$

$$\dot{m}_{cu}\,(h_e - h_i)_{cu} = \dot{m}_{air}(h_i - h_e)_{air}$$

$$\dot{m}_{cu}\, C_{cu}\,(T_e - T_i)_{cu} = \dot{m}_{air}\, C_{p\,air}(T_e - T_i)_{air}$$

Heat capacities from A.3 for copper and A.5 for air

$$(T_e - T_i)_{cu} = \frac{\dot{m}_{air} C_{p\,air}}{\dot{m}_{cu} C_{cu}}(T_e - T_i)_{air} = \frac{1.5 \times 1.004}{0.25 \times 0.42}(20 - 60) = -573.7\ K$$

$$T_e = T_i - 573.7 = 1000 - 573.7 = \mathbf{426.3\ K}$$

5- Mixing Chambers

The section where the mixing process takes place is commonly referred to as a **mixing chamber.** The mixing chamber does not have to be a distinct "chamber." An ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams. Then all there is left in the energy equation is the total energies of the incoming streams and the outgoing mixture.

6.85 A cooler in an air conditioner brings 0.5 kg/s air at 35°C to 5°C, both at 101 kPa and it then mix the output with a flow of 0.25 kg/s air at 20°C, 101 kPa sending the combined flow into a duct. Find the total heat transfer in the cooler and the temperature in the duct flow.

Cooler section   Mixing section

C.V. Cooler section (no W)

Energy Eq.6.12:
$$\dot{m} h_1 = \dot{m} h_2 + \dot{Q}_{cool}$$

$$\dot{Q}_{cool} = \dot{m}(h_1 - h_2) = \dot{m}\, C_p\,(T_1 - T_2) = 0.5 \times 1.004 \times (35\text{-}5) = 15.06\ kW$$

C.V. mixing section (no $\dot{W}, \dot{Q}$)

Continuity Eq.:
$$\dot{m}_2 + \dot{m}_3 = \dot{m}_4$$

Energy Eq.6.10: $\dot{m}_2 h_2 + \dot{m}_3 h_3 = \dot{m}_4 h_4$

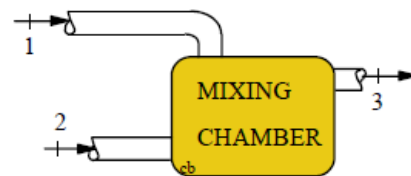$\dot{m}_4 = \dot{m}_2 + \dot{m}_3 = 0.5 + 0.25 = 0.75$ kg/s

$\dot{m}_4 h_4 = (\dot{m}_2 + \dot{m}_3) h_4 = \dot{m}_2 h_2 + \dot{m}_3 h_3$

$\dot{m}_2 (h_4 - h_2) + \dot{m}_3 (h_4 - h_3) = \emptyset$

$\dot{m}_2 C_p (T_4 - T_2) + \dot{m}_3 C_p (T_4 - T_3) = \emptyset$

$T_4 = (\dot{m}_2 / \dot{m}_4) T_2 + (\dot{m}_3 / \dot{m}_4) T_3 = 5(0.5/0.75) + 20(0.25/0.75) = 10°C$

6.91 An open feedwater heater in a power plant heats 4 kg/s water at 45°C, 100 kPa by mixing it with steam from the turbine at 100 kPa, 250°C. Assume the exit flow is saturated liquid at the given pressure and find the mass flow rate from the turbine.

C.V.   Feedwater heater.

No external $\dot{Q}$ or $\dot{W}$

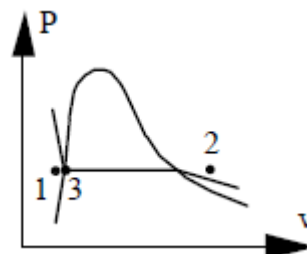Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

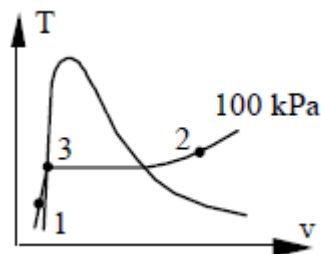Energy Eq.6.10: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 = (\dot{m}_1 + \dot{m}_2) h_3$

