1^{ST} Class
Thermodynamics

By Hassan Ahmed

Chapter One: Introduction

Objectives

1. Identify the unique vocabulary associated with thermodynamics.
2. Review the metric SI and the English unit systems that will be used throughout the text.
3. Explain the basic concepts of thermodynamics such as system, state, equilibrium, process, and cycle.
4. Discuss properties of a system and define density, specific gravity, and specific weight.
5. Review concepts of temperature, temperature scales, pressure, and absolute and gage pressure.

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

1.1 Definitions

- **Thermodynamics** It is the science of energy and entropy and it is the science that deals with heat and work and those properties of substances that bear a relation between eat and work.
- **Working substance.** All the thermodynamic systems require, some working substance in order to perform various operations.
- **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.
- **State:** 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.
- **Phase:** It is defined as a quantity of matter in homogeneous throughout. When more than one phase is present the phases are separated from each other by the phase boundary. Homogeneity in physical structure means that the matter is all solid, or all liquid, or all vapor (or equivalently all gas). A system can contain one or more phases. For example, a system of liquid water and water vapor (steam) contains two phases.
- **Cycle.** When a system in a given initial state goes through a number of different change of states or processes and finally returns to its initial state, the system has undergone a cycle. Also it can be defined as system

is said to have undergone a cycle if it returns to its initial state at the end of the process. That is, for a cycle, the initial and the final states are identical.

1.2 Thermodynamic System:

It is defined as a quantity of fixed mass and identity upon which attention is focused for study. Every thing external to the system is the ***surrounding***, and the system is separated from surrounding by the system ***boundaries***. These boundaries may be either movable or fixed. Mathematically, the boundary has zero thickness, no mass, and no volume.

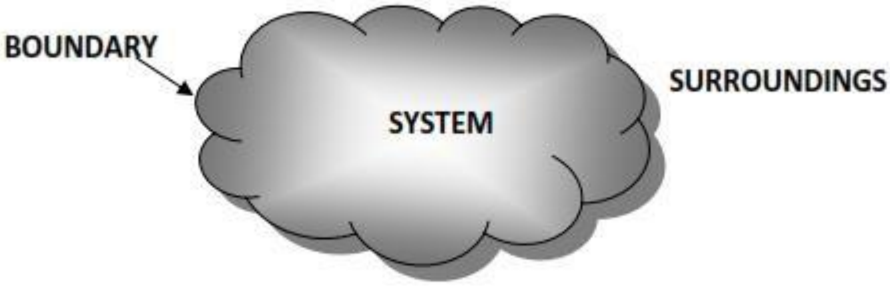


Figure1 . System, Surrounding and Boundary.

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. The wide realm of application of these principles is suggested bellow:

- Automobile engines.
- Turbines.
- Compressors, pumps.
- Fossil- and nuclear-fueled power stations.
- Propulsion systems for aircraft and rockets.
- Combustion systems.
- Cryogenic systems, gas separation, and liquefaction.
- Heating, ventilating, and air-conditioning systems.
- Vapor compression and absorption refrigeration.
- Heat pumps.
- Fuel cells.
- Thermoelectric and thermionic devices.
- Magneto hydrodynamic (MHD) converters.
- Solar-activated heating, cooling, and power generation.
- Geothermal systems.
- Ocean thermal, wave, and tidal power generation.

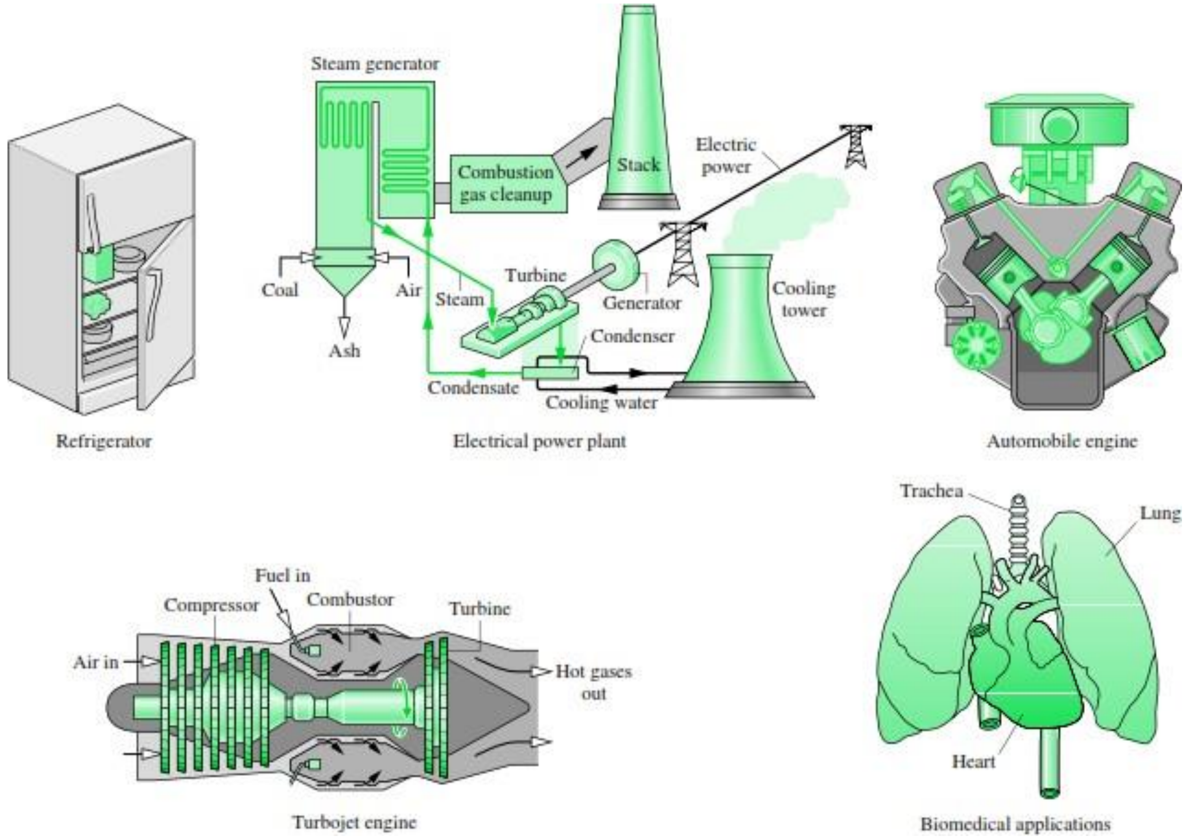


Figure2 . Some applications of engineering thermodynamics

1.3 Classification of thermodynamics system

The system may be closed or open depending on whether a fixed mass or a fixed volume in space is chosen for study.

- **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. 3a. 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.
- **Open system:** (also known as a **control volume**) is a properly selected region in space. It usually encloses a device that involves mass flow as shown in Fig. 3b, such as a compressor, turbine, or nozzle. Flow through these devices is best studied by selecting the region within the device as the control volume. Both mass and energy can cross the boundary of a control volume.
- **Isolated system:** A special type of closed system that does not interact in any way with its surroundings.

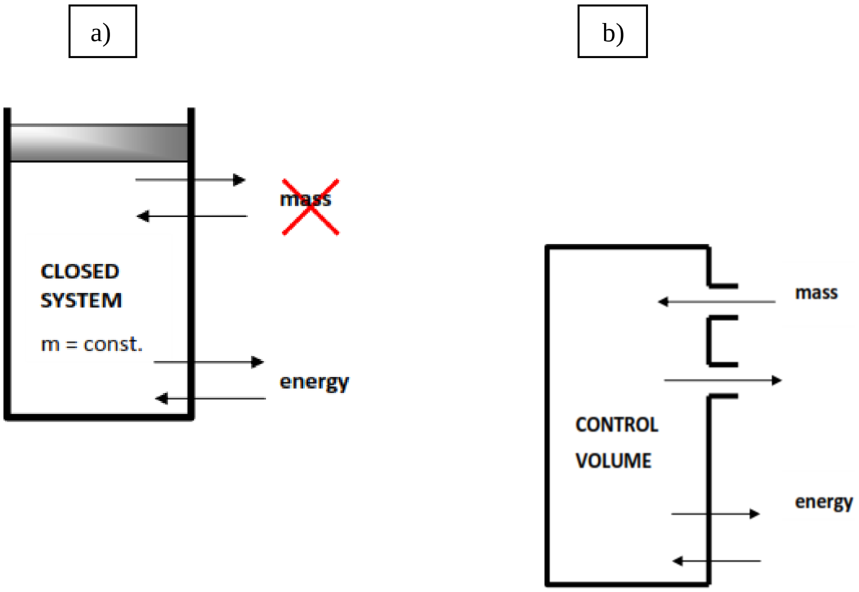


Figure3 . The system:

a) Closed system, mass cannot cross the boundaries, but energy can (control mass).

b) Control volume, both mass and energy can cross the boundaries.

In the closed system, the energy crosses the boundary but the substance does not. In the open system, the energy and substance cross the boundary.

Closed system (Control mass)	Open system (Control volume
Fixed amount of mass	A device that involves mass flow such a compressor, water heater or nozzle
No mass can cross its boundary.	Mass can cross its boundary
Energy can cross (heat or work).	Energy can cross (heat or work).
Volume can change.	Volume can change but it is often fixed

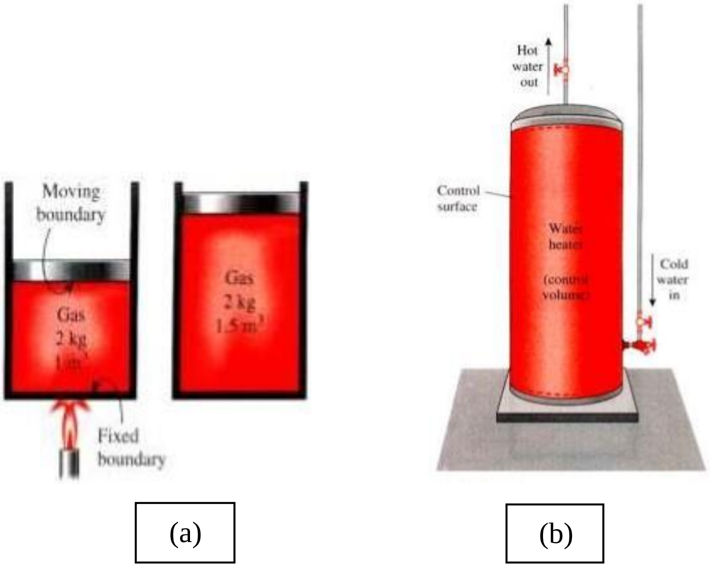


Figure 4. A closed system with moving boundary

a) An open system (control volume) with one inlet and on exit.

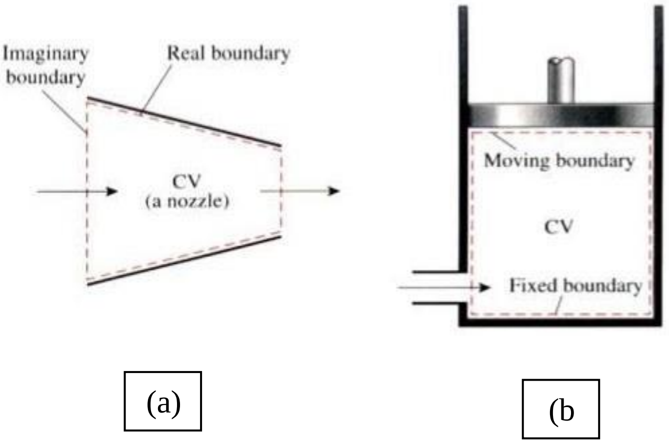


Figure 5. A control volume with real and imaginary boundaries.
a) A control volume with fixed and moving boundaries.

1.4 Processes and Cycles

Any change that a system undergoes from one equilibrium state to another is called a **process**, and the series of states through which a system passes during a process is called the **path** of the process (Fig. 6). To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings.

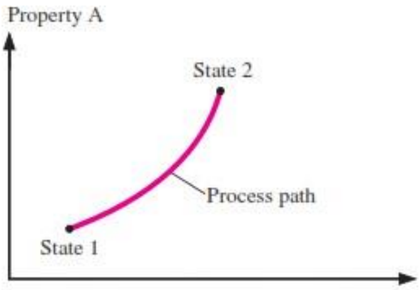


Figure6 . A process between states 1 and 2 and the process path.

When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a **quasistatic**, or **quasi-equilibrium**, **process**. A quasi-equilibrium process can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.

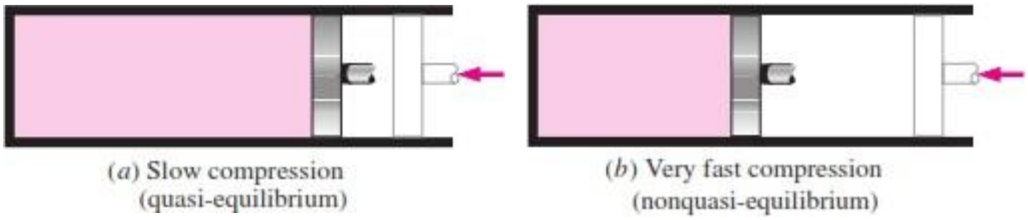

(*a*) Slow compression (quasi-equilibrium)
(*b*) Very fast compression (nonquasi-equilibrium)

Figure7 . Quasi-equilibrium and nonquasi- equilibrium compression processes.

1.5 Dimensions and Units

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.

Table 1. The fundamental dimensions and their units

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)

A number of unit systems have been developed over the years. Despite strong efforts in the scientific and engineering community to unify the world with a single unit system, 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, which is also known as the **International System**.

The prefixes used to express the multiples of the various units are listed in Table 2, they are standard for all units.

Table 2. SI Unite Prefixes

Factor	prefix	symple
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	Micro	μ
10^{-9}	Nano	N
10^{-12}	Pico	P

The basic units of mass, length and time is kg, meter and second respectively. These units are used to find the other units that called the secondary units like force, work, energy, power, torque, and acceleration.

Acceleration $=\alpha =[m/sec^2]$

Force =F =Newton[N]

The force is defined as product of acceleration and mass

$$F = \alpha \times m \qquad N = [m/\sec^2]\times[kg]$$

The torque can be defined as the force multiply by length

$$T = F \times L \qquad J = N \times m = kg.m^2/\sec^2$$

The work also defined as force into distance so the unit of work is Joule [J].

The power is the rate of doing work, the unit of power is Watt [W].

$$P = W/t \qquad W = J/\sec = kg.\, m^2/\sec^3$$

Example 1.1

A school is paying $0.12/kWh for electric power. To reduce its power bill, the school installs a wind turbine (Fig. 8) with a rated power of 30 kW. If the turbine operates 2200 hours per year at the rated power, determine the amount of electric power generated by the wind turbine and the money saved by the school per year.

Solution: given; Unit cost of energy= $0.12/kWh, Energy per unit time= 30 kW =30 KJ/sec, Time interval= 2200h.

Total energy = (Energy per unit time) *(Time interval)
= (30 kW) * (2200 h)
= 66,000 kWh

The money saved per year is the monetary value of this energy determined as

Money saved = (Total energy) * (Unit cost of energy)
= (66,000 kWh) * ($0.12/kWh) = $7920

Note; The annual electric energy production also could be determined in kJ by unit manipulations as

$$\text{Total energy} = (30\ \text{kW})\ (2200\ \text{h})\left(\frac{1\ kJ/s}{1\ kW}\right)\left(\frac{3600\ s}{1\ h}\right) = 2.38 * 10^8\ \text{kJ}$$

Figure 8. wind turbine

1.6 Properties of a System

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.

Thermodynamic properties can be divided into two general classes, **intensive** and **extensive** properties. Thus, if a quantity of matter in a given state is divided into two equal parts, each part will have the same value of intensive properties as the original, and half the value of the extensive properties.

- **Intensive property.**

properties which are independent upon mass such as, Pressure, temperature, density……

- **Extensive properties**

properties which are dependent upon mass such as, volume and energy into various forms. Extensive properties per unit mass such as specific volume are intensive properties.

1.7 Specific Volume and Density:

The specific volume of a substance is defined as the volume per unit mass and is given the symbol **υ.** The density of a substance is defined as the mass per unit volume, and is therefore the reciprocal of the specific volume. Density is designated by the symbol **ρ**. Specific volume and density are intensive properties.

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

where ***m*** is the mass in (kg), and ***V*** is the volume in (m^3). So the units of **υ=[m^3/kg]** and for **ρ=[kg/m^3].**

In certain applications it is convenient to express properties such as a specific volume on a molar basis rather than on a mass basis. The amount of a substance can be given on a **molar basis** in terms of the kilomole (kmol) or the pound mole (lbmol), as appropriate. In either case we use

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

The number of kilomoles of a substance, n, is obtained by dividing the mass, ***m***, in kilograms by the molecular weight, ***M***, in kg/kmol. Appendix Table A-1 provides molecular weights for several substances.

If the mass is measured by molecular weight so the specific volume can be designated by the symbol $\bar{v}$ and its unit becomes [m^3/kmol] or [m^3/mol]. And the density also becomes $\bar{\rho}$**,** and its unit becomes [kmol/m^3] or [mol/m^3].

Sometimes the density of a substance is given relative to the density of a well-known substance. Then it is called **specific gravity**, or **relative density**, and is defined as the ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C, for which $\boldsymbol{\rho}_{H2O}$=1000 kg/m^3). That is,

$$SG = \frac{\rho}{\rho_{H_2O}}$$

Table 3 . Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3- 0.9
Gold	19.2
Bones	1.7- 2.0
Ice	0.92
Air (at 1 atm)	0.0013

1.8 Temperature and the Zeroth Law of Thermodynamics

- Equality of Temperature:

Two bodies have equality of temperature when no change in any observation property occurs when they are in thermal communication.

- Zeroth Law of Thermodynamics:

When two bodies have equality of temperature with a third body, they are in turn have equality of temperature with each other.

1.8.1. Temperature Scale:

Celcsius scale symbol ^oC or called Centigrade. The Celsius scale was based on two fixed, easily duplicated points, the ice point and the steam point, these two points are numbered 0^oC and 100^oC on the Celsius scale. And absolute scale related to Celsius is referred to as the Kelvin scale and is designated as K.

$$T(K) = T(^o C) + 273.15$$

There is other scale of temperature called Fahrenheit scale has symbol ^oF at which the ice point and steam point are numbered 32^oF and 212^oF.

$$0^o C \rightarrow 32^o F$$

$$100^o C \rightarrow 212^o F$$

$$T(^o F) = 32 + 1.8T(^o C)$$

And the absolute scale related to Fahrenheit scale is referred as the Rankin and designated R

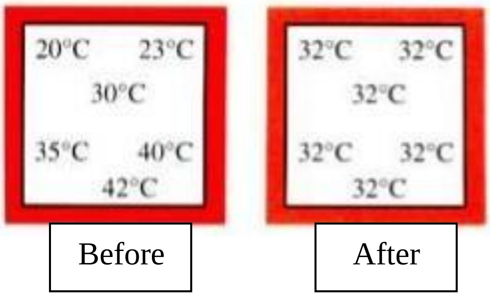
$$T(R) = T(^{o}F) + 460$$

$$T(R) = 1.8T(K)$$

1.8.2. Thermodynamic Equilibrium:

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

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, as shown in Fig.6. That is, the system involves no temperature differential, which is the driving force for heat flow. **Mechanical equilibrium** is related to pressure, and a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time. However, the pressure may vary within the system with elevation as a result of gravitational effects. For example, the higher pressure at a bottom layer is balanced by the extra weight it must carry, and, therefore, there is no imbalance of forces. The variation of pressure as a result of gravity in most thermodynamic systems is relatively small and usually disregarded. If a system involves two phases, it is in **phase equilibrium** when the mass of each phase reaches an equilibrium level and stays there. Finally, a system is in **chemical equilibrium** if its chemical composition does not change with time, that is, no chemical reactions occur. A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.



Before

After

Figure 9. A closed system recharging thermal equilibrium

1.9. Pressure:

It is defined as the normal component of force per unit area. We speak of pressure only when we deal with a gas or a liquid.

$$P = \lim \frac{\delta F_n}{\delta A}$$

The unit of pressure in SI units is N/m^2 which is called the Pascal (Pa).

$$1Pa = 1 \, {}^{N}\!/_{m^2}$$

Two other units continue to be widely used, and should noted here. These are the **bar**, where

$$1bar = 10^5 \, Pa = 100 \, kPa = 0.1MPa$$

And the standard atmosphere (**atm**), where

$$1atm = 101325 \, Pa = 101.325kPa = 1.01325 \, bar$$

In the English unit system, the pressure unit is pound-force per square inch (lb/in^{2}or psi), 1atm=14.696psi.

In most thermodynamic investigation we are concerned with absolute pressure. Most pressure and vacuum gage, however, read the difference between the absolute pressure and the atmospheric pressure existing at the gage, and this is referred to as gage pressure. This is shown graphically in Fig. 9.

$$P_{abs} = P_{atm} + P_g$$

$$P_{abs} = P_{atm} - P_{vac}$$

Where P_{abs}= absolute pressure

P_{atm}=atmospheric pressure

P_g= gage pressure

P_{vac}=vacuum pressure

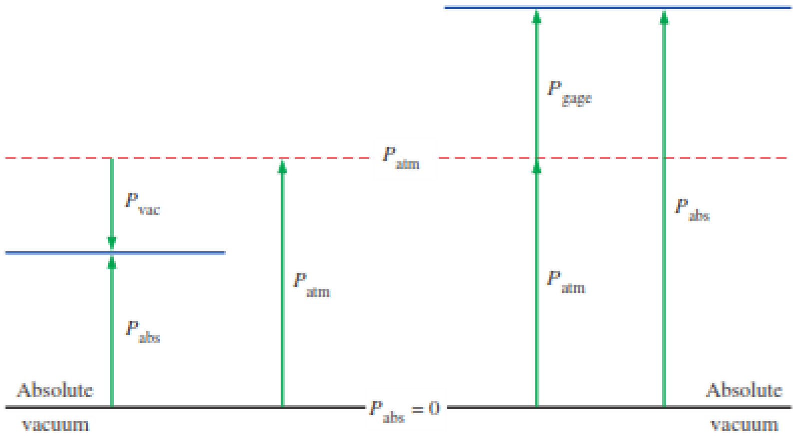


Figure10 . Absolute, gage, and vacuum pressures.

From the principle of hydrostatics one concludes that a difference in level of h meters, the pressure difference in Pascals is calculated by the relation.

$$\Delta P = \rho g h$$

where ρ is the fluid density and g=9.81m/s^2.

If we take point 1 to be at the free surface of a liquid open to the atmosphere (Fig. 10), where the pressure is the atmospheric pressure P_{atm}, then the pressure at a depth ***h*** from the free surface becomes Liquids are essentially incompressible substances, and thus the variation of density with depth is negligible.

$$P = P_{atm} + P_g \qquad , \qquad P_g = \rho g h$$

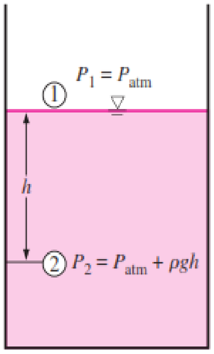


Figure11 . Pressure in a liquid at rest increases linearly with distance from the free surface.

When the variation of density with elevation is known, the pressure difference between points 1 and 2 can be determined by integration to be

$$\Delta P = P_2 - P_1 = -\int_1^2 \rho g dz$$

Pressure in a fluid at rest is independent of the shape or cross section of the container. It changes with the vertical distance, but remains constant in other directions. Therefore, the pressure is the same at all points on a horizontal plane in a given fluid.

Many techniques have been developed for the measurement of pressure and vacuum. Instruments used to measure and display pressure in an integral unit are called pressure gauges or vacuum gauges.

1.9.1. The Barometer

Atmospheric pressure is measured by a device called a barometer; thus, the atmospheric pressure is often referred to as the barometric pressure.

The Italian Evangelista Torricelli (1608–1647) was the first to conclusively prove that the atmospheric pressure can be measured by inverting a mercury-filled tube into a mercury container that is open to the atmosphere, as shown in Figure below. The pressure at point B is equal to the atmospheric pressure, and the pressure at point C can be taken to be zero since there is only mercury vapor above point C and the pressure is very low relative to P_{atm} and can be neglected to an excellent approximation. Writing a force balance in the vertical direction gives

$$P_{atm} = \rho g h$$

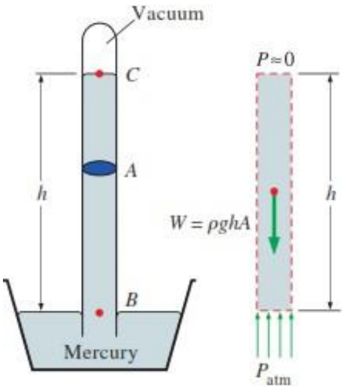


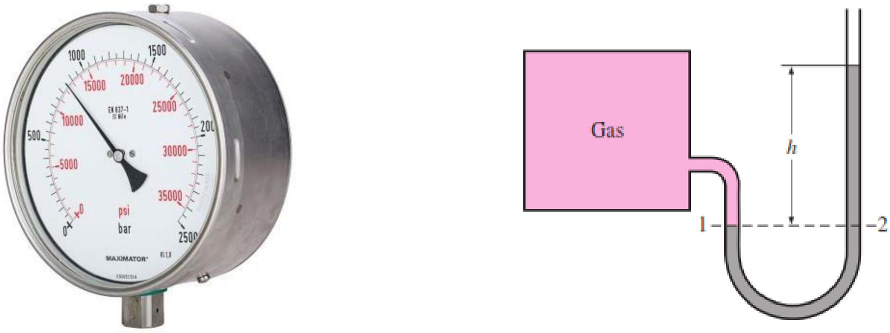
Figure 12. the basic barometer

1.9.2. The Manometer

A manometer is a good example as it uses a column of liquid to both measure and indicate pressure Fig. 13a. Likewise, the widely used Bourdon gauge is a mechanical device which both measures and indicates Fig. 13b.

A vacuum gauge is an absolute pressure gauge used to measure the pressures lower than the ambient atmospheric pressure.

Other methods of pressure measurement involve sensors which can transmit the pressure reading to a remote indicator or control system.



(a)

(b)

Figure 13. a) Bourdon pressure gauge,
b) The basic manometer

1.10. Form of Energy:

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the total energy **E** of a system. The total energy of a system on a unit mass basis is denoted by **e** and is defined as

$$e = \frac{E}{m} \quad (J/kg) \quad or \quad (kJ/kg)$$

In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups, macroscopic and microscopic. The macroscopic forms of energy, on one hand, are those a system possesses as a whole with respect to some out side reference frame, such as kinetic and potential energies. The microscopic forms of energy, on the other hand, are those related to the molecular structure of a system and the degree of the molecular activity, and they are independed of outside reference frames. The sum of all the microscopic forms of energy is called the **internal energy** of a system and is denoted by **U**.

The macroscopic energy of a system is related to a motion and the influence of some external effects such as gravity, electricity, and surface tension.

1. **Kinetic Energy:** it is the energy that a system possesses as a result of its motion relative to some reference frame, when all parts of a system move with the same velocity, the kinetic energy is expressed as

$$KE = \frac{1}{2} mC^2 \quad [J]$$

Or, on a unit mass basis,

$$ke = \frac{1}{2} C^2 \quad [J/kg]$$

And the change in kinetic energy between two states of the system

$$\Delta KE = \frac{1}{2}(m_2 C_2^2 - m_1 C_1^2) \quad [J]$$

Or

$$\Delta KE = \frac{1}{2000}(m_2 C_2^2 - m_1 C_1^2) \quad [kJ]$$

And for the same mass m

$$\Delta KE = \frac{1}{2000} m(C_2^2 - C_1^2) \quad [kJ]$$

Where C denotes the velocity of the system relative to some fixed reference frame.

2. **Potential Energy:** It is the energy that a system possesses as a result of its elevation in a gravitational- field and is expressed as

$$PE = mgZ \quad [J]$$

Or, on a unit mass basis

$$pe = gZ \quad [J/kg]$$

and the change in the potential energy is

$$\Delta PE = mg(Z_2 - Z_1) \quad [J]$$

Or $$\Delta PE = \frac{1}{1000} mg(Z_2 - Z_1) \quad [kJ]$$

The total energy of a system consists of the kinetic, potential, and internal energies and is expressed as

$$E = U + KE + PE \quad \text{kJ}$$

or per unit mass $$e = u + ke + pe \quad \text{kJ/kg}$$

internal energy is defined as the sum of all the microscopic forms of energy of a system. It is related to the molecular structure and the degree of molecular activity, and it may be viewed as the sum of the kinetic energy of the molecular.

Example 1.2

What is the weight of a 1 kg mass at an altitude where the local acceleration of gravity is 9.75 m/s^2?

Solution: given, mass m=1 kg

Acceleration g= 9.75 m/sec^2

weight w= m x g =1kg × 9.75m/sec^2=9.75N

Example 1.3

What is the force required to accelerate a mass of 30kg at a rate of 15m/sec^2?

Solution: given, mass m=30kg

Acceleration a = 15m/sec^2

F= m × a = 30kg × 15m/sec^2 =450N

Example 1.4

5kg plastic tank that has a volume of 0.2m^3 is filled with liquid water. Assuming the density of water is 1000kg/m^3, determine the weight of the combined system.

Solution: given mass of tank m_t=5kg

Volume of the tank V=0.2m^3

Density of water ρ_w=1000kg/m^3

Mass of water $m_w = V_w \times \rho_w$

=0.2m^3 x 1000kg/m^3 =200kg

total mass $m = m_w + m_t$

=200kg+5kg

total weight w= m × g =205kg × 9.81m/sec^2=2011N

Example 1.5

The deep body temperature of a healthy person is 37°C. What is it in Kelvin.

Solution: given t=37°C

T=t+273=310K

Example 1.6

Consider a system whose temperature is 18^{o}C. Express this temperature in R, K, and ^{o}F.

Solution: given $t=18^oC$

$$t(^oF)=32+1.8t(^oC)$$
$$=32+1.8\times 18=64.4^oF$$
$$T(K)=t(^oC)+273$$
$$=18+273.15=291.15K$$
$$T(R)=t(^oF)+459.67$$
$$=64.4+459.67=524.07R$$

or $T(R)=1.8T(K)=1.8\times 291.15=524.07R$

Problems

1.1. A large fraction of the thermal energy generated in the engine of a car is rejected to the air by the radiator through the circulating water. Should the radiator be analyzed as a closed system or as an open system? Explain.

1.2. What is the difference between intensive and extensive properties?

1.3. Is the weight of a system an extensive or intensive property?

1.4. What is the weight, in N, of an object with a mass of 200 kg at a location where g 5 9.6 m/s2?

1.5. Can mass cross the boundary of a closed system? How about energy?

1.6. What is the difference between the macroscopic and microscopic?

1.7. For a system to be in thermodynamic equilibrium, do the temperature and pressure have to be the same everywhere?

1.8. What is the difference between gage pressure and absolute pressure?

1.9. What is the zeroth law of thermodynamic?

1.10. What are the ordinary and absolute temperature scale in the SI and English unit systems?

1.11. A steady force of 5kN acts on a mass of 20kg. What is the acceleration of this mass? (250m/sec^2)

1.12. The “standard “acceleration (at sea level and 45 degree latitude) due to gravity is 9.80665m/sec^2. Calculate the force due to “standard” gravity acting on a mass of 50kg.

1.13. The reading on a pressure gage is 1.75Mpa, and the local barometer reading is 94kPa. Calculate the absolute pressure that is being measured.

1.14. A gas is contained in a vertical cylinder fitted with a piston as shown in Figure below. atmospheric pressure is 1bar, and the piston area is 400mm^2. what is the mass of piston, if the gas pressure inside is 120kPa? Assume standard gravitational acceleration.

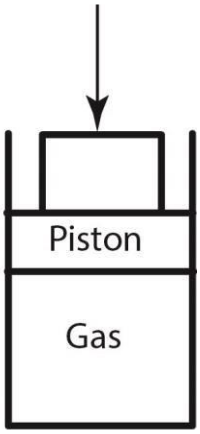


Figure 14. Sketch for Problem 11

1.15. A vacuum gage connected to a tank reads 30kPa at a location where the barometric reading is 755mm Hg. Determine the absolute pressure in the tank. Take ρHg=13590kg/m^3.

1.16. A pressure gage connected to a tank reads 3.15bar at a location where the barometric reading is 75cm Hg. Determine the absolute pressure in tank. Take ρHg=13590kg/m^3. (4.15 bar).

1.17. A pressure gage connected to a tank reads 600kPa at a location where the atmospheric pressure is 94kPa. Determine the absolute pressure in the tank.

1.18. The barometer of a mountain hiker reads 930mbar at the beginning of hiker tip and 780mbar at the end. Neglecting the effect of altitude on local gravitational acceleration, determine the vertical distance climbed? Assume an average air density of 1.2kg/m^3 and take g=9.7m/sec. (1288.65m).

1.19. The basic barometer can be used to measure the height of a building. If the barometric readings at the top and at the bottom of a building are 730 and 755mm Hg, respectively. Determine the height of the building, assume an average air density of 1.18kg/m^3. (288m).

1.20. A gas is contained in a vertical, frictionless piston-cylinder device. The piston has a mass of 4kg and cross-sectional area of 35cm^2. a compressed spring above the piston exerts a force 60N on the piston. If the atmospheric pressure is 95kPa, determine the pressure inside the cylinder. (123.35kPa)

1.21. Both a gage and a manometer are attached to a gas tank to measure its pressure. If the reading on the gage is 80kPa, determine the distance between the two fluid levels of the manometer if the fluid is (a) mercury (ρ=13600kg/m^3) or is (b) water (ρ=1000kg/m^3).

1.22. The level of the water in an enclosed water tank is 40m above ground level. The pressure in the air space above the water is 120kPa, and the density of water is 1000kg/m^3. what is the water pressure at ground level. (512.4 kPa)

1.23. A manometer contains a fluid having a density of 800kg/m3. The difference in height of the two columns 300mm. What pressure difference is indicated? What would be the height difference be if a manometer containing mercury (density of 13600kg/m3) had measured this same pressure difference?

1.24. During a heating process, the temperature of a system rises by 10^{o}C. Express this rise in temperature in K,R, and ^{o}F.

1.25. The deep body temperature of a healthy person is 98.6^{o}F. What is it in Rankine.

1.26. Consider a system whose temperature is 18^{o}C. Express this temperature in R, K, ^{o}F.

1.27. Consider two closed systems A and B. System A contains 2000kJ of thermal energy at 20^{o}C whereas system B contains 200kJ of thermal energy at 50^{o}C. Now the two systems brought into contact with each other. Determine the direction of any heat transfer between the systems.

1.28. A lift of mass 972kg moving up a distance 14.5km. Determine the minimum work required.

1.29. Determine the kinetic energy possesses by a car has a mass of 1050kg with a speed of 82km/hr.

1.30. Water is stored in a tank at a height of 85.3m over a hydraulic turbine.(a) calculate the potential energy per unit mass of the water (b)the mass flow rate to product 75000kW.

1.31. Determine the mass and the weight of the air contained in a room whose dimensions are 6m by 6m by 8m. Assume the density of the air is 1.16kg/m^3.

1.32. A 5-kg rock is thrown upward with a force of 150N at a location where the local gravitational acceleration is 9.79m/sec2. Determine the acceleration of the rock in m/sec2.

Chapter Two: Pure Substance

2.1. Pure Substance:

A substance which has a fixed chemical composition throughout is called a pure substance. Water, nitrogen, helium, and carbon dioxide, for example, are all pure substance.

A mixture of various chemical elements or compounds also qualifies as a pure substance as long as the mixture is homogeneous.

A mixture of two or more phases of pure substance is still a pure substance as long as the chemical composition of all phases is the same. A mixture of ice and liquid water, for example, is a pure substance because both phases have the same chemical composition.

2.2. Phase-Change Process of Pure Substance:

Consider a piston-cylinder device containing liquid water at 20^{o}C and 1atm pressure (state 1- fig.15). under these conditions water exits 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^{o}C. As a temperature rises, the liquid water will expand slightly, and so its specific volume will increased. The pressure in the cylinder remains constant at 1atm during the process. Water is still a compressed liquid at this state since it has not started to vaporize.

As more heat is transferred, the temperature will keep rising until it reach 100^{o}C (state 2 fig.15). At this point water is still a liquid, but any heat addition will cause some of liquid to vaporize. This is a phase change process from liquid to vapor is about to take place. A liquid which is about to vaporize is called a **saturated liquid**. Therefore, state 2 is a saturated liquid state.

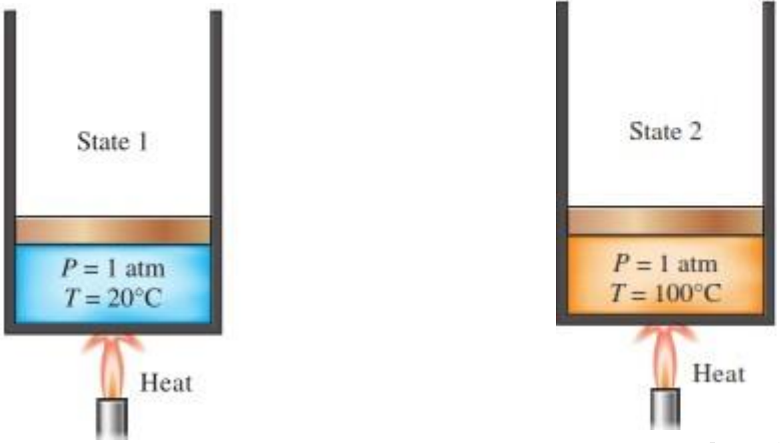
The temperature will remain constant during the entire phase change process if the pressure is held constant. During a vaporization (boiling) process, the only change we will observe is a large increase in the volume and a steady decline in the liquid level as a result of more liquid turning to vapor.