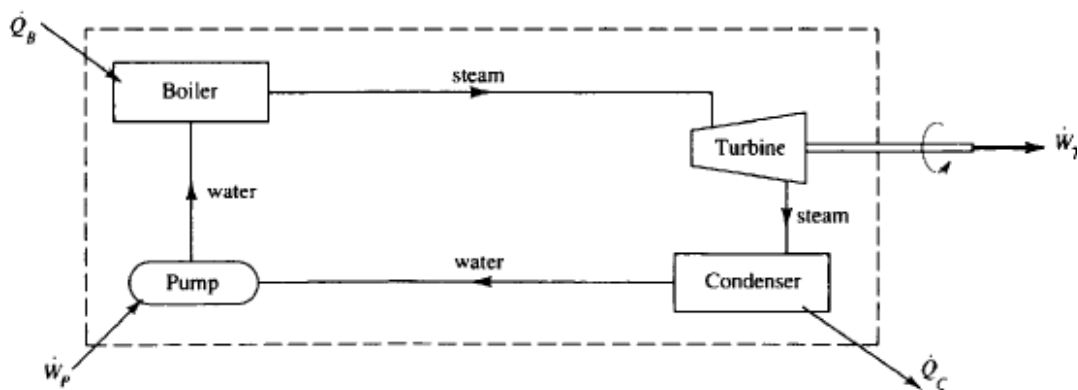| State 1: | Table B.1.1 | $h = h_f = 188.42$ kJ/kg at 45°C |
| State 2: | Table B.1.3 | $h_2 = 2974.33$ kJ/kg |
| State 3: | Table B.1.2 | $h_3 = h_f = 417.44$ kJ/kg at 100 kPa |

$$\dot{m}_2 = \dot{m}_1 \times \frac{h_1 - h_3}{h_3 - h_2} = 4 \times \frac{188.42 - 417.44}{417.44 - 2974.33} = 0.358 \text{ kg/s}$$
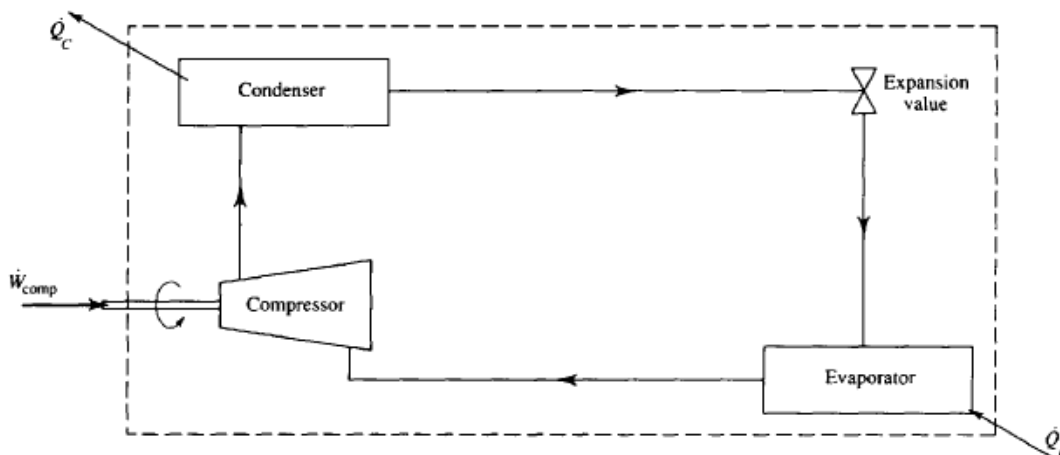
System integration (*Power plant and Refrigeration Cycles***)**

When energy in the form of heat is transferred to a working fluid, energy in the form of work may be extracted from the working fluid. The work may be converted to an electrical form of energy, such as is done in a power plant, or to a mechanical form, such as is done in an automobile. In general, such conversions of energy are accomplished by a power cycle. One such cycle is shown in Figure. In the boiler (a heat exchanger) the energy contained in a fuel is transferred by heat to the water which enters, causing a high-pressure steam to exit and enter the turbine. **A** condenser (another heat exchanger) discharges heat, and a pump increases the pressure lost through the turbine.