Midway about the vaporization line (state 3 fig.15) the cylinder contains equal amount of liquid and vapor. As we continue adding heat, the vaporization process will continue until the last drop of liquid is vaporize (state 4 Fig.15). the vapor which 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 often referred to as **saturated liquid-vapor mixture**.

Once the phase-change process is completed, we are back to a single-phase region again (this time vapor), and further transfer of heat will result in an increase in both the temperature and the specific volume (state 5 fig.15). At state 5, the temperature of the vapor is, let us say 300^{o}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^{o}C (for P=1 atm.).

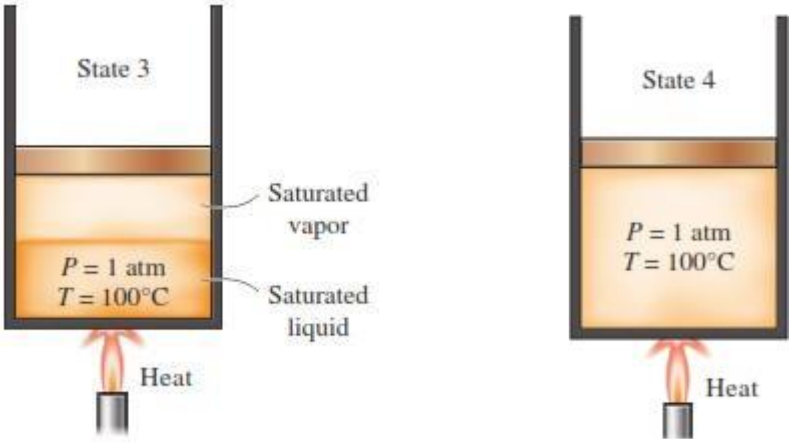
A vapor which is not about to condense (not a saturated vapor) is called a **superheated vapor**.

The constant-pressure phase-change process discussed above is illustrated on a T-v diagram in (fig.16)



At 1atm and 20°C water exists in the liquid phase (compressed liquid)

At 1 atm pressure and 100°C, water exists a liquid is ready to vaporize



As more heat is transferred, part of saturated liquid vaporizes (saturated liquid- vapor mixture)

At 1atm, the temperature remains constant at 100°C until the last drop of liquid is vaporized (saturated vapor)

As more heat is transfer, the temperature of the vapor starts to rise (superheated vapor)

Figure15 phase-change processes of pure substances

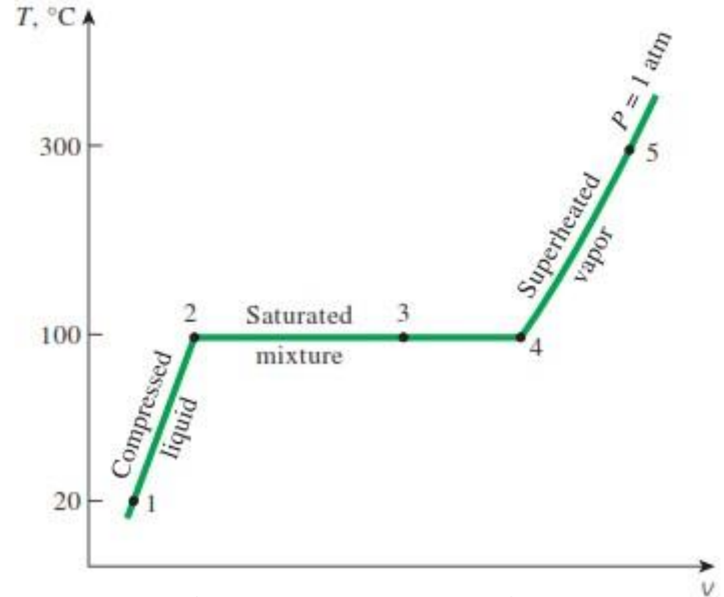


Figure 16. T-v Diagram for the heating process of water at constant pressure

2.3. Saturation Temperature and Saturation Pressure:

It probably came as no surprise to you that the water started ‘boiling’ at 100ºC. Strictly speaking, the statement ”water boils at 100ºC” is incorrect. The correct statement is “water boils at 100ºC at 1-atm pressure”. If the pressure inside the cylinder were raised to 500kPa by adding weights on top of the piston, the water would start, boiling at 151.9ºC.

That is, the temperature at which water starts boiling depends on the pressure, therefore, if the pressure is fixed: so is the boiling temperature at the given pressure, the temperature at which a pure substance starts boiling is called, the **saturation temperature** T_{sat}. Likewise, at a given temperature, the pressure at which a pure substance starts boiling is called the **saturation pressure** P_{sat}.

During a phase-change process, pressure and temperature are obviously dependent properties, and there is a definite relation between them that is $T_{sat}=f(P_{sat})$. A plot of T_{sat} Vs. P_{sat}, such as the one given for water in fig.12 is called liquid-vapor saturation. A curve of this kind is characteristic of all pure substance.

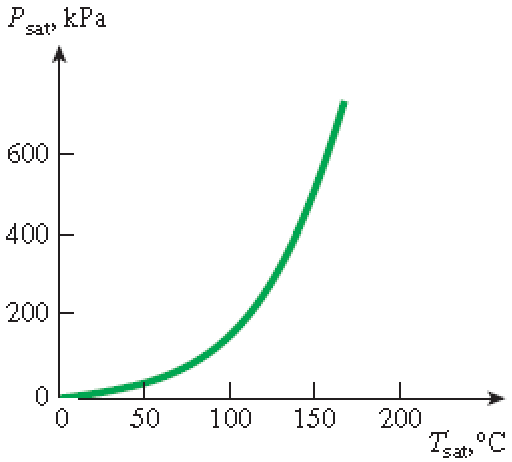


Figure 17. The liquid – vapor saturation curve of a pure substance

2.4. Property Diagram for Phase- Change Process

2.4.1. The T-v diagram:

The phase- change process of water at 1atm pressure was described in detail in the last section and plotted on a T-v diagram in Fig. 16. Now we repeat this process at different pressures to develop the T-v diagram for water. At 1-MPa, water will have a some what smaller specific volume than it did at 1-atm pressure. As heat is transferred to the water at this pressure, the processes will follow a path which looks very much like the process path at 1-atm pressure, as shown in fig. 18, but there are some noticeable differences. First, water will start boiling at a much higher temperature (179.9°C) at this pressure. Second, the specific volume of saturated liquid is larger, and the specific volume of saturated vapor is smaller than the corresponding values at 1-atm pressure. That is the horizontal line that connects the saturated liquid and saturated vapor states is much shorter.

As the pressure is increased further, this saturation line will continue to get, shorter, as shown in fig. 18, and it will become a point when the pressure reaches 22.09MPa for the case of water. This point is called the ***critical point***, and it may be defined as the point at which the saturated liquid and saturated vapor states are identical. The temperature, pressure and volume of a substance at the critical point are called, respectively, the critical temperature T_{cr}, critical pressure P_{cr}, and critical specific volume υ_{cr}.

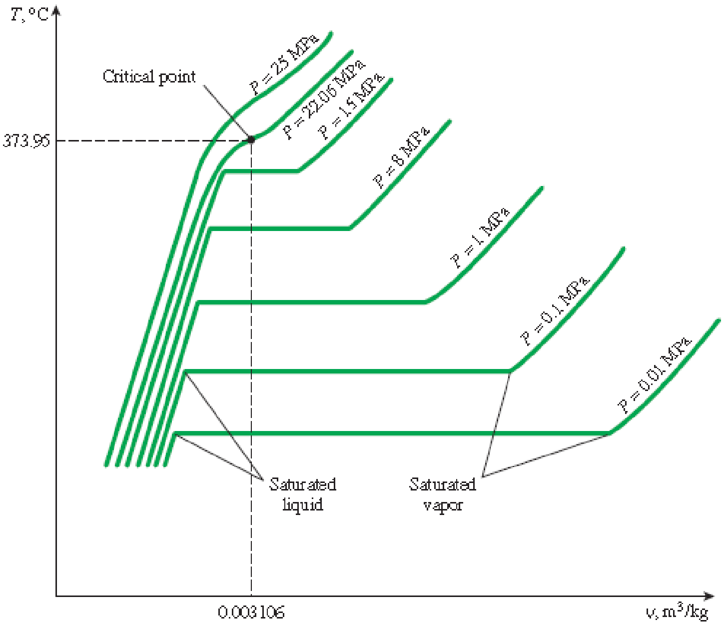


Figure 18. T-υ diagram of constant- pressure phase change process of a pure substance at various pressure.

At pressures above the critical pressure, there will not be a distinct phase-change process, fig. 19. instead, the specific volume of the substance will continually increase, and at all times there will be only one phase present. Eventually, it will resemble a vapor, but we can never tell when the change has occurred. Above the critical state there is no line that separate the compressed liquid region and the superheated vapor region. However, it is customary to refer to the substance as superheated vapor at temperatures above the critical temperature and as compressed liquid at temperatures below the critical temperature.

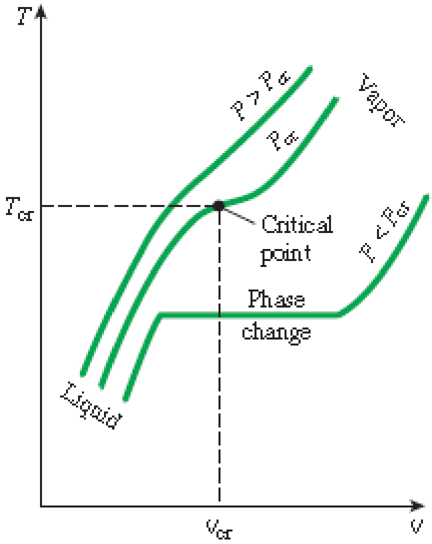


Figure 19. At supercritical pressure ($P>P_{cr}$) there is no distinct phase-change process.

The saturated liquid states in fig. 18 can be connected by a line which is called the **saturated liquid line**, and saturated vapor states in the same figure can be connected by another line which is called the **saturated vapor line**. These two lines meet each other at the critical point forming a dome as shown in fig. 20. All the compressed liquid states are located in the region to the left of the saturated liquid line, and it is called the **compressed liquid region**. All the superheated vapor states are located to the right of the saturated vapor line which is called **superheated vapor region**. In these two regions, the substance exits in a single phase, a liquid or a vapor. All the states that involve both phases in equilibrium are located under the dome which is called the **saturated liquid-vapor mixture region** or the **wet region**.

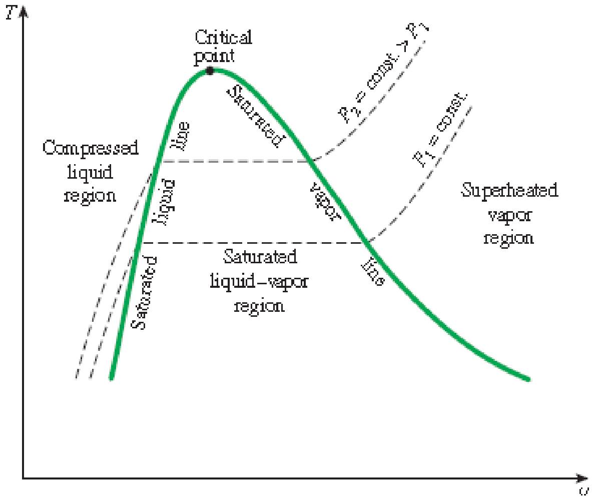


Figure 20. typical T-v diagram for phase-change region at constant pressure

2.4.2. The P-υ Diagram

The general shape of the **P-υ** diagram of a pure substance is very much like the **T-υ** diagram, but T=constant lines on this diagram have a down trend as shown in fig. 21.

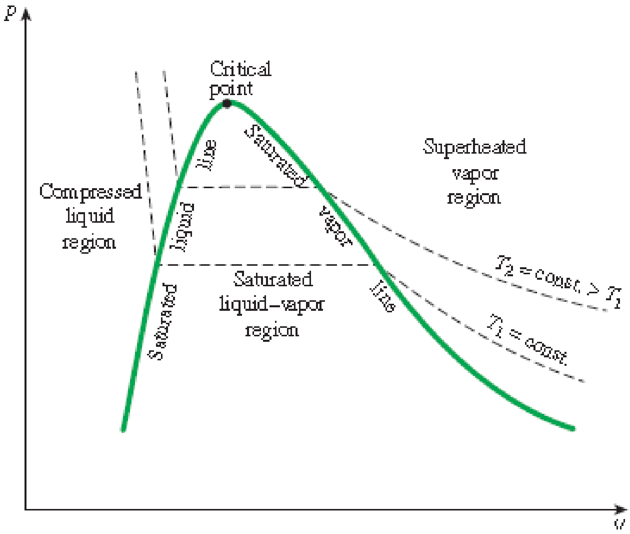


Figure 21. typical P-v diagram for phase-change region at constant temperature.

2.4.3. extended diagrams to include the solid phase

These two diagrams can easily be extended to include the solid phase as well as the solid-liquid and the solid vapor saturation regions, as in figs. 22 and 23.

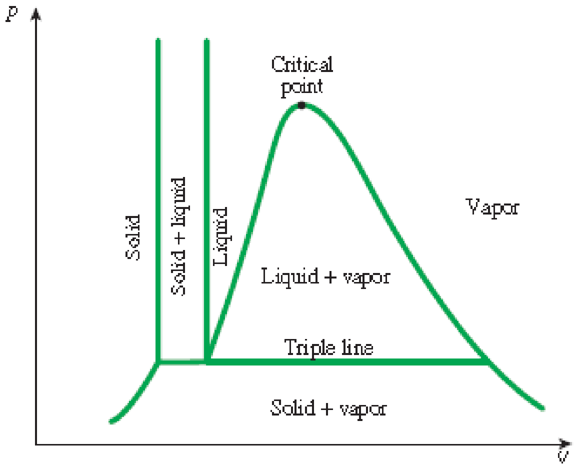


Figure 22. P-υ diagram of substance on freezing

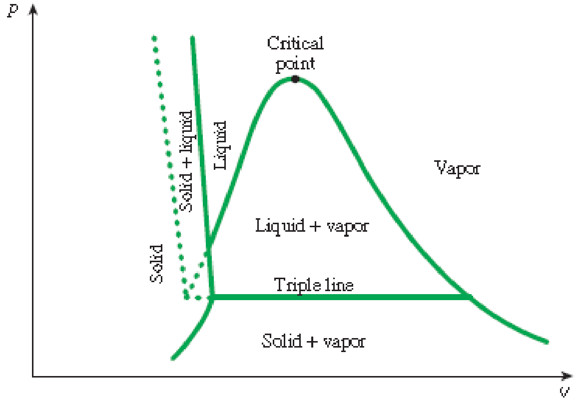


Figure 23. P-υ diagram of substance that expands on freezing (such as water)

We are all familiar with two phase being in equilibrium, but under some conditions all three phases of a pure substance coexist in equilibrium. On P-υ and T- υ diagrams, these triple-phase states from line called **triple line**. The same pressure and temperature but different specific volume. The triple line appears as a point on the P-T diagrams, and, therefore, is often called the **triple point**, fig. 24.

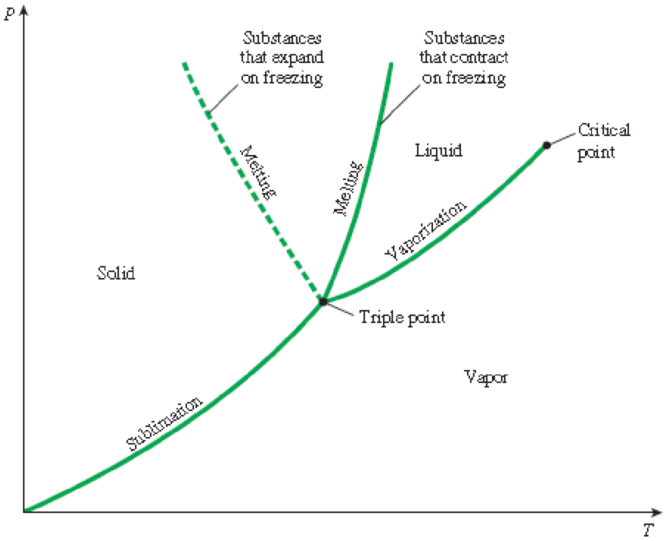


Figure 24. *P-T* diagram for pure substance

2.5. Property Tables:

For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations. Therefore, properties are frequently presented in the form of tables. Some thermodynamic properties can be measured easily, but others cannot be measured directly and calculated by using the relations that relate them to measurable properties.

For each substance, the thermodynamic properties are listed in more than one table, in fact, a separate table is prepared for each region of interest such as the superheated vapor, compressed liquid, and saturated mixture regions.

2.5.1. Enthalpy-A combination property

A person looking at the tables carefully will notice two new properties: enthalpy ***h*** and entropy ***s*.** Entropy is a property associated with the second law of thermodynamic and we will not use it until it is properly defined. It is appropriate to introduce enthalpy at this point. The enthalpy is a combination of *U* and *PV* and it is written as:

$$H = U + PV \quad [\text{kJ}]$$

or per unit mass

$$h = u + Pv \qquad [\text{kJ/kg}]$$

In some tables encountered in practice, the internal ***u*** is frequently not listed, but it can be determined from

$$u = h - Pv \ \text{[kJ/kg]}$$

2.5.2. Saturation Liquid and Saturation Vapor:

The properties of saturated liquid and saturated vapor of water are listed in two tables. Both give the same information. The only difference is that in one table properties are listed under temperature and in other under pressure.

Therefore, it is more convenient to use temperature table when temperature is given and the other table when pressure is given.

The subscript ***f*** is used to denote properties of a saturated liquid, and the subscript ***g*** to denote the properties of saturated vapor. Another subscript commonly is ***fg***, which denotes the difference between the saturated liquid values of same property. For example

υ_f=specific volume of saturated liquid
υ_g=specific volume of saturated vapor
υ_{fg}=difference between υ_g and υ_f (that is $\upsilon_{fg} = \upsilon_g - \upsilon_f$)

The quantity h_{fg} is called the **enthalpy of vaporization** (or latent heat of vaporization). It represents amount of energy needed to vaporize a unit mass of saturated liquid at given pressure and temperature. It is decreases as the pressure and temperature increases, it becomes zero at the critical point.

Example 2.1

A rigid tank contains 50kg of saturated liquid water at 85°C. Determine the pressure in the tank and the volume of the tank?

Solution: The state of the saturated liquid water is shown on a ***T- υ*** diagram. Since saturated condition exist in the tank, the pressure must be the saturation pressure at 85°C.

$P = P_{\text{sat at } 85^{\circ}C} = 57.83\text{kPa}$ (table A-4)

The specific volume of the saturated liquid at 85°C.

$\upsilon = \upsilon_{f \text{ at } 85^{\circ}C} = 0.001033 \text{ m}^3/\text{kg}$ (table A-4)

Then the total volume of the tank

$V = m\,\upsilon = (50\text{kg})(0.001033\text{m}^3/\text{kg}) = 0.050165\text{m}^3$

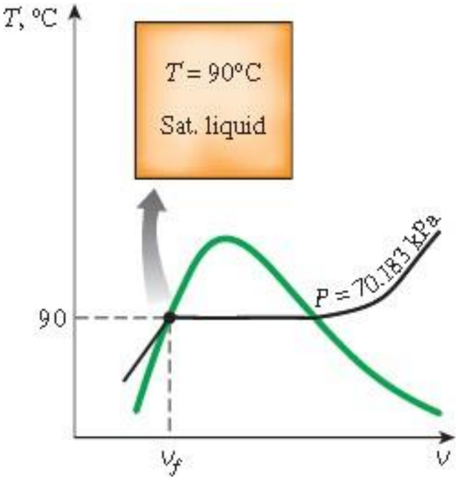


Figure 25. Schematic and T-v diagram for example 2–1.

Example 2.2

A piston- cylinder device contains $0.2m^3$ of saturated water vapor at 700kPa pressure. Determine the temperature of the vapor and the mass of the vapor inside the cylinder?

Solution: the state of the saturation water vapor is shown on the P- υ diagram. Since the cylinder contains saturated vapor at 700kPa, the temperature inside must be the saturation temperature at this pressure.

$$T = T_{sat\ at\ 700kPa} = 164.97^oC$$

The specific volume of the saturated vapor at 700kPa is

$$\upsilon = \upsilon_{g\ at\ 700kPa} = 0.2729 m^3/kg$$

then the mass of water vapor inside cylinder becomes

$$m = \frac{V}{v} = \frac{0.2}{0.2729} = 0.7329 kg$$

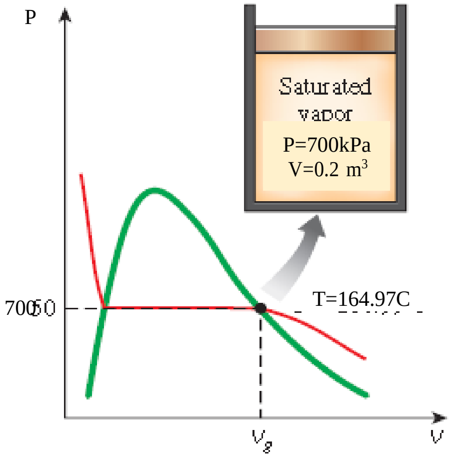


Figure 26. Schematic and P-v diagram for example 2– 2.

2.5.3. Saturated Liquid-Vapor Mixture

During a vaporization process, a substance exists as part liquid and path vapor. That is, a mixture of saturated liquid and saturated vapor. To analyze this mixture property, we need to know the proportions of liquid and vapor phases in the mixture. This is done by new property called quality (dryness fraction) $\boldsymbol{x}$ as the ratio of the mass of vapor to the total mass of the mixture.

$$x = \frac{m_{vapor}}{m_{total}}$$

$$m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$$

consider a tank that contains a saturated liquid-vapor mixture. The volume occupied by saturated liquid $\boldsymbol{V_f}$, and the volume occupied by vapor is $\boldsymbol{V_g}$. The total volume $\boldsymbol{V}$ is the sum of these two volumes.

$$V = V_f + V_g$$

$$V = mv \qquad V_f = m_f v_f \qquad V_g = m_g v_g$$

$$mv = m_f v_f + m_g v_g$$

dividing by ***m*** yields

$$v = \frac{m_f}{m} v_f + \frac{m_g}{m} v_g$$

$$x = \frac{m_g}{m}$$

$$\frac{m_f}{m} = (1 - \frac{m_g}{m}) = 1 - x$$

$$v = (1 - x)v_f + xv_g$$

$$v = v_f + x(v_g - v_f)$$

$$v = v_f + xv_{fg}$$

and also, there two equations similar to that for specific volume can be used to find the internal energy and enthalpy for the mixture:

$$u = u_f + xu_{fg}$$

$$h = h_f + xh_{fg}$$

All the results are of same format, and they can be summarized in a single equation as:

$$Y = Y_f + xY_{fg}$$

the values of the average property of the mixtures are always between the values of the saturated liquid and the saturated vapor properties. That is

$$Y_f \le Y \le Y_g$$

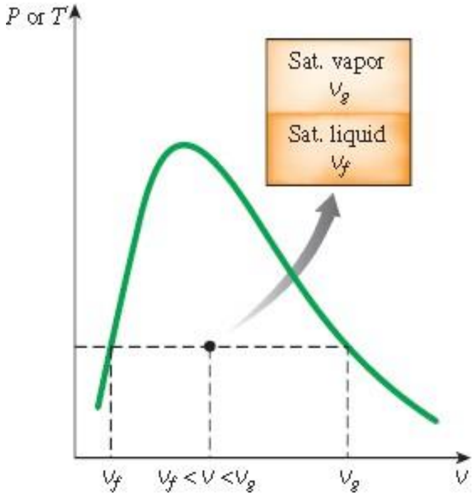


Figure 27. The ***v*** value of a saturated liquid–vapor mixture lies between the $\boldsymbol{v_f}$ and $\boldsymbol{v_g}$ values at the specified ***T*** or ***P***.

Example 2.3

A rigid tank contains 10 kg of water at 90°C. If 8kg of the water is in the liquid form and the rest is in the vapor form. Determine (a) the pressure in the tank and (b) the volume of the tank.

Solution: (a) at T= 90°C there is a saturated mixture of vapor and liquid in equilibrium.

So $P = P_{\text{sat at } 90^{o}C} = 70.14\text{kPa}$ (Table A– 4)

(b) At 90°C, $\upsilon_f = 0.001036 m^3/kg$ and $\upsilon_g = 2.361 m^3/kg$ (Table A– 4)

one way to find the volume of the tank is to determine volume occupied by each phases

$$V = V_f + V_g = m_f v_f + m_g v_g$$

$$V = 8 \times 0.001036 + 2 \times 2.361 = 4.73 m^3$$

another way is to determine the quality x.

$$x = \frac{m_g}{m} = \frac{2}{10} = 0.2$$

$$v = v_f + x(v_g - v_f) = 0.001036 + 0.2(2.361 - 0.001036)$$

$$v = 0.473 m^3 / kg$$

$$V = mv = 10 \times 0.473 = 4.73 m^3$$

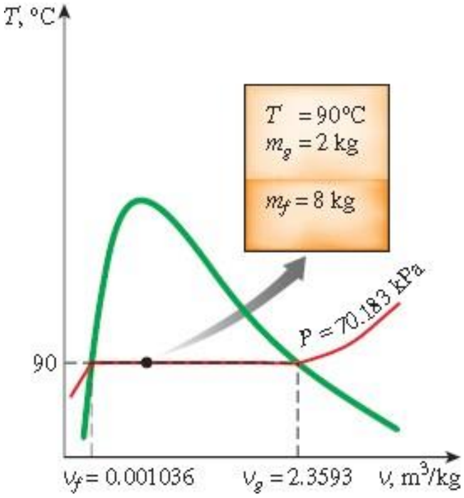


Figure 28. Schematic and T-v diagram for example 2–3.

2.5.4. Superheated Vapor:

In the region to the right of the saturated vapor line a substance exits as superheated vapor. Since the superheated region is a single-phase region (vapor phase only), the temperature and pressure are no longer dependent properties and these can conveniently be used as the two independent properties in the table.

In these tables, the properties are listed versus temperature for selected pressures starting from saturated vapor data. The saturated temperature is given in parentheses following the pressure value.

Superheated vapor is characterized by :

Lower pressure	($P<P_{sat}$ at given T)
Higher temperature	($T>T_{sat}$ at given P)
Higher specific volume	($\upsilon > \upsilon_g$ at given P or T)
Higher internal energy	($u> u_g$ at given P or T)
Higher enthalpy	($h> h_g$ at given P or T)

Example 2.5

Determine the temperature of water at a state of P=0.5MPa and h=3064.2kJ/kg.

Solution: given water at P=0.5MPa , h=3064.2kJ/kg

The enthalpy of saturated water vapor is hg=2748.7kJ/kg

And since h>hg it is superheated vapor, and from the superheated table it is found that T=300°C.

2.5.5. Compressed Liquid:

There is only date for compressed liquid water and the data of this table is not take a wide range of pressures and temperatures

In the absence of the compressed liquid data, a general approximation is to treat compressed liquid as saturated liquid at the given temperature. This is because the compressed liquid properties depend on temperature more strongly than they do on pressure.

Thus

$$v \cong v_{f\ at\ T}$$

$$u \cong u_{f\ at\ T}$$

$$h \cong h_{f\ at\ T}$$

This approximation gives a negligible error in υ and u but the error in h may reach undesirable levels. However the error in h at very high pressure can be reduced significantly by evaluating it from

$$h = h_{f\ at\ T} + v_f\,(P - P_{sat})$$

In general compressed liquid is characterized by

Higher pressure	($P > P_{sat}$ at a given T)
Lower temperature	($T < T_{sat}$ at a given P)
Lower specific volume	($\upsilon < \upsilon_f$ at a given P or T)
Lower internal energy	($u < u_f$ at a given P or T)
Lower enthalpy	($h < h_f$ at a given P or T)

Example 2.6:

Determine the internal energy of compressed liquid water at 80°C and 5MPa using (a) data from compressed liquid table and (b) saturated liquid data depending saturated temperature (c) saturated liquid data depending saturated pressure. What is the error involved in the second and third cases.

Solution: given compressed liquid at $T=80^oC$ $P=5MPa$

We can first check if the case is compressed liquid as the problem said or not.

At $T=80^oC$ $P_{sat}= 47.39kPa$ so $P>P_{sat}$ it is compressed liquid or
At $P=5MPa$ $T_{sat}=263.99^oC$ so $T< T_{sat}$ it is compressed liquid

(a) from compressed liquid table (Table A-7) at $P=5MPa$ and $T=80^oC$

$$u=333.72kJ/kg$$

(b) by using the data depending the temperature (Table A-4):

$$u=u_f \text{ at } 80^oC =334.86kJ/kg$$

(c) by using the data depending the pressure:

$$u=u_f \text{ at } 5MPa =1147.81kJ/kg$$

error in second case on the first case is

$$error\% = \left|\frac{334.86-333.72}{333.72}\right| \times 100 = 0.3416\%$$

error in third case on the first case is

$$error\% = \left|\frac{1147.81-333.72}{333.72}\right| \times 100 = 243.94\%$$

Note: it is shown from the example that the value taken at temperature is more accurate than that taken at the pressure.

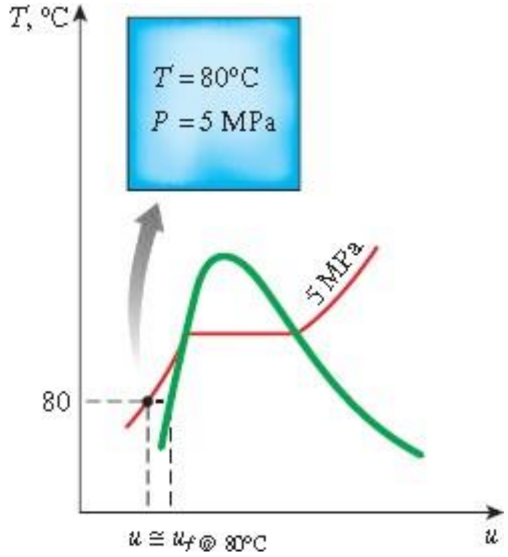


Figure 29. Schematic and *T-u* diagram for Example 3–6.

2.5.6. Linear Interpolation:

It is assumed that the relation between any two values followed each other in the table is a linear relation. The equation of a straight line can be used to find the values of any properties against any given values having no value in the table. The method is as following. From the fig.(30) on the x,y coordinate and assuming that, there are two point (y_1,x_1) and (y_2,x_2) connected by a straight line. The slop of this line R is equal

$$R = \frac{y_2 - y_1}{x_2 - x_1}$$

the equation of the line

$$\frac{y - y_1}{x - x_1} = \frac{y_2 - y_1}{x_2 - x_1} = R$$

hence $y = y_1 + R(x - x_1)$

$$y = y_1 + \frac{y_2 - y_1}{x_2 - x_1}(x - x_1)$$

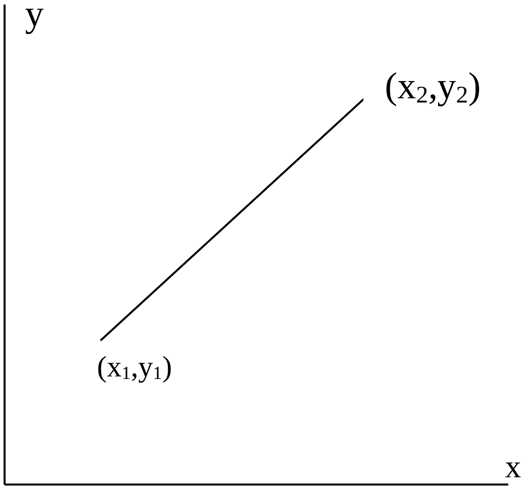


Figure 30. the interpolation

This equation can be used to find the values by substituting the known property instead of x and the needed property instead of y.

Example 2.7:

Determine the temperature of a superheated water vapor at a pressure of 0.5MPa and enthalpy 2890kJ/kg.

Solution: the given P=0.5MPa h=2890kJ/kg superheated vapor
From the superheated vapor water at 0.5MPa we read:

T°C	h [kJ/kg]
200	2855.4
250	2960.7

The value h=2890kJ/kg is greater than 2855.4kJ/kg at 200°C, and less than 2960.7kJ/kg at 250°C, thus the temperature value must be between 200 and 250°C and by using the linear interpolation.

	T	h
(1)	200	2855.4
		2890
(2)	250	2960.7

$$T = T_1 + \frac{h - h_1}{h_2 - h_1}\left(T_2 - T_1\right)$$

$$T = 200 + \frac{2890.0 - 2855.4}{2960.7 - 2855.4}\left(250 - 200\right)$$

$$= 216.4^{o}C$$

2.6. Ideal-Gas Equation of State:

Any equation that relates the pressure, temperature, and specific volume of a substance is called an equation of state. Property relations which involve other properties of a substance at equilibrium states are also referred to as equation of states. There are several equations of states, some simple and other very complex. The simplest and the best known equation of state for substances in the gas phase is the ideal gas equation of state. This equation predicts the P-υ-T behavior of a gas quite accurately within some properly selected region.

In 1662 Robert Boyle, an Englishman, observed during his experiments with vacuum chamber that the pressure of gases is inversely proportional to their volume.

$$P \propto \frac{1}{v} \qquad at \quad T = constant$$

$$P = \frac{K}{v} \qquad K = proportionalty \quad constant$$

In 1802, J. Charles and J.Gay-Lussase, Frenchmen, experimentally determined that at low pressures the volume of a gas is proportional to its temperature.

$$v \propto T$$

$$v = kT$$

that is $$v \propto \frac{T}{P}$$

or $$Pv \propto T$$

and $$Pv = RT$$

Problems-2

2.1 Is iced water a pure substance? Why?

2.2 What is the difference between saturated vapor and superheated vapor?

2.3 Can the enthalpy of a pure substance at a given state be determined from a knowledge of u, P, and υ? How?

2.4 What is the physical significance of h_{fg}? can it be obtained from a knowledge of h_f and h_g ? How?

2.5 What is the quality? Does it have any meaning in the superheated region?

2.6 Complete the following table for H_2O:

T,°C	P, kPa	**υ**, m^3/kg	Phase description
60		4.131	
	300		Saturated liquid
250	200		
150	1000		

2.7 Complete the following table for H_2O:

T,°C	P,kPa	u, kJ/kg	Phase Description
20	5000		
150		631.68	
	225	2000	
	30		Saturated vapor
300		2600	

2.8 Complete the following table for H_2O:

T, °C	P, kPa	h, kJ/kg	Phase Description
500	200		
	175	486.99	
55		600	
400	4000		
255			Saturated vapor

2.9 Complete the following table for H_2O:

T, °C	P, kPa	**υ**, m^3/kg	x, if applicable	Phase Description
100	10000			
130		0.00107		
	550		.75	
	750	0.2556		
150	75			

2.10 Complete the following table for H_2O:

T, ^oC	P, kPa	U, kJ/kg	x, if applicable	Phase Description
200	10000			
200				Saturated liquid
200		1744.7		
200			1	
200	1000			

2.11 Complete the following table for H_2O:

T, ^oC	P, kPa	H, kJ/kg	x, if applicable	Phase Description
30	100			
	100		0.0	
	100	2000		
	100			Saturated vapor
	100	3074.3		

2.12 Determine whether the state of the following water system is compressed liquid, mixture of saturated liquid and saturated vapor, or superheated vapor.

(a) $T=100^oC$, $P=3.0MPa$ (b) $T=300^oC$, $P=100kPa$

(c)$T=100^oC$, $\upsilon=1.6m^3/kg$ (d) $P=0.2MPa$, $u=700kJ/kg$

2.13 Steam at 500kPa and a quality of 90 percent occupied a rigid vessel of volume $0.3m^3$. Calculate the mass, internal energy, and enthalpy of the steam.

2.14 A rigid vessel of volume $0.2m^3$ contains 10 kg of (liquid + vapor) water at 200^oC. What are the pressure and internal energy of the water?

2.15 400-L rigid tank contains 5kg of water at 200kPa. Determine (a) the temperature, (b) the total enthalpy, and (c) the mass of each phase of water?

2.16 A rigid tank with a volume of $2.5m^3$ contains 8kg of saturated liquid – vapor mixture of water at 100^oC. Now the water is slowly heated. Determine the temperature at which the liquid in the tank is completely vaporized. Also show the process on a T-v diagram with respect to saturation lines?

2.17 Superheated water vapor at 1MPa and 300^{o}C is allowed to cool at constant volume until the temperature drops to 120^{o}C. At the final state, (a) the pressure (b) the quality, and (c)the enthalpy, also show the process on a T-v diagram with respect to saturation lines?