Other components can be combined in an arrangement like that shown in

Figure, resulting in a refrigeration cycle. Heat is transferred to the working fluid (the refrigerant) in the evaporator (a heat exchanger). The working fluid is then compressed by the compressor. Heat is transferred from the working fluid in the condenser, and then its pressure is suddenly reduced in the expansion valve. A refrigeration cycle may be used to add energy to a body (heat transfer $\dot{Q}_c$) or it may be used to extract energy from a body (heat transfer $\dot{Q}_E$).

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6.105 A proposal is made to use a geothermal supply of hot water to operate a steam turbine, as shown in Figure. The high-pressure water at 1.5 MPa, 180°C, is throttled into a flash evaporator chamber, which forms liquid and vapor at a lower pressure of 400 kPa. The liquid is discarded while the saturated vapor feeds the turbine and exits at 10 kPa, 90% quality. If the turbine should produce 1 MW, find the required mass flow rate of hot geothermal water in kilograms per hour.

Separation of phases in flash-evaporator constant h in the valve flow so
Table B.1.3 & B.1.1: h_{1f} = 763.5 kJ/kg & at P = 400 kpa from table B.1.2

$$h_1 = 763.5 = 604.74 + x \times 2133.8 \rightarrow x = 0.07439 = \dot{m}_2/\dot{m}_1$$

Table B.1.2: h_{2g} = 2738.6 kJ/kg;

$$h_3 = 191.83 + 0.9 \times 2392.8 = 2345\backslash.4 \text{ kJ/kg}$$

$$\dot{W} = \dot{m}_2(h_2 - h_3) \rightarrow \dot{m}_2 = \frac{1000}{2738.6 - 2345.4} = 2.543 \text{ kg/s} \rightarrow$$
$$\dot{m}_1 = \dot{m}_2/x = 34.19 \text{ kg/s} = \textbf{123 075 kg/h}$$

6.99 The following data are for a simple steam power plant as shown in Fig.

State	1	2	3	4	5	6	7
P MPa	6.2	6.1	5.9	5.7	5.5	0.01	0.009
T °C		45	175	500	490		40
h kJ/kg	-	194	744	3426	3404	-	168

State 6 has $x_6 = 0.92$, and velocity of 200 m/s. The rate of steam flow is 25 kg/s, with 300 kW power input to the pump. Piping diameters are 200 mm from steam generator to the turbine and 75 mm from the condenser to the steam generator. Determine the velocity at state 5 and the power output of the turbine.

Turbine $A_5 = (\pi/4)(0.2)^2 = 0.031\ 42\ m^2$

$V_5 = \dot{m}v_5/A_5 = 25 \times 0.061\ 63 / 0.031\ 42 = \textbf{49 m/s}$

$h_6 = 191.83 + 0.92 \times 2392.8 = 2393.2\ kJ/kg$

$w_T = h_5 - h_6 + \frac{1}{2}(V_5^2 - V_6^2)$

$= 3404 - 2393.2 + (49^2 - 200^2)/(2 \times 1000) = 992\ kJ/kg$

$\dot{W}_T = \dot{m}w_T = 25 \times 992 = \textbf{24 800 kW}$

6.100 assume the cooling water comes from a lake at 15°C and is returned at 25°C. Determine the rate of heat transfer in the condenser and the mass flow rate of cooling water from the lake.