2.18 A piston- cylinder initially contains 100L of liquid water at 50^{o}C and 300kPa. Heat is transferred to the water at constant pressure until the entire liquid is vaporized.

(a) What is the mass of the water?
(b) What is the final temperature?
(c) Determine the total enthalpy change?
(d) Show the process on a T-v diagram with respect to saturation lines?

2.19 A 1m^3 rigid vessel initially contains saturated liquid-vapor mixture of water at 120^{o}C. The water is now heated until reaches the critical state. Determine the mass of liquid water and the volume occupied by the liquid at the initial state.

2.20 Determine the specific volume, internal energy, and enthalpy of compressed liquid water at 100^{o}C and 20MPa using the saturation approximation. Compare these values to the ones obtained from the compressed liquid tables?

2.21 Consider 1kg of water at its triple point. The volume of the liquid phase is equal to that of the solid phase, and the volume of the vapor phase is 10^4 times that of the liquid phase. Determine the mass of water in each phase at this state?

2.22 A cylinder-piston arrangement contains water at 105^{o}C, 85% quality with a volume of 1L. the system is heated, causing the piston to rise and encounter a linear spring, as shown in Figure 33. at this point the volume is 1.5L, the piston diameter is 150mm, and the spring constant is 100N/mm. The heating continues, so the piston compress the spring. What is the temperature when the pressure reaches 200kPa?

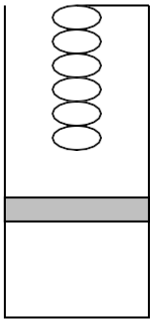


Figure 33. problem 2.34

2.23 A sealed rigid vessel of $2m^3$ contains a saturated mixture of liquid and vapor R-134a at 10^oC. If it is heated to 50^oC, the liquid phase disappears. Find the pressure at 50^oC and the initial mass of the liquid.

2.24 Water in a piston-cylinder is at 90^oC, 100kPa, and the piston loading is such that pressure is proportional to volume, P=CV. Heat is now added until the temperature reaches 200^oC. Find the final pressure and the quality if in two-phase region.

2.25 A spring-loaded piston-cylinder contains water at 500^oC, 3MPa. The setup is such that pressure is proportional to volume, P=CV. It is now cooled until the water becomes saturated vapor. Sketch the p-v diagram and find the final pressure.

2.26 Two tanks are connected, both containing water. Tank A is at 200kPa, $\upsilon=0.5m^3/kg$, $V_A=1m^3$ and tank B contains 3.5kg at 0.5MPa, 400^oC. The valve is now opened and the two come to a uniform state. Find the final specific volume?

2.27 A rigid tank of $0.4m^3$volume is filled with steam at 2MPa and 250^oC. The tank and contents are then cooled to 120^oC. What will be the final amounts of saturated vapor and saturated liquid water(in kg), and what is the corresponding quality of the mixture?

2.28 A closed rigid vessel contains 2percent liquid and 98 percent water vapor by volume in equilibrium at 150^oC. Determine the quality of the mixture. If the mixture is cooled to 100^oC, what will be the quality and the liquid and vapor percentages by volume at the new state?

2.29 A rigid thermally insulated vessel contains 0.2kg of a liquid-vapor water mixture at 75kPa and quality of 30%. An electric heater supplies energy to the vessel till the pressure in the vessel reaches 200kPa. Determine (a) the volume of the vessel, (b) the quality of the mixture in the final state.

2.30 A rigid vessel of volume of $0.5m^3$ initially contains a water-vapor mixture at 0.6MPa. (a) If the quality of mixture is 40%, calculate the mass of the mixture. (b) If the pressure in the vessel is raised to 0.9MPa by the transfer of heat, what will be the mass of the vapor and mass of the liquid.

2.31 A spherical balloon with a diameter of 6m is filled with helium at 20°C and 200kPa. Determine the mole number and the mass of the helium in the balloon.

2.32 The air in an automobile tire with a volume of 0.015m^3 is at 30°C and 150kPa (gage). Determine the amount of air that must be added to raise the pressure to the recommended value of 200kPa (gage). Assume the atmospheric pressure to be 98kPa and the temperature and the volume to remain constant.

2.33 The pressure gage on a 1.2m^3 oxygen tank reads 500kPa. Determine the amount of oxygen in the tank if the temperature is 24°C and the atmospheric pressure is 97kPa.

2.34 A cylinder gas tank 1m long, inside diameter of 20cm, 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?

2.35 A hollow metal sphere of 150mm inside diameter is weighed on a precision beam balance when evacuated and again after being filled to 875 kPa with an unknown gas. The difference in mass is 0.0025kg, and the temperature is 25°C. What is the gas, assuming it is a pure substance.

2.36 A piston cylinder arrangement, shown in Figure 34, contains air at 250kPa, 300°C. The 50-kg piston has a diameter of 0.1m and initially pushes against the stops. The atmosphere is at 100kPa and 20°C. The cylinder now cools as heat is transferred to the ambient.
(a) at what temperature does the piston begin to move down?
(b) How far has the piston dropped when the temperature reaches ambient?

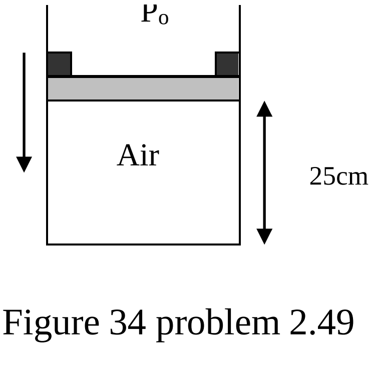


Figure 34 problem 2.49

2.37 Air in a tire is initially at –10°C, 190kPa. After driving awhile, the temperature goes up to 10°C. find the new pressure.

2.38 An initially deflated and flat balloon is connected by a valve to a 12m^3 storage tank containing helium gas at 2MPa and ambient temperature, 20^{o}C. the valve is opened and the balloon is inflated at constant pressure P_o=100kPa, equal to ambient pressure, until it becomes spherical at D_1=1m. If the balloon is larger than this, the balloon material is starched giving a pressure inside as

$$P = P_o + C\left(1 - \frac{D_1}{D}\right)\frac{D_1}{D}$$

the balloon is inflated to a final diameter of 4m, at which point the pressure inside is 400kPa. The temperature remains constant at 20^{o}C. What is the maximum pressure inside the balloon at any time during this inflating process? What is the pressure inside the helium storage tank at this time?

2.39 The helium balloon described in 2.48 is released into the atmosphere and rises to an elevation of 5000m, with a local ambient pressure of P_o=50kPa and temperature of –20^{o}C. What is then the diameter of the balloon.

2.40 A rigid vessel A is connected to a spherical elastic balloon B as shown in figure 35. both contain air at the ambient temperature 25^{o}C. The volume of the vessel A is 0.1m^{3} and the initial pressure is 300kPa. The initial diameter of the balloon is 0.5m and the pressure inside is 100kPa. The valve connecting A and B is now opened, and remains open. It may be assumed that the pressure inside the balloon is directly proportional to its diameter, and also that the final temperature of the air is uniform throughout at 25^{o}C. Determine the final pressure in the system and the final volume of the balloon?

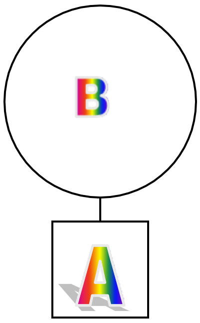


Figure 35. problem 2.53

Chapter three: The first law of thermodynamic, Closed system

3.1. Heat transfer

Heat is defined as the form of energy that transferred between systems (or system and surroundings) by virtue of a temperature difference.

Heat is energy in transition. It is recognized only as it crosses the boundary of a system.

A process during which there is no heat transfer is called an adiabatic process. The word adiabatic comes from the Greek word adiabatos which means not to be passed.

As a form of energy, heat has energy unit kJ(Btu) being most common one. The amount of heat transferred during the process between two states (states 1 and 2) is denoted $\boldsymbol{Q_{12}}$ or just $\boldsymbol{Q}$. heat transfer per unit mass of a system is denoted $\boldsymbol{q}$ and is determined from:

$$q = \frac{Q}{m}\, kJ/kg\ .$$

The heat transfer rate is denoted $\dot{Q}$, where the over dot stands for the time derivative, or per unit time. The heat transfer rate $\dot{Q}$ has the unit kJ/sec, which is equivalent to kW. When $\dot{Q}$ varies with time

$$Q = \int_{t_1}^{t_2} Q dt \quad \text{(kJ)}$$

Heat transfer to the system is positive and heat transfer from system is negative.

3.2. Work

Work, like heat, is an energy interaction between a system and its surroundings. Therefore, if the crossing the boundary of a closed system is not heat, it must be work.

Work is also a form of energy has energy units such as kJ. The work done during a process between states 1and 2 is denoted $\boldsymbol{W_{12}}$ or $\boldsymbol{W}$. the work per unit mass of a system is denoted $\boldsymbol{w}$ and is defined as

$$w = \frac{W}{m}\, kJ/kg$$

The work done per unit time is called power and is denoted $\dot{W}$. The unit of the power is kJ/sec or kW. Work done by a system is positive, and work done on the system is negative, Figure 32.

Figure32 . The system and the effect of work and heat

Heat transfer and work are interaction between a system and its surroundings, and there are many similarities between phenomena.

1- Both are recognized at the boundaries of the system as they cross them. That, is both heat transfer and work are boundary phenomena.
2- Systems possess energy, but not heat transfer or work. That is, heat transfer and work are transfer phenomena.
3- Both are associated with a process, not a state. Unlike properties, heat transfer or work has no meaning at a state.
4- Both are path functions (i,e their magnitudes depend on the path followed during a process as well as the end states).

Path functions have inexact differentials designed by the symbol ***δ***. Therefore, a differential amount of heat or work is represented by ***δQ*** or ***δW*** respectively instead of ***dQ*** or ***dW***. Properties, however, are point functions and they have exact differentials designated by the symbol ***d***. A small change in volume, for example, is represented by ***dV*** and the total volume change during a process between 1 and 2 is

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

3.3. Type of Works

3.3.1 Electrical Work

When ***N*** coulombs of electrons moves through potential difference ***V***, the electrical work done is

$$W_e = VN (kJ)$$

which can also be expressed in the rate form as

$$\dot{W}_e = VI \ [kJ]$$

where $\dot{W}_e$ is the electrical power and ***I*** is the number of electrons flowing per unit time i.e. (the current).

$$W_e = \int_1^2 VIdt \ [kJ]$$

if both ***V*** and ***I*** remain constant during the time interval Δ***t***, this equation will reduce to

$$W_e = IV\Delta t \ [kJ]$$

the electrical work in fan, compressor and heater is negative.

3.3.2 Mechanical Form of Work

In elementary mechanics, the work done by a constant force ***F*** on a body which is displaced a distance ***S*** in the direction of force

$$W_m = FS \ [kJ]$$

If the force is not constant, the work done is obtained by adding the differential amounts of work

$$W_m = \int_1^2 F ds \quad [kJ]$$

Example 3.1:

Find the electrical work done by heating of voltage 240V and the current passes is 5A operates for 15 minutes.

Solution: V=240 V I=5A and Δt=15 minutes =900sec

$$W_e = VI\Delta t = 240 \times 5 \times 900 = 1102500\ J = 1102.5kJ$$

3.3.3 Shaft Work

Energy transmission with a rotation is very common in engineering practice. Often the torque ***T*** applied to the shaft is constant, which means that the force ***F*** applied is also constant. For a specified constant torque, the work done during ***n*** revolutions is a determined as follows: A force ***F*** acting through a moment arm ***r*** generates a torque ***T*** which is determined from.

$$T = Fr \rightarrow F = \frac{T}{r}$$

This force acts through a distance ***S***

$$S = (2\pi r)n$$

then the shaft work is determined from

$$W_{sh} = FS = \frac{T}{r}(2\pi rn) = 2\pi nT \quad [kJ]$$

The power transmitted through the shaft is the shaft work done per unit time, which can be expressed as

$$\dot{W}_{sh} = 2\pi\dot{n}T \quad [kW]$$

where $\dot{n}$ is number of revolution per second.

Example 3.2:

Determine the power transmitted through the shaft of a car when torque applied is 200N.m and the shaft rotates at a rate of 4000r.p.m

Solution: T=200N.m=0.2kN.m $\dot{n}$=4000rpm=4000/60 rps

$$\dot{W}_{sh} = 2\pi\dot{n}T = 2\pi\,\frac{40000}{60}0.2 = 83.7kW$$

3.3.4 Spring Work

It is common knowledge that when a force is applied on a spring, the length of the spring changes

When the length of the spring changes by differential amount ***dx*** under the force ***F***.

$$\delta W_{spring} = Fdx$$

$$and\ F = Kdx$$

where K= stiffness of spring or spring constant [kN/m]

$$W_{spring} = \int_1^2 kxdx = \frac{1}{2}K\left(x_2^2 - x_1^2\right)$$

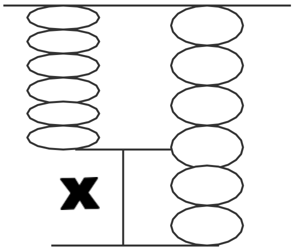


Figure33 .Spring work

The spring can be used in thermodynamic in the system with piston and cylinder. In this case the pressure in the cylinder can be changed with volume linearly.

$P = AV + B$ where A and B are constants

the work done can be calculated from the following equation

$$W = \frac{1}{2}A\left(V_2^2 - V_1^{\,2}\right) + B\left(V_2 - V_1\right)$$

or $$W = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

The process can be shown on a P-v diagram the triangle give the work of spring, and the lower rectangular give the work of the piston.

$$W_s = \frac{1}{2}(P_2 - P_1)(V_2 - V_1)$$

$$W_p = P_1\left(P_2 - P_1\right)$$

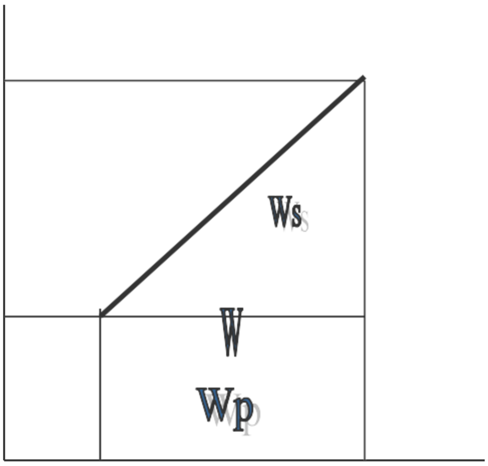


Figure34 . Spring work on p-v daigram

If the cross-sectional area of the piston and the spring stiffness are given the pressure on the cylinder at any moment can be calculated by the following equation

$$P = P_1 + \frac{K}{A_P^2}(V - V_1)$$

Where P_1 *and* V_1 *are due to piston effect only*

And the work can be represented by

$$W = P_1(V_2 - V_1) + \frac{K}{2A_P^2}(V_2 - V_1)^2$$

<u>Example 3.3</u>

A piston-cylinder device contains 0.05m^3 of a gas initially at 200kPa. At this state a linear spring which has a spring constant of 150kN/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 0.25m^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.

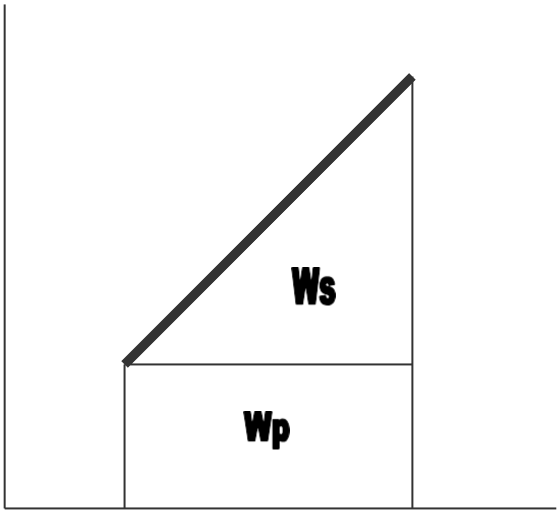
<u>Solution</u>: Given V_1 =0.05m^3
P_1=200kPa, V_2=2V_1=0.1m^3
K=150N/m^2, A_p=0.25m^2

(a) the final pressure

$$P_2 = P_1 + \frac{K}{A_p^2}(V_2 - V_1)$$

$$P_2 = 200 + \frac{150}{0.25^2}(0.1 - 0.05)$$

$$P_2 = 320kN/m^2$$



(b) the work done

$$W = P_1(V_2 - V_1) + \frac{K}{2A_p^2}(V_2 - V_1)^2$$

$$W = 200(0.1 - 0.05) + \frac{150}{2 \times 0.25^2}(0.1 - 0.05)^2$$

$$W = 13kJ$$

Or

$$W = \frac{(P_2 + P_1)}{2}(V_2 - V_1) = \frac{(320 + 200)}{2}(0.1 - 0.05) = 13kJ$$

© fraction of spring work from the total.

$$W_s = W - W_p$$

$$W_p = P_1(V_2 - V_1) = 200 \times (0.1 - 0.05) = 10kJ$$

$$Ws = 13 - 10 = 3kJ$$

$$Or \;\; W_s = \frac{P_2 - P_1}{2}(V_2 - V_1) = \frac{320 - 200}{2}(0.1 - .05) = 3kJ$$

$$Ws\% = \frac{W_s}{W} \times 100 = \frac{3}{13} \times 100 = 23\%$$

3.4. Moving Boundary Work

One form of mechanical work frequently encountered in practice is associated with the expansion and compression of a gas in a piston-cylinder device. During this process, part of boundary moves back and forth. Therefore, the expansion and compression work is often called moving boundary work, or simply boundary work.

Consider the gas enclosed in the piston-cylinder device shown in figure33. The initial pressure ***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*** in a quasi-equilibrium manner, the differential work done during this process is

$$\delta W_b = Fds = PAds = PdV$$

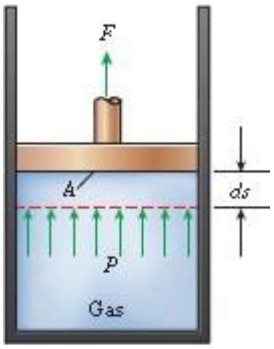


Figure 35. Piston cylinder device to show the boundary work.

That is, the boundary work in the differential form is equal to the product of the absolute pressure and the differential change in the volume ***dV*** of the system. This expression also explains why the moving boundary work is sometimes called the ***PdV*** work.

The total boundary work done during the entire process as the piston moves is obtained by adding all the differential works from the initial and final state:

$$W_b = \int_1^2 PdV$$

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 available. Note that

P=f(V) is simply the equation of the process path on ***P-V*** diagram. The quasi-equilibrium expansion process described above is shown on a ***P-V*** diagram in figure 34.

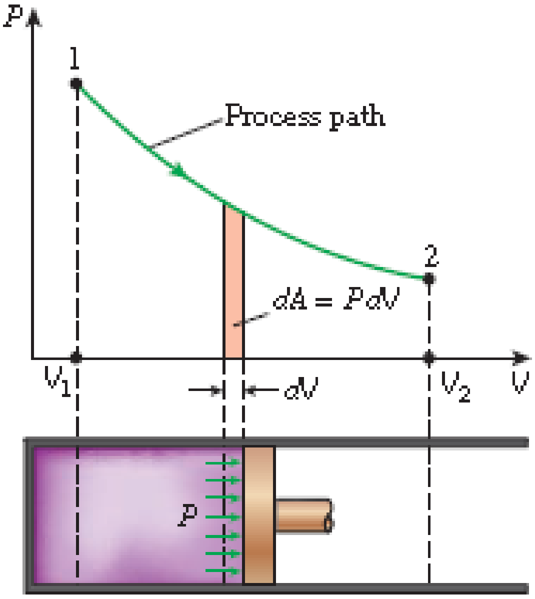


Figure 36. The area under the process curve on a P-V diagram represents the boundary work.

The area under the process curve on a P-v diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.

The gas can follow several different paths as it expands from state 1 to state 2. these paths represent different processes as follows

3.4.1. Constant volume process

In this process

$V = constant$

$dV = 0$

$W = \int_1^2 PdV = 0$

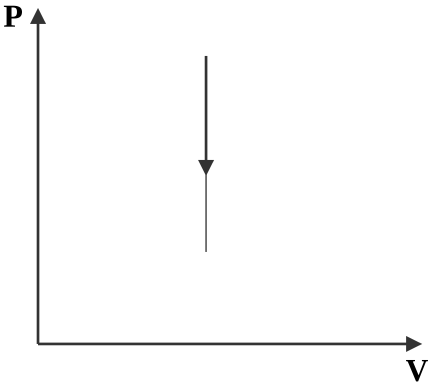


Figure37 . constant volume process

Example 3.4

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

Solution: Given T_1=150°C and P_1=500kPa

T_2=65°C and P_2=400kPa withno change in volume because the tank is rigid.

V=constant and dv=0 and so W=0

3.4.2. Constant Pressure Process (isobaric process)

$$P = constant$$

$$P = P_1 = P_2$$

$$W = \int_1^2 PdV = P(V_2 - V_1)$$

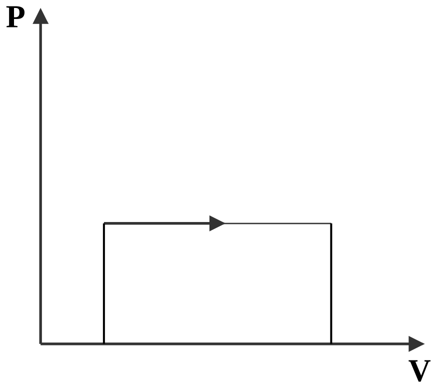


Figure38 . Constant Pressure process

in this process the work of ideal gas is

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

$$W = MR(T_2 - T_1)$$

and for vapor

$$W = mP(v_2 - v_1)$$

Example 3.5

Five kilograms of saturated vapor water at 1Mpa is contained in a cylinder fitted with a movable piston. This system is now heated at constant pressure until the temperature of the steam is 300°C. Calculate the work done by the steam during the process.

Solution: Given sat vapor water

m=5kg P_1=P_2=1MPa

T_2=300°C

From the saturated water table

$$v_1 = v_{g_{at 1MPa}} = 0.19444\, m^3/kg$$

$$T_{sat} = 179.91^o\, C$$

the second state is a super heated vapor because $T_2 > T_{sat}$

$$v_2 = v_{at\ iMPa\ 300^o C} = 0.2579 m^3/kg$$

the process is constant pressure expansion

$$W = mP(v_2 - v_1)$$

$$W = 5kg \times 1000kPa \times (0.2579m^3/kg - 0.19444m^3/kg)$$

$$W = 317.3kJ$$

3.4.3. Hyperbolic Process

In this process

$$PV = Const. = c \quad \rightarrow \quad P = \frac{c}{V}$$

$$W = \int_1^2 pdV = \int_1^2 \frac{c}{V} dV = c\int_1^2 \frac{dV}{V} = c \ln \frac{V_2}{V_1}$$

$$W = P_1V_1 \ln \frac{V_2}{V_1} = P_2V_2 \ln \frac{V_2}{V_1} = P_1V_1 \ln \frac{P_1}{P_2} = P_2V_2 \ln \frac{P_1}{P_2}$$

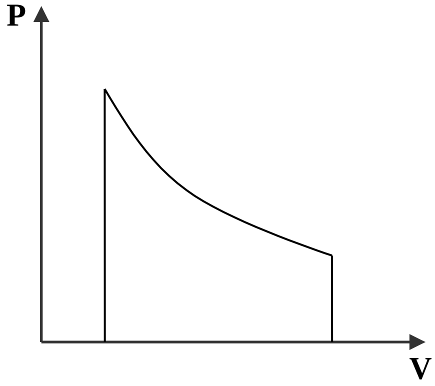


Figure39 . hyperbolic process

this process is called isothermal process for ideal gas(only), because for ideal gases when $PV = const.\ so\ \ T = const.$

Example 3.6

One tenth kg of saturated vapor water is at 2MPa is compressed in hyperbolic process to a pressure of 4MPa. Find the final temperature of the water and the work done.

Solution: Given m=0.1kg P_1=2MPa sat water vapor

P_2=4MPa and the process is PV=constant

At the first state $v_1 = v_{g\ \ at\ \ 2MPa} = 0.09963 m^3/kg$

$$P_2 v_2 = P_1 v_1 \quad OR \quad v_2 = v_1 \frac{P_1}{P_2} = 0.09963 m^3/kg \times \frac{2MPa}{4MPa} = 0.04982 m^3/kg$$

the sat. volume at 4MPa $v_g = 0.04978\, m^3/kg$

it is found that $v_2 > v_{g\ \ at\ \ 4MPa}$ so the state is superheated vapor

to find the temperature by using the superheated water table and interpolation as follows

T °C	$v \ m^3/kg$
250.4	0.04978
	0.04982
275.0	0.05457

$$T = 250.4 + \frac{(0.04982 - 0.04978)}{(0.05457 - 0.04978)}(275 - 250.4) = 250.6^o C$$

and the work can be calculated by

$$W = mP_1 v_1 \ln\frac{P_1}{P_2} = 0.1 \times 2000 \times 0.09963 \ln\frac{2}{4} = -13.812 kJ$$

3.4.4. Isothermal Process (Constant Temperature Process)

This process can be discussed separately for ideal gas and vapor

1- Ideal gas

when the temperature is constant ($T = constant$) and from the ideal gas equation of state, with no change in the mass ($PV = constant$) . the process becomes hyperbolic process and

$$W = P_1V_1 \ln\frac{V_2}{V_1} = P_2V_2 \ln\frac{V_2}{V_1} = P_1V_1 \ln\frac{P_1}{P_2} = P_2V_2 \ln\frac{P_1}{P_2}$$

$$PV = mRT$$

$$W = mRT \ln\frac{V_2}{V_1} = mRT \ln\frac{P_1}{P_2}$$

Example 3.7

One kilogram of air at 500°C is expanded isothermally from a pressure of 2MPa to a pressure of 0.5MPa, find the work done by the air.

Solution: Given Air of m=1kg at P_1=2MPa P_2=0.5MPa T_1=T_2=T=500°C

It is an ideal gas and isothermal process of expansion

$$W = mRT \ln\frac{P_1}{P_2} =$$

$$W = 1kg \times 0.287 \times (500 + 273.15) \ln\frac{2}{0.5} = 307.61 kJ$$

2-Substance with phase change

i- Saturated region

In saturated region when the temperature is constant the pressure is also constant because the pressure and temperature are dependent properties ***P=f(T)***. Therefore, the work in this process is the same to that as in constant pressure process

ii- Superheated region

In this region the temperature and pressure are not dependent properties $(P \neq f(T) \;\; only)$. Therefore, the process can be assumed as polytropic process $(PV^n = constant)$

Example 3.8

0.4kg of saturated liquid water at 120°C is vaporized in piston cylinder device isothermally until the volume of liquid becomes one tenth of the total volume. Find the work done by the system.

Solution: Given sat. liquid water m=0.4 kg T=120°C isothermally

$$V_{f2} = \frac{V_2}{10}, \quad V_{g2} = \frac{9V_2}{10}$$

as the water is still in the saturated region the expansion is also constant pressure of $P = P_{sat\ at\ 120^oC} = 198.53kPa$

$$v_f = 0.00106 m^3/kg \quad v_g = 0.8919 m^3/kg \quad v_1 = v_f = 0.00106 m^3/kg$$

$$V_{f2} = m_f v_f = \frac{V_2}{10} = \frac{mv_2}{10} \rightarrow v_2 = 10\frac{m_f}{m}v_f = 10(1-x)v_f$$

$$V_{g2} = m_g v_g = \frac{9V_2}{10} = \frac{9mv_2}{10} \rightarrow v_2 = \frac{10}{9}\frac{m_g}{m}v_g = \frac{10}{9}xv_g$$

$$v_2 = 10(1-x)v_f = \frac{10}{9}xv_g \rightarrow x = \frac{v_f}{\frac{1}{9}v_g + v_f} = \frac{0.00106}{\frac{0.8919}{9} + 0.00106} = 0.0106$$

$$v_2 = v_f + x(v_g - v_f) = 0.00106 + .0106(0.8919 - .00106) = 0.0105 m^3/kg \quad or$$

$$v_2 = \frac{10}{9}xv_g = \frac{10}{9} \times 0.0106 \times 0.8919 = 0.0105 m^3/kg$$

$$W = mP(v_2 - v_1) = 0.4 \times 198.53 \times (0.0105 - 0.00106) = 0.75kJ$$

3.4.5. Polytropic Process

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

$$W = \int_1^2 P\,dV$$

$$PV^n = c \quad \rightarrow \quad P = \frac{c}{V^n} = cV^{-n}$$

$$W = \int_1^2 cV^{-n}\,dV = \left.\frac{cV^{-n+1}}{1-n}\right|_1^2 = \left.\frac{PV^nV^{1-n}}{1-n}\right|_1^2 = \left.\frac{PV}{1-n}\right|_1^2$$

$$W = \frac{P_2V_2 - P_1V_1}{1-n}$$

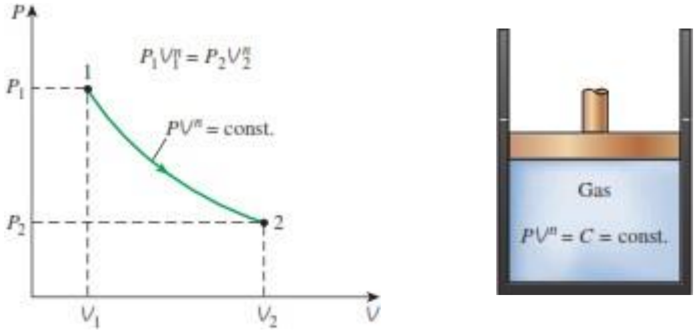


Figure40 . Polytropic process

For change phase substance, the polytropic process

$$W = \frac{m(P_2v_2 - P_1v_1)}{1-n}$$ where ν is the specific volume

the ideal gas polytropic process can be written as

$$W = \frac{P_2V_2 - P_1V_1}{1-n} \quad or \qquad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n$$

$$W = \frac{mR(T_2 - T_1)}{1-n} \qquad \frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$$

for ideal gas in polytropic process we can drive the following relation:

$$P_1V_1 = mRT_1 \qquad\qquad P_2V_2 = mRT_2$$
$$P_1V_1^n = C \quad \text{and} \quad P_2V_2^n = C$$

$$P_1V_1^{\,n} = P_2V_2^{\,n}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{n} = \left(\frac{T_2}{T_1}\right)^{\frac{n}{n-1}}$$

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} = \left(\frac{T_1}{T_2}\right)^{\frac{1}{n-1}}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}$$

for ideal gas only

Example 3.9

Carbon dioxide with mass of 5kg at 100kPa pressure and 300K temperature is compressed polyropically according to the law $PV^{1.32}=C$ until the pressure of 500kPa. Find (a) initial and final volume (b) the final temperature (c) the work done

Solution: Given CO_2 gas $m = 5kg \quad P_1 = 100kPa \quad T_1 = 300^oC$

$P_2 = 500kPa$ for CO_2 the gas constant R=0.2968kJ/kg.K

$$V_1 = \frac{mRT_1}{P_1} = \frac{5\times 0.1889\times 300}{100} = 2.8335m^3$$

$$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} = 2.8335\times\left(\frac{100}{500}\right)^{\frac{1}{1.32}} = 0.8371m^3$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = 300\times\left(\frac{500}{100}\right)^{\frac{1.32-1}{1.32}} = 443.2K$$

$$W = \frac{mR(T_2 - T_1)}{1-n} = \frac{5\times 0.1889(443.2-300)}{1-1.32} = 422.5kJ \quad or$$

$$W = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{500\times 0.8371 - 100\times 2.8335}{1-1.32} = -422.5$$

3.3 FIRST LAW OF THERMODYNAMICS

It is also known as the conservation of energy principle. It states that energy can be neither created nor destroyed; it can only change forms. The first law of thermodynamics, or the conservation of energy principle for a closed system or a fixed mass, may be expressed as follows:

$$\begin{bmatrix} Net \quad energy \quad transfer \\ to \ (or \quad from) \quad the \quad system \\ as \quad heat \quad and \quad work \end{bmatrix} = \begin{bmatrix} Net \quad increase \ (or \quad decrease) \\ in \quad the \quad total \quad energy \\ of \quad the \quad system \end{bmatrix}$$

or $$Q - W = \Delta E \qquad (kJ)$$

Where

Q=net heat transfer across system boundary ($= \sum Q_{in} - \sum Q_{out}$)

W=net work done in all forms ($= \sum W_{out} - \sum W_{in}$)

ΔE = net change in the total energy of system ($E_2 - E_1$)

the change in total energy of a system during a process can be expressed as the sum of the change in its internal, kinetic, and potential energies:

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

and by substituting this relation in the energy equation:

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

where

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{m}{2000}(V_2^2 - V_1^2)$$

$$\Delta PE = \frac{m}{1000}(Z_2 - Z_1)$$

Most closed system encountered in practice are stationary i.e. they do not involve any change in their velocity or the elevation of their center of gravity during a process. Thus for stationary closed system the change in kinetic and potential energies are negligible ($\Delta KE = \Delta PE = 0$), and the first – law relation reduces to

$$Q - W = \Delta U \quad (kJ)$$

Sometimes it is convenient to consider the work term in two parts: ***W***

Sometimes it is convenient to consider the work term in two parts: $\boldsymbol{W_{other}}$ and $\boldsymbol{W_b}$. where $\boldsymbol{W_{other}}$ represents all forms of work except the boundary work. Then the first law takes the following form:

$$Q - W_{other} - W_b = \Delta U \quad (kJ)$$

It is extremely important that the sign convention be observed for heat and work interactions. Heat flow to a system and work done by a system are positive and heat flow from a system and work done on a system are negative.

Other Forms of the First-Law Relation:

The first law relation for closed system can be written in various forms. It can be represented by unit mass:

$$q - w = \Delta u \quad (kJ/kg)$$

The rate form of the first law is Written as:

$$\dot{Q} - \dot{W} = \frac{dU}{d\tau} \quad (kW)$$

where $\dot{Q}$ is the rate of net heat transfer, $\dot{W}$ is the power, and $\frac{dU}{d\tau}$ is the rate of change of internal energy.

It can also be expressed in the differential form as

$\delta Q - \delta W = dU$

$\delta q - \delta w = du$

for a cyclic process, the initial and final state are identical, and therefore $\Delta U = U_2 - U_1 = 0$. then the first law relation for a cycle simplifies to

$Q - W = 0$

that is, the net heat transfer and network done during a cycle must be equal.

Example 3.10

A rigid vessel of .1m^3 volume contains refrigerant-12 5% liquid and 95% vapor by volume at 24^{o}C. the vessel is heated until the refrigerant exit as saturated vapor. Find (a) the initial pressure in the vessel (b) the mass of Refrigerant-12, (c) the final pressure and temperature, and (d) heat transfer occurs during the process:

Solution: Given V=0.1m^3 10% liquid 90% vapor T$_1$=24^{o}C second state is sat. vapor.

$V_f = 0.05V = 0.05 \times 0.1 = 0.005 m^3, \quad V_g = 0.95V = 0.95 \times 0.1 = 0.095 m^3$

and from the sat. R-12 table we find that the following properties at 24^{o}C

$$P_{sat} = 634.05 kPa, \quad v_f = 0.0007607 m^3/kg, \quad v_g = 0.02759 m^3/kg,$$

$$u_f = 58.25 kJ/kg, \quad u_g = 179.85 kJ/kg$$

The initial pressure: because the initial state is saturated mixture at 24^{o}C, then P$_1$=P$_{sat\ at\ 24\ ^oC}$ =634.05 kPa

The mass of R-12 in the vessel

$$m_f = \frac{V_f}{v_f} = \frac{0.005}{0.0007607} = 6.573 kg, \quad m_g = \frac{V_g}{v_g} = \frac{0.095}{0.02759} = 3.443 kg$$

$$m = m_f + m_g = 6.573 + 3.443 = 10.016 kg$$

(c) The final pressure and temperature of the R-12 in the vessel: the final state is saturated vapor with $v_2 = \frac{V}{m} = \frac{0.1}{10.016} = .01 m^3/kg$

and at the second state $v_g = v_2 = 0.01 m^3/kg$

From the pressure table, we find the following data and using extrapolation we can find the data at the v$_g$ =0.01m^3/kg

P kPa	T ^{o}C	v$_f$ m^3/kg	v$_g$ m^3/kg	u$_f$ kJ/kg	u$_g$ kJ/kg
1400	56.09	0.0008448	0.01222	90.28	191.11
1600	62.19	0.0008660	0.01054	96.80	192.95
1664.4	64.15	0.0008728	0.01	98.90	193.54

So P$_2$=1664.4kPa, T$_2$ =64.15^{o}C

(d)The heat transfer: because there is no change in volume so W=0

$$Q = m(u_2 - u_1)$$

$$u_1 = u_f + x(u_g - u_f) = 58.25 + 0.344(179.85 - 58.25) = 100.08 kJ/kg$$

$$u_2 = u_{g\ \text{at second state}} = 193.54 kJ/kg$$

$$Q = 10.016 \times (193.54 - 100.08) = 2940.9 kJ$$

Example 3.11

A rigid insulated tank of 0.5m^3, contains 5 kg of water at 100^{o}C. An electric heater is passing through the tank with a voltage of 200V and a current of 5A for 30 minutes. Find the final state of water.