Condenser $A_7 = (\pi/4)(0.075)^2 = 0.004\ 418\ m^2$, $v_7 = 0.001\ 008\ m^3/kg$

$V_7 = \dot{m}v_7/A_7 = 25 \times 0.001\ 008 / 0.004\ 418 = 5.7\ m/s$

$h_6 = 191.83 + 0.92 \times 2392.8 = 2393.2\ kJ/kg$

$q_{COND} = h_7 - h_6 + \frac{1}{2}(V_7^2 - V_6^2)$

$= 168 - 2393.2 + (5.7^2 - 200^2)/(2 \times 1000) = -2245.2\ kJ/kg$

$\dot{Q}_{COND} = 25 \times (-2245.2) = \textbf{-56 130 kW}$

This rate of heat transfer is carried away by the cooling water so

$-\dot{Q}_{COND} = \dot{m}_{H_2O}(h_{out} - h_{in})_{H_2O} = 56\ 130\ kW$

$\Rightarrow \quad \dot{m}_{H_2O} = \dfrac{56\ 130}{104.9 - 63.0} = \textbf{1339.6 kg/s}$

6.101 determine the rate of heat transfer in the economizer, which is a low temperature heat exchanger. Find also the rate of heat transfer needed in the steam generator.

Economizer $A_7 = \pi D_7^2/4 = 0.004\ 418\ m^2$, $v_7 = 0.001\ 008\ m^3/kg$

$V_2 = V_7 = \dot{m}v_7/A_7 = 25 \times 0.001\ 008/0.004\ 418 = 5.7\ m/s$,

$V_3 = (v_3/v_2)V_2 = (0.001\ 118 / 0.001\ 008)\ 5.7 = 6.3\ m/s \approx V_2$

so kinetic energy change unimportant

$q_{ECON} = h_3 - h_2 = 744 - 194 = 550.0\ kJ/kg$

$\dot{Q}_{ECON} = \dot{m}q_{ECON} = 25\ (550.0) = \textbf{13 750 kW}$

Generator $\quad A_4 = \pi D_4^2/4 = 0.031\ 42\ m^2, \quad v_4 = 0.060\ 23\ m^3/kg$

$V_4 = \dot{m}v_4/A_4 = 25 \times 0.060\ 23/0.031\ 42 = 47.9\ m/s$
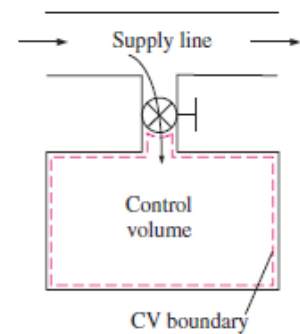
$q_{GEN} = 3426 - 744 + (47.9^2 - 6.3^2)/(2\times1000) = 2683\ kJ/kg$

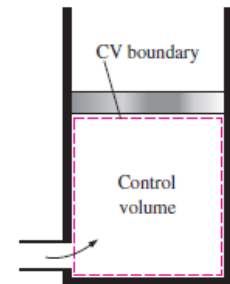$\dot{Q}_{GEN} = \dot{m}q_{GEN} = 25 \times (2683) = \mathbf{67\ 075\ kW}$

Energy analysis of unsteady-flow Processes (Transient processes)

Many processes of interest, however, involve *changes* within the control volume with time. Such processes are called *unsteady-flow,* or *transient flow,* processes. The steady-flow relations developed earlier are obviously not applicable to these processes. When an unsteady-flow process is analyzed, it is important to keep track of the mass and energy contents of the control volume as well as the energy interactions across the boundary.

Some familiar unsteady-flow processes are the charging of rigid vessels from supply lines (Figure below), discharging a fluid from a pressurized vessel, driving a gas turbine with pressurized air stored in a large container, inflating tires or balloons, and even cooking with an ordinary pressure cooker. Unlike steady-flow processes, unsteady-flow processes start and end over some finite time period instead of continuing indefinitely. Therefore in this section, we deal with changes that occur over some time interval Δt instead of with the rate of changes (changes per unit time). An unsteady-flow system, in some respects, is similar to a closed system, except that the mass within the system boundaries does not remain constant during a process.

Another difference between steady- and unsteady-flow systems is that steady-flow systems are fixed in space, size, and shape. Unsteady-flow systems, however, are not. They are usually stationary; that is, they are fixed in space, but they may involve moving boundaries and thus boundary work.