Solution: Given V=0.5m^3, rigid, insulated Q=0, m=5kg water, T=100^{o}C, electric heater V=200Volt, I=5A, time=30minutes=1800sec.

The energy equation can be written as:

$$Q - W_e - W_b = \Delta U$$

where Q=0 for insulated tank, W$_b$=boundary work=0 rigid tank

W$_e$= electric work=$V \times I \times time /1000 = 200 \times 5 \times 1800 /1000 = 1800\ kJ$

This work is negative because it is done in the system.

$$-W_e = m\Delta u$$

$$-(-1800) = 5\Delta u$$

$$\Delta u = 360 kJ$$

from the first state T=100^{o}C, and $v_1 = \frac{V}{m} = \frac{0.5}{5} = .1 m^3/\sec$

and it is shown that the state is saturated mixture because $v_f < v_1 < v_g$

$$x_1 = \frac{v_1 - v_f}{v_g - v_f} = \frac{0.1 - .001044}{1.6729 - .001044} = .06$$

$$u_1 = u_f + x_1 u_{fg} = 418.94 + 0.06 \times 2087.6 = 542.5 kJ/kg$$

$$u_2 = u_1 + \Delta u = 542.5 + 360 = 902.5 kJ/kg$$

$$v_2 = v_1 = 0.1 m^3/kg$$

It is shown from the values of the internal energy and specific volume that the water is still saturated mixture. And by trial and error we can get the temperature or pressure.

$$T_2 = 134.9^o C, \quad P_2 = 312.3 kPa, \quad x = .1696 = 16.96\%$$

Example 3.12

A piston cylinder device contains water at 300kPa, and 250^{o}C with a volume of 0.4m^3. If the weight of the piston is required a pressure of 300kPa to rise it. The heat is transfer until the water become saturated mixture with quality of 80%. (a) prove that the heat transfer in a constant pressure process equal to the change in enthalpy. (b) the work done. (c) heat transfer during the process.

Solution: Given $P_1 = 300kPa, \ V_1 = 0.4m^3, \ T_1 = 250^o C$ constant pressure process.

$x_2 = 0.8$

for constant pressure process $W = P(V_2 - V_1) = PV_2 - PV_1$

the energy equation for closed system $Q = W + \Delta U$

$$Q = PV_2 - PV_1 + U_2 - U_1 = (P_2V_2 + U_2) - (P_1V_1 + U_1)$$

$$Q = H_2 - H_1 = \Delta H$$

For $P_1 = 300kPa, \quad T_1 = 250^oC,$ from superheated water table

$$v_1 = 0.7964m^3/kg, \quad u_1 = 2728.7kJ/kg, \quad h_1 = 2967.6kJ/kg$$

at state 2 $P_2 = 300kPa, \quad x_2 = 0.8$

$$v_2 = v_f + x(v_g - v_f) = 0.001073 + 0.8(0.6058 - .001073) = 0.4849m^3/kg$$

$$u_2 = u_f + xu_{fg} = 561.15 + 0.8 \times 1982.4 = 2147.07kJ/kg$$

$$h_2 = h_f + xh_{fg} = 561.47 + 0.8 \times 2163.8 = 2292.51kj/kg$$

$$m = \frac{V_1}{v_1} = \frac{0.4}{0.7964} = 0.5023m^3 / kg$$

$$W = mP(v_2 - v_1) = 0.5023 \times 300 \times (0.4849 - 0.7964) = -46.94kJ$$

(c) the heat transfer: it can be calculated by two ways,

(i) $Q = W + m\Delta u = -46.94 + 0.5023 \times (2147.07 - 2728.7) = -339.1kJ$

(ii) $Q = m\Delta h = 0.5023 \times (2292.5 - 2967.6) = -339.1kJ$

3.5. Specific heats:

The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree.

We are interested in two kinds of specific heats.

3.5.1 Specific Heat at Constant Volume *Cv*:

It is the energy required to raise the temperature of the unit mass of substance by one degree as the volume maintained constant.

$$Cv = \frac{\delta Q}{dT}$$

$$\delta Q = CvdT$$

In a closed system at a constant volume process of heating the energy equation can be written as:

$$\delta Q - \delta W = dU$$

and for constant volume

$$\delta W = 0$$

so

$$\delta Q = dU$$

$$CvdT = dU$$

and $Cv = \left(\frac{dU}{dT}\right)_V$

3.5.2 Specific heat at constant pressure C_p:

It is the energy required to raise the temperature of the unit mass of substance by one degree as the pressure maintained constant.

$$Cp = \frac{\delta Q}{dT}$$

$\delta Q = CpdT$ at constant pressure.

$$\delta Q - \delta W = dU$$

$$\delta Q = dU + Pdv = dH$$

$$CpdT = dH$$

$$Cp = \left(\frac{dH}{dT}\right)_P$$

Note: That ***Cp*** and ***Cv*** are expressed in terms of other properties, thus they must be properties themselves. Like any other property, the specific heats of a substance depend on the state which, in general, is specified by two independent, intensive properties. That is, the energy required to raise the temperature of substance by one degree will be different at different temperatures and pressures.

Example 3.13

Determine the specific heats at constant pressure and volume for saturated water vapor at 200^o

Solution: Given sat. water vapor T=200^oC

$$Cv = \frac{\Delta u}{\Delta T}, \quad C_p = \frac{\Delta h}{\Delta T}$$

we can take the temperature around 200^oC at sat vapor state

$$T_1 = 195^o C, \quad u_g = 2592.8 kJ/kg, \quad h_g = 2790 kJ/kg$$

$$T_2 = 205^o C, \quad u_g = 2597.5 kJ/kg, \quad hg = 2796.kJ/kg$$

$$Cv = \frac{2597.5 - 2592.8}{205 - 195} = 0.47 kJ/kg.K, \quad Cp = \frac{2796 - 2790}{205 - 195} = 0.6 kJ/kg.K$$

3.6. Internal energy, enthalpy and specific heat of ideal gas:

The equation of state of ideal gas:

$$Pv = RT$$

It has been demonstrated mathematically (Chap. 12) and experimentally (Joule, 1843) that for an ideal gas the internal energy is a function of the temperature only. That is,

$$u = u(T)$$

The enthalpy is also defining as a combined property of internal energy plus the product of pressure and specific volume.

$$\left.\begin{aligned} h &= u + pv \\ pv &= RT \end{aligned}\right\} h = u + RT$$

The ideal gas constant ***R*** is a constant of all gases so the enthalpy is function of temperature only like internal energy.

$$h = h(T)$$

and from the equation of definition of specific heat at constant pressure and volume. We can find the relation of calculating ***h*** and ***u***.

$$du = CvdT \rightarrow \Delta u = Cv\Delta T \rightarrow \Delta U = mCv\Delta T \rightarrow (U_2 - U_1) = mCv(T_2 - T_1)$$

$$dh = CpdT \rightarrow \Delta h = Cp\Delta T \rightarrow \Delta H = mCp\Delta T \rightarrow (H_2 - H_1) = mCp(T_2 - T_1)$$

and sometimes the values of *Cv* and *Cp* is function of *T*

$$du = Cv(T)dT \rightarrow \Delta u = \int_1^2 Cv(T)dT \rightarrow \Delta U = m\int_1^2 Cv(T)dT$$

$$dh = Cp(T)dT \rightarrow \Delta h = \int_1^2 Cp(T)dT \rightarrow \Delta H = m\int_1^2 Cp(T)dT$$

The values of the ideal gas constants (*Cp*, *Cv*, *R*, and the specific heat ratio $k = \frac{Cp}{Cv}$) are represented in a table of the ideal gas properties.

3.7. specific heat relations of ideal gases:

A special relationship between *Cp* and *Cv* for ideal gases can be obtained by differentiating the relation $h = u + RT$,which yields.

$$dh = du + RdT$$

and replacing dh by $CpdT$ and du by $CvdT$ so:

$$CpdT = CvdT + RdT$$

$$Cp = Cv + R \quad (kJ / kg.K)$$

When the specific heats are given on a molar basis, ***R*** in the above equation should be replaced by the universal gas constant ***R_u***

$$\overline{C}p = \overline{C}v + R_u \quad (kJ / kmol.K)$$

and there is another ideal gas property called the specific heat ratio k.

$$k = \frac{Cp}{Cv}$$

there are author relations relates these four constants. That are

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

$$Cp = \frac{kR}{k-1}$$

Example 3.14

Air is in a rigid tank of volume 1m^3 at initial pressure of 500kPa and temperature of 300K. It is heated to a final temperature of 700K.(a) find the final pressure in the tank, (b) the change in internal energy and enthalpy, (c) heat transfer to the system.

Solution: Given P_1=500kPa, T_1=300K, The tank is rigid with volume of V=1m^3 , T_2 =700K, from table of ideal gas properties.

R=0.287kJ/kg.K, Cp=1.005kJ/kg.K, Cv=0.718kJ/kg.K

(a)

$$P_2 = P_1 \frac{T_2}{T_1} = 500 \times \frac{700}{300} = 1166.67kPa$$

(b)

$$m = \frac{P_1 V}{RT_1} = \frac{500 \times 1}{0.287 \times 300} = 5.807kg$$

$$\Delta U = mCv(T_2 - T_1) = 5.807 \times 0.718 \times (700 - 300) = 1667.77kJ$$

$$\Delta H = mCp(T_2 - T_1) = 5.807 \times 1.005 \times (700 - 300) = 2334.414kJ$$

(c) because the tank is rigid, W=0

$$Q = \Delta U = 1667.77kJ$$

Example 3.15

Nitrogen gas is heated in a piston-cylinder device from 30^{o}C to 120^{o}C at constant pressure of 200kPa. The mass of nitrogen in the system is 0.2 kg. Find the work done and heat transfer during the process.

Solution: Given N_2, m=0.2 kg, T_1=30^{o}C=303K, T_2 =120^{o}C=393K at P=200kPa, from table R=0.2968kJ/kg.K, Cp=1.039kJ/kg.K

$$W = mR\Delta T = 0.2 \times 0.2968 \times (120 - 30) = 5.3424kJ$$

$$Q = mCp\Delta T = 0.2 \times 1.039 \times (120 - 30) = 18.702kJ$$

There are tables to give the properties of gases as real gases. These are ***h*** and ***u*** as a function ***T***, also we can use the heat capacity to find the internal energy and enthalpy as a function temperature. These two method give more accurate values for the property of gases.

3.8. Internal energy-enthalpy, and specific heat of solids and liquids:

The substance which has constant specific volume is called an incompressible substance. The specific volume of solids and liquids remains constant during a process. Therefore, liquids and solids can be approximated as incompressible substance.

It can be mathematically shown that the constant-volume specific heat is equal to constant-pressure specific heat. Therefore, for solids and liquids the subscripts on ***Cp*** and ***Cv*** can be dropped, and both specific heats can be represented by a single symbol ***C***. That is

$$Cp = Cv = C$$

Therefore, the change in internal energy can be calculated as:

$$du = CvdT = C(T)dT$$

$$\Delta u = u_2 - u_1 = \int C(T)dT \qquad (kJ/kg)$$

the change in enthalpy represented by

$$dh = du + d(Pv)$$

$$dh = du + vdP \qquad v = cons\tan t$$

$$\Delta h = \Delta u + v\Delta P$$

$$h_2 - h_1 = u_2 - u_1 + v(P_2 - P_1)$$

so for compressed liquid

$$h = h_f + v_f\left(P - P_{sat}\right)$$

Problems-3

3.1 Piston-cylinder device contains saturated liquid-vapor mixture of water at 100°C and volume of 0.1m^3, with 90% vapor and 10 % liquid. The system is heated at constant volume until the final state of saturated vapor. Find the work done, and the change in internal energy.

3.2 5kg of O_2 is heated at constant pressure in a closed system from 25°C to 300°C. If the initial volume 0.2m^3. find (a) the pressure in the system, (b) the final volume of the system, (c) the work done.

3.3 A piston-cylinder device contains 50kg of water at 200kPa with a volume of 0.1m^3. Stops in the cylinder restrict the enclosed volume to 0.5m^3, (Figure 41). The is now heated to 200°C. Find the final pressure, volume, and the work done by the water.

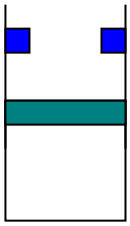


Figure41 . P3.3.

3.4 A piston cylinder device shown in Figure 42, initially contains air at 150kPa, 400°C. The setup is allowed to cool to the ambient temperature of 20°C. (a) Is the piston resting on the stops. What is the final pressure in the cylinder? (b) What is the specific work done by the air during this process.

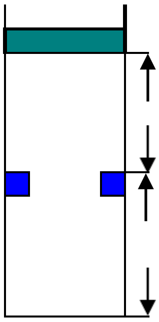


Figure 42. P3.4.

3.5 Saturated liquid water at 50°C is heated at constant temperature until it becomes saturated vapor. Find the work done per unit mass.

3.6 Piston-cylinder device contains 5kg of water liquid-vapor mixture with quality of 80% at 100kPa. It is compressed in such a process that (PV=c) until the final pressure is doubled. Find (a) the final state of vapor, (b) the work done.

3.7 A mass 1.5kg of air at 150kPa and 27°C is contained in a frictionless piston-cylinder device. The air is now compressed to a final pressure of 750kPa. During the process heat is transferred from the air such that the temperature inside the cylinder remains constant. Calculate (a) the initial and the final volume of the air, (b) the work done during the process.

3.8 Nitrogen at an initial state of 300K, 150kPa, and 0.2m^3 is compressed slowly in an isothermal process to a final pressure of 800kPa. Determine the work done during the process.

3.9 Water vapor at 300kPa and 300°C is compressed in hyperbolic process to 1000kPa. Find the final state of the vapor and the work done during this process per unit mass.

3.10 A gas is compressed from initial volume of 0.4m^3 to a final volume of 0.1m^3. During the quasi-equilibrium process, the pressure changes with volume according to the relation P=aV+b, where a=-1000kPa/m^3, and b=600kPa. Calculate the work done during this process.

3.11 A cylinder contains 0.085m^3 of a gas at 103.2kPa and 38°C. The gas is compressed according to the law $PV^{1.3}$=constant until the pressure is 550kPa. Determine the final temperature and the work done.

3.12 Carbon dioxide contained in a piston cylinder device is compressed from 0.3m^3 to 0.1m^3. During the process, the pressure and the volume are related by $P=aV^{-2}$, Where a =8kPa.m^6. Calculate the work done on the carbon dioxide during this process.

3.13 Hydrogen is contained in a piston-cylinder device at 100kPa and 1m^3. At this state, a linear spring($F\propto x$)with a spring constant of 200kN/m is touching the piston but exerts no force on it. The cross-sectional area of the piston is 0.8m^2. Heat is transferred to the hydrogen, causing it to expand until its volume doubles. Determine (a) the final pressure, (b)the total work done by the hydrogen, and (c) the fraction of the work done against the spring. Also show the process on a p-v diagram.

3.14 A piston-cylinder device contains 50kg of water at 150kPa and 25°C. The cross-sectional area of the piston is 0.1m^2. heat is now transferred to the water, causing part of it to evaporate and expand. When the volume reaches 0.2m^3, the piston reaches a linear spring whose spring constant is 100kN/m. More over heat is transferred to the water until the piston raises 20cm more.

Determine (a) the final pressure and temperature and (b) the work done during this process. Also show the process on a P-V diagram.

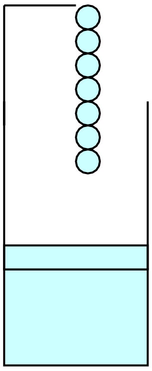


Figure 43. p3.14.

3.15 A paddle wheel supplies work at the rate of 0.75kW to a system, shown in figure P3.15. During a period of minute, the system expands in volume from 0.03m^3 to 0.09m^3 while the pressure remains constant at 500kPa. Find the net work done during this 1-min period.

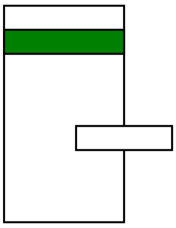


Figure 44. p3.15.

3.16 Consider the system shown in figure P3.16. The initial volume inside the cylinder is 0.1m^3. At this state the pressure inside is 100kPa, which just balances the atmospheric pressure out side plus the piston weight: the spring is touching nut exerts no force on the piston at this state. The gas is now heated until the volume is doubled. The final pressure of the gas is 300kPa, and during the process the spring force is proportional to the displacement of the piston from the initial position.

(a) Show the process on a P-V diagram

(b) Considering the gas inside as the system, calculating the work done by the system. What percentage of this work is done against the spring?

3.17 The cylinder shown in figure P3.17, contains 1kg of saturated water at 30°C. The piston has a cross-sectional area of $0.065m^2$, a mass of 40kg, and is resting on the stops as shown. The volume at this point is $0.1m^3$. Atmospheric pressure outside is 94kPa, and the local gravitational acceleration is $9.75m/sec^2$. Heat is now transferred to the system until the cylinder contains saturated vapor. (a) What is the temperature of the water when the piston first rises from the stops? (b) Calculate the work by the water during the overall process.

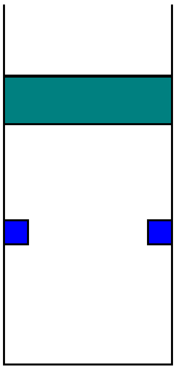


Figure 45. p3.17.

3.18 A balloon that is initially flat is inflated by filling it with air from a tank of compressed air. The final volume of the balloon is $5m^3$. The barometer reads 95kPa. Considering the tank, the balloon, and the connecting pipe as a system, calculate the work done during the process.

3.19 A spherical balloon contains 2kg of water at 250°C, 400kPa. The balloon material has an elasticity such that the pressure inside is always proportional to the balloon diameter. The water is now allowed to cool until the volume is one-half the initial volume.

3.20 Tank A shown in figure P.3.22 has a volume of 400L and contains argon gas at 250kPa, 30°C. Cylinder B contains a frictionless piston of a mass such that a pressure of 150kPa inside the cylinder is required to raise the piston. The valve connecting the two is now opened, allowing gas to flow into the cylinder. Eventually, the argon reaches a uniform state of 150kPa, 30°C throughout. Calculate the work done by the argon during this process.

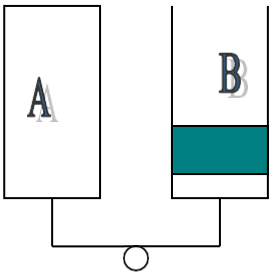


Figure 46. p3.22

3.21 A rigid tank containing 0.4m^3 of air at 400kPa and 30^{o}C is connecting by valve a piston-cylinder device with zero clearance. The mass of the piston is such that a pressure of 200kPa is required to raise the piston. The valve is now opened slightly, and air is allowed to flow into the cylinder until the pressure in the tank drops to 200kPa. During this process, heat is exchanged with the surroundings such that the entire air remains at 30^{o}C at all times. Determine the work done during this process.