The *mass balance* for any system undergoing any process can be expressed as:

$$m_{in} - m_{out} = \Delta m_{system}$$

Where $\Delta m_{system} = m_{final} - m_{initial}$ is the change in the mass of the system. For control volumes, it can also be expressed more explicitly as

$$m_i - m_e = (m_2 - m_1)_{CV}$$

Where i = inlet, e = exit, 1 = initial state, and 2 = final state of the control volume. Often one or more terms in the equation above are zero. For example, $m_i = 0$ if no mass enters the control volume during the process, $m_e = 0$ if no mass leaves, and $m_1 = 0$ if the control volume is initially evacuated.

When analyzing an unsteady-flow process, we must keep track of the energy content of the control volume as well as the energies of the incoming and outgoing flow streams.

The energy balance for a uniform-flow system can be expressed as

$$\dot{Q}_{C.V.} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gZ_i \right) = \frac{dE_{C.V.}}{dt} + \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gZ_e \right) + \dot{W}_{C.V.}$$

$$\dot{Q}_{C.V.} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gZ_i \right) = \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gZ_e \right) + \frac{d}{dt} \left[m \left(u + \frac{V^2}{2} + gZ \right) \right]_{C.V.} + \dot{W}_{C.V.}$$

for this period of time t, we can write the first law for the transient process as

$$Q_{C.V.} + \sum m_i \left(h_i + \frac{V_i^2}{2} + gZ_i \right) = \sum m_e \left(h_e + \frac{V_e^2}{2} + gZ_e \right)$$
$$+ \left[m_2 \left(u_2 + \frac{V_2^2}{2} + gZ_2 \right) - m_1 \left(u_1 + \frac{V_1^2}{2} + gZ_1 \right) \right]_{C.V.} + W_{C.V.}$$

When the kinetic and potential energy changes associated with the control volume and fluid streams are negligible, as is usually the case, the energy balance above simplifies to

$$Q - W = \sum_{out} mh - \sum_{in} mh + (m_2 u_2 - m_1 u_1)_{system}$$

If no mass enters or leaves the control volume during a process ($m_i = m_e = 0$, and $m_1 = m_2 = m$), this equation reduces to the energy balance relation for closed systems

6.108 A 1-m³, 40-kg rigid steel tank contains air at 500 kPa, and both tank and air are at 20°C. The tank is connected to a line flowing air at 2 MPa, 20°C. The valve is opened, allowing air to flow into the tank until the pressure reaches 1.5 MPa and is then closed. Assume the air and tank are always at the same temperature and the final temperature is 35°C. Find the final air mass and the heat transfer.

Control volume: Air and the steel tank.

Continuity Eq : $m_2 - m_1 = m_i$

Energy Eq : $(m_2 u_2 - m_1 u_1)_{AIR} + m_{ST}(u_2 - u_1)_{ST} = m_i h_i + {}_1 Q_2$

$$m_{1 \, AIR} = \frac{P_1 V}{RT_1} = \frac{500 \times 1}{0.287 \times 293.2} = 5.94 \text{ kg}$$

$$m_{2 \, AIR} = \frac{P_2 V}{RT_2} = \frac{1500 \times 1}{0.287 \times 308.2} = \textbf{16.96 kg}$$

$$m_i = (m_2 - m_1)_{AIR} = 16.96 - 5.94 = 11.02 \text{ kg}$$

The energy equation now gives

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$$_1Q_2 = (m_2u_2 - m_1u_1)_{AIR} + m_{ST}(u_2 - u_1)_{ST} - m_ih_i$$

$$= m_1(u_2 - u_1) + m_i(u_2 - u_i - RT_i) + m_{ST}C_{ST}(T_2 - T_1)$$

$$\cong m_1C_v(T_2 - T_1) + m_i[C_v(T_2 - T_i) - RT_i] + m_{ST}C_{ST}(T_2 - T_1)$$

$$= 5.94 \times 0.717(35 - 20) + 11.02[0.717(35 - 20) - 0.287 \times 293.2]$$

$$+ 40 \times 0.46(35 - 20)$$

$$= 63.885 - 808.795 + 276$$

$$= -468.9 \text{ kJ}$$

6.109 An evacuated 150-L tank is connected to a line flowing air at room temperature, 25°C, and 8 MPa pressure. The valve is opened allowing air to flow into the tank until the pressure inside is 6 MPa. At this point the valve is closed. This filling process occurs rapidly and is essentially adiabatic. The tank is then placed in storage where it eventually returns to room temperature. What is the final pressure?

C.V. Tank:

Continuity Eq.6.15: $m_i = m_2$

Energy Eq.6.16: $m_ih_i = m_2u_2$ => $u_2 = h_i$

Use constant specific heat C_{Po} from table A.5 then energy equation:

$$T_2 = (C_P/C_V) T_i = kT_i = 1.4 \times 298.2 = 417.5 \text{ K}$$

Process: constant volume cooling to T_3:

$$P_3 = P_2 \times T_3/T_2 = 6.0 \times 298.15/ 417.5 = \textbf{4.29 MPa}$$
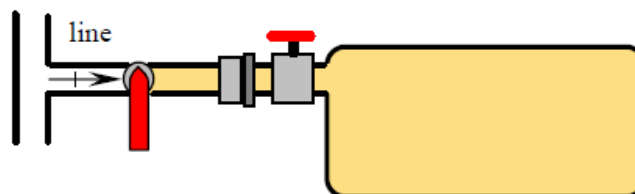
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TABLE 6.1
Typical Steady-Flow Devices

Device	Purpose	Given	Assumption
Aftercooler	Cool a flow after a compressor	$w = 0$	P = constant
Boiler	Bring substance to a vapor state	$w = 0$	P = constant
Condenser	Take q out to bring substance to liquid state	$w = 0$	P = constant
Combustor	Burn fuel; acts like heat transfer in	$w = 0$	P = constant
Compressor	Bring a substance to higher pressure	w in	$q = 0$
Deaerator	Remove gases dissolved in liquids	$w = 0$	P = constant
Dehumidifier	Remove water from air		P = constant
Desuperheater	Add liquid water to superheated vapor steam to make it saturated vapor	$w = 0$	P = constant
Diffuser	Convert KE energy to higher P	$w = 0$	$q = 0$
Economizer	Low-T, low-P heat exchanger	$w = 0$	P = constant
Evaporator	Bring a substance to vapor state	$w = 0$	P = constant
Expander	Similar to a turbine, but may have a q		
Fan/blower	Move a substance, typically air	w in, KE up	$P = C$, $q = 0$
Feedwater heater	Heat liquid water with another flow	$w = 0$	P = constant
Flash evaporator	Generate vapor by expansion (throttling)	$w = 0$	$q = 0$
Heat engine	A device that converts part of heat into work	q in, w out	
Heat exchanger	Transfer heat from one medium to another	$w = 0$	P = constant
Heat pump	A device moving a Q from T_{low} to T_{high}, requires a work input, refrigerator	w in	
Heater	Heat a substance	$w = 0$	P = constant
Humidifier	Add water to air–water mixture	$w = 0$	P = constant
Intercooler	Heat exchanger between compressor stages	$w = 0$	P = constant
Nozzle	Create KE; P drops Measure flow rate	$w = 0$	$q = 0$
Mixing chamber	Mix two or more flows	$w = 0$	$q = 0$
Pump	Same as compressor, but handles liquid	w in, P up	$q = 0$
Reactor	Allow reaction between two or more substances	$w = 0$	$q = 0$, $P = C$
Regenerator	Usually a heat exchanger to recover energy	$w = 0$	P = constant
Steam generator	Same as boiler, heat liquid water to superheat vapor	$w = 0$	P = constant
Supercharger	A compressor driven by engine shaft work to drive air into an automotive engine	w in	
Superheater	A heat exchanger that brings T up over T_{sat}	$w = 0$	P = constant
Turbine	Create shaft work from high P flow	w out	$q = 0$
Turbocharger	A compressor driven by an exhaust flow turbine to charge air into an engine	$\dot{W}_{turbine} = \dot{W}_{C.V.}$	
Throttle	Same as valve		
Valve	Control flow by restriction; P drops	$w = 0$	$q = 0$

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