3.22 Water initially at 50kPa, 100^{o}C is contained in a piston and cylinder arrangement with initial volume of 3m^3. the water is then slowly compressed according to the relation PV=constant until a final pressure of 1MPa is reached. Determine the work done for this process.

3.23 Fill in the missing data for each of the following processes of a closed system between states 1 and 2. (every thing in kJ)

	Q	W	U_1	U_2	ΔU
(a)	20	-6		35	
(b)	-13			4	-15
(c)		15	3		32
(d)	20		14		10

3.24 A closed system undergoes a cycle consisting of two processes. During the first process, 50kJ of heat is transferred to the system while the system does 80kJ of work. During the second process, 45kJ of work is done on the system. (a) Determine the heat transfer during the second process, and (b) calculate the network and the net heat transfer for the cycle.

3.25 A closed system undergoes a cycle consisting of three processes. During the first process, which is adiabatic, 50kJ of work is done on the system. During the second process,210kJ of heat is transferred to the system while no work interaction takes place. And during the third process, the system does 90kJ of work as it return to its state.
(a) determine the heat transfer during the last process.
(b) determine the net work done during this process.

3.26 A radiator of a steam heating system has a volume of 25L. At a time when this radiator is filled with saturated vapor steam at 225kPa, both valves to the radiator are closed. How much heat will have been transferred to the room when the steam pressure in the radiator has dropped to 100kPa?

3.27 A rigid 500L tank contains R-134a at 500kPa, 60°C. The tank is now cooled to 0°C. Determine the heat transfer for this process.

3.28 A well-insulated rigid tank contains 5kg of saturated liquid-vapor mixture of water at 125kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistor placed in the tank is connected to a 110V source, and a current of 10A flows through the resistor when the switch is turned on. Determine how long it will take place to evaporate all the liquid in the tank. Also, show the process on a T-v diagram with respect to saturation liners.

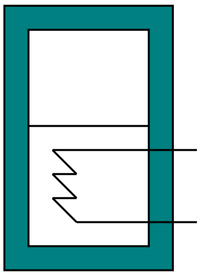


Figure 47. p3.32

An insulated tank is divided into two parts by a partition. One part of the tank contains 2.5kg of compressed liquid water at 50°C and 600kPa while the other part is evacuated. The partition is removed, and the water is expand to fill the entire tank. Determine the final temperature of the water and the volume of the tank for a final pressure of 10kPa.

3.29 An insulated piston-cylinder device contains 5L of saturated liquid water at a constant pressure of 150kPa. Water is stirred by a paddle wheel while a current of 10A flows for 40minuts through a resistor placed in the water. If one-half of the liquid is evaporated during this constant pressure process and the paddle wheel work amounts to 280kJ, determine the voltage of the source. Also, show the process on P-v diagram with respect to saturation lines.

3.30 A piston-cylinder device contains steam initially at 1MPa, 400°C, and 1.6m^3. Steam is allowed to cool at constant pressure until it first starts condensing. Show the process on T-v diagram with respect to saturation lines, and determine (a) the mass of the steam, (b) the final temperature, and (c) the amount of heat transfer.

3.31 A piston-cylinder device initially contains steam at 200kPa, 200°C, and 0.5m^3. At this state, a linear spring ($F \propto x$) is touching the piston but exerts no force on it. Heat is now slowly transferred to the system, causing the pressure and the volume to rise to 500kPa and 0.65m^3, respectively. Show the process on a P-v diagram with respect to saturation lines, and Determine

(a) the final temperature, (b) the work done by the steam, and (c) the total heat transfer.

3.32 Two rigid tanks are connected by a valve. Tank A contains 0.3m^3 of water at 400kPa and 80% quality. Tank B contains 0.5m^3 of water at 200kPa and 250°C. The valve is now opened, and the two tanks eventually come to the same state. Determine the pressure and the amount of heat transfer when the system reaches thermal equilibrium with the surrounding at 25°C.

3.33 A 4m x 5m x 7m room is heated by the radiator of steam heating system. The steam radiator transfer heat at a rate of 10000kJ/hr, and 100W fan is used to distribute the warm air in the room. The rate of heat loss from the room is estimated to be about 5000kJ/hr. If the initial temperature of the room air is 10°C, determine how long it will take for the air temperature to rise to 20°C.

3.34 An insulated rigid tank is divided into two equal parts by a partition. Initially, one part contains 3kg of an ideal gas at 800kPa and 50°C, and the other part is evacuated. The partition is now removed, and the gas expands into the entire tank. Determine the final temperature and pressure in the tank.

3.35 An insulated piston-cylinder device contains 100L of air at 400kPa and 25°C. A paddle wheel within the cylinder is rotated until 15kJ of work is done on the air while the pressure is held constant. Determine the final temperature of the air.

3.36 5kg of an ideal gas are heated by supplying 180kJ. During this process, the volume is held constant at 4m^3 and the pressure increases from 100kPa to 120kPa. Compute (a) the work done; (b) internal energy change of the gas; (c) density of the gas before and after the process.

3.37 One kg of air is compressed in a piston-cylinder device from 80kPa and 300K to 120kPa according to the law $P(v+0.2)$=constant, where P is in kPa an v in m^3/kg. Calculate the heat transfer. Assume air to be an ideal gas.

3.38 A cylinder contains 0.28 m^3 of an air at 103.5kPa and 29°C. the air is compressed according to the law $PV^{1.3}$=constant until the volume is reduced to 0.028m^3. Heat is then supplied at constant pressure until the volume becomes 0.056m^3. Determine; (a) the temperature and pressure at the end of each process, (b) the total change in internal energy, (c) the work done during each process, and (d) the total heat transfer.

3.39 During a polytropic process in a piston cylinder device, 0.182m^3 of air at 1.035bar and 300K is compressed until the pressure and temperature becomes 12.4bar and 282^{o}C respectively. Determine (a) the value of the index of compression, (b) the work done, (c) the change in internal energy, and (d) the heat transfer.

3.40 A balloon contains at the initial state 5kg of air at 100 kPa and 27^{o}C. the pressure in the balloon is directly proportional to the diameter square of the balloon. The air in the balloon is heated until the temperature becomes 377^{o}C. (a) find the final pressure and volume of the balloon, (b) the work done, and (c) the heat transfer.

3.41 A frictionless piston-cylinder device and a rigid tank initially contain 12kg of an ideal gas each at the same temperature, pressure, and volume. It is desired to raise the temperature of both systems by 15^{o}C. Determine the amount of extra heat must be supplied to the gas in the cylinder, which is maintained at constant pressure, to achieve this result. Assume the molar mass of the gas is 25.

3.42 Helium which is contained in a cylinder fitted with a piston expands slowly according to the relation $PV^{1.5}$=constant. The initial volume of the helium is 0.1m^3, the initial pressure is 500kPa, and the initial temperature is 300K. after expansion the pressure is 150kPa. Calculate the work done and heat transfer during the expansion.

3.43 An unknown mass of aluminum at 60^{o}C is dropped into an insulated tank which contains 40L of water at 25^{o}C and atmospheric pressure. If the final equilibrium temperature is 30^{o}C, determine the mass of the aluminum. Assume the density of liquid water to be 1000kg/m^3.

3.44 A 50kg mass of copper at 70^{o}C is dropped into an insulated tank which contains 80kg of water at 25^o.

Chapter four: First law of thermodynamic control volume

4.1. Thermodynamic analysis of control volume

A large number of engineering problems involve mass flow in and out of a system and, therefore, are modeled as control volumes. A water heater, car radiator, a turbine, and a compressor all involve mass flow and should be analyzed as control volumes (open system) instead of as control mass (closed system). In general, any arbitrary region in space can be selected as a control volume.

The boundaries of a control volume are called a control surface, and they can be real or imaginary (Fig 4.1).

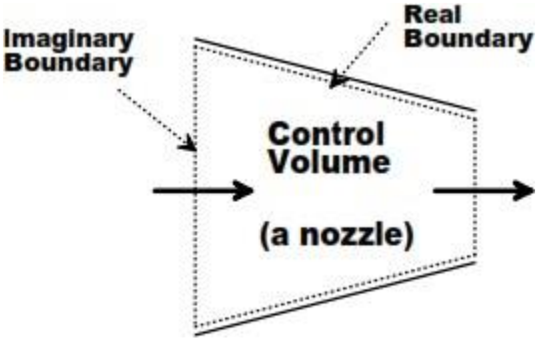


Fig 4.1 The Nozzle

A control volume can be fixed in size and shape, as in the case of a nozzle, or it may involve moving boundaries. Most control volumes, however, have fixed boundaries and thus do not involve any moving boundary work. A control volume may also involve heat and work interactions just as a closed volume, in addition to mass interaction.

A large variety of thermodynamic problems may be solved by the control volume analysis. Even it is possible to drive the relevant equations for the most general case and simplify them for special cases.

The terms steady and uniform used extensively in this chapter, and thus it is important to have a clear understanding of their meanings. The term steady implies no change with time. The opposite of steady is unsteady or transient. The term uniform, however implies no change with location over a specified region.

4.1.1. Mass and Volume Flow rate

The amount of mass flowing through a cross section per unit time is called the ***mass flow rate*** and denoted $\dot{m}$. As before, the dot over a symbol is used to indicate a quantity per unit time.

The mass flow rate of fluid flowing in a pipe or duct is proportional to the cross-sectional ***A*** of the pipe or duct, the density ρ , and the velocity ***C*** of the fluid. The mass flow rate through a differential area ***dA*** can be expressed as: -

$$d\dot{m} = \rho C_n dA$$

Where C_n is the velocity component normal to ***dA.***

The mass flow rate through the entire cross-section area of pipe or duct is obtained by integration.

$$\dot{m} = \int_A \rho C_n dA \quad \text{(kg/sec)}$$

In most practical application, the flow of a fluid through pipe or duct can be approximated to be one dimensional flow. That is, the properties can be assumed to vary in one dimension only (the direction of flow). As a result, all properties are uniform at any cross section normal to the flow direction, and properties are assumed to have bulk average values over the cross section. But the values of the properties at a cross section may change with time.

The integration result of the upper equation will give: -

$$\dot{m} = \rho C_{av} A \qquad \text{(kg/sec)}$$

or

$$\dot{m} = \rho C A \qquad \text{(kg/sec)}$$

Where:

ρ= density, kg/m^3 (=1/υ)
C=C_{av} = average fluid velocity normal to ***A***, m/sec
A= cross-sectional area normal to flow direction, m^2

The volume flow rate $\dot{V}$ through a cross-section per unit time

$$\dot{V} = \int C_{av} dA = CA \qquad \text{(m}^3\text{/sec)}$$

The mass and volume flow rates are related by

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

4.1.2. Conservation of Mass Principle

The conservation of mass is one of the most fundamentals principles in nature. Mass, like energy, is a conserved property, and it can not be created or destroyed.

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 volume, however, mass can cross the boundaries, that amount of mass entering and leaving the control volume (Fig 4.2).

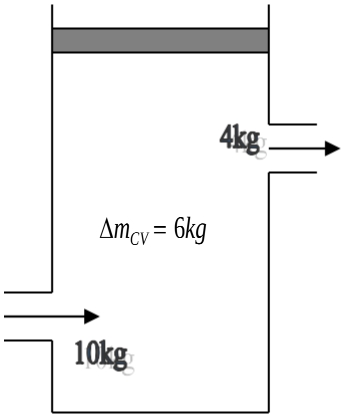


Fig. 4.2. Conservation of mass principle

The conservation of mass principle for a control volume ***CV*** undergoing a process can be expressed as

$$(Total\ mass\ entring\ CV) - (Total\ mass\ leaving\ CV) = (Net\ Chane\ in\ Mass\ Within\ CV)$$

or

$$\sum m_i - \sum m_e = \Delta m_{CV}$$

where the subscripts ***i***, ***e***, and ***CV*** stand for inlet, exit, and control volume, respectively.

The conservation of mass equation could also expressed in the rate form by expressing the equation per unit time. The conservation of mass equation is often referred to as the continuity equation in fluid mechanics.

4.1.3. Conservation of Energy Principle

For control volume, an additional mechanism can change the energy of a system: mass flow in and out the control volume. When mass enters a control volume, the energy of the control volume increases because the entering mass carries some energy with it. Likewise, when some mass leaves the control volume, the energy contained within the control volume decreases because the leaving mass takes out some energy with it.

Then the conservation of energy equation for control volume undergoing a process can be expressed as

$$\begin{pmatrix} Total\ energy \\ crossing\ boundary \\ as\ heat\ and\ work \end{pmatrix} + \begin{pmatrix} Total\ energy \\ of\ mass \\ entering\ CV \end{pmatrix} - \begin{pmatrix} Total\ energy \\ of\ mass \\ leaving\ CV \end{pmatrix} = \begin{pmatrix} Net\ change \\ in\ energy \\ of\ CV \end{pmatrix}$$

Or

$$Q - W + \sum E_{in} - \sum E_{out} = \Delta E_{CV}$$

Heat transfer to or from a control volume should not be confused with the energy transported with mass into and out of a control volume. Remember that heat is form of energy transferred as a result of a temperature difference between the control volume and the surroundings.

4.1.4. Flow Work

The energy required to push fluid into or out of a control volume is called the flow work, or flow energy. It is considered to be part of the energy transported with the fluid.

To obtain a relation for flow work, consider a fluid element of volume ***V*** as shown in fig. 4.3. The fluid immediately upstream will force this fluid element to enter the control volume; thus, it can be regarded as an imaginary piston. The fluid element can be chosen to be sufficiently small so that it has uniform properties throughout.

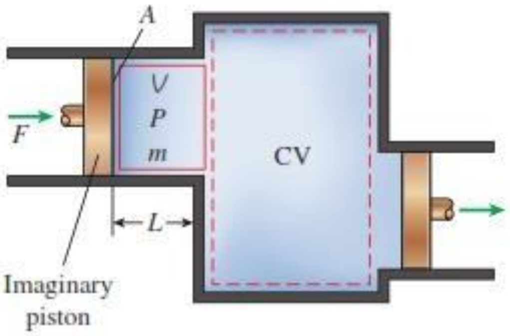


Fig.4.1.3. Schematic of flow work

If the fluid pressure is ***P*** and the cross-sectional area of the fluid element is ***A*** (fig. 4.4), the force applied on the fluid element by the imaginary piston is

$F = PA$

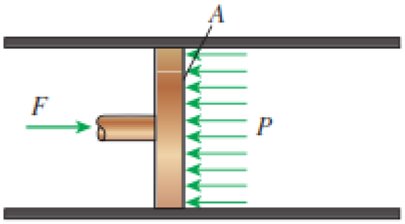


Fig. 4.1.4 The force applied on the piston by the fluid

To push the entire fluid element into the control volume, this force must act through a distance ***L***. Thus, the work done in pushing the fluid element across the boundary (i.e., the flow work) is

$W_{flow} = FL = PAL = PV$ (kJ)

The flow work per unit mass is obtained by dividing both sides of this equation by the mass of the fluid element:

$w_{flow} = P/\upsilon$ (kJ/kg)

4.1.5. Total Energy of a Flowing Fluid

As we discussed in Chapter 1, the total energy of a simple compressible system consists of three parts: internal, kinetic, and potential energies. On a unit mass basis, it is expressed as

$$e = u + ke + pe = u + \frac{C^2}{2000} + \frac{gz}{1000} \text{ (kJ/kg)}$$

where **C** is the velocity and **z** is the elevation of the system relative to some external reference frame.

The fluid entering or leaving a control volume possesses an additional form of energy- the flow energy ***Pv***, as discussed above. Then the total energy of a flowing fluid on a unit-mass basis (denoted by θ) becomes

$$\theta = P\upsilon + e = P\upsilon + (u + ke + pe)$$

But the combination $P\upsilon + u$ has been previously defined as the enthalpy ***h***, so the above relation reduces to

$$\theta = h + ke + pe = h + \frac{C^2}{2000} + \frac{gz}{1000} \qquad (kJ/kg)$$

Professor J. Kestin proposed in 1966 that the term $\boldsymbol{\theta}$ be called methalpy (from metaenthalpy, which means beyond enthalpy)

4.2. The steady- flow process

A large number of engineering devices such as turbines, compressors, and nozzles operate for long time under the same conditions, and they are classified as steady-flow devices.

The processes involving steady- flow devices can be represented reasonably well by a somewhat idealized process, called the steady-flow processes. A ***steady-flow process*** can be defined as a process during which a fluid flows through a control volume steadily. That is, the fluid properties can change from point to point within control volume, but at any fixed point they remain the same during the entire process. (Remember, steady means no change with time.) A steady- flow process is characterized by the following.

No properties (intensive or extensive) within the control volume change with time. Thus, the volume ***V***, and the mass m, and the total energy ***E*** of the control volume remain constant during a steady-flow process (fig. 4.5). As a result, the boundary work is zero for steady-flow system (since V_{CV}=constant), and the total mass or energy entering the control volume must equal to the total mass or energy leaving it (since m_{CV}=constant and E_{CV}=constant). These observations greatly simplify the analysis.

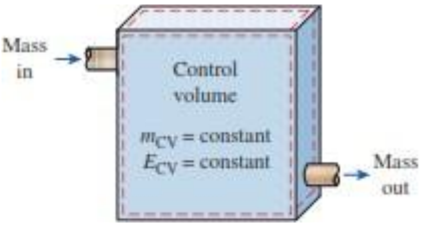


Fig. 4.5. Steady flow system

No properties change at the boundaries of the control volume with time. Thus, the fluid properties at an inlet or an exit will remain the same during the entire process. The properties may, however, be different at different openings (inlets and exits). They may vary over the cross section of an inlet or an exit. But all properties, including velocity and elevation, must remain constant with time at a fixed position.

The heat and work interaction between a steady-flow system and its surroundings do not change with time. Thus, the power delivered by a system and the rate of heat transfer to or from a system remain constant during a steady-flow process.

4.2.1. Conservation of Mass

During a steady-flow process, the total mass contained within a control volume does not change with time (***m_{CV}***= constant). The conservation of mass principle requires that the total amount of mass entering a control volume equal the total amount of mass leaving it (Fig. 4.6).

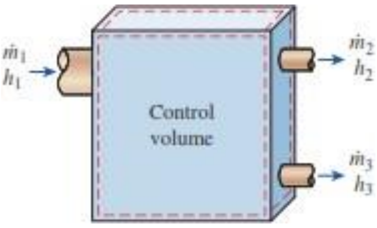


Fig. 4.6. Conservation of mass principle

The conservation of mass principle relation can be represented as

$$\begin{pmatrix} Total \quad mass \quad entering \quad CV \end{pmatrix} = \begin{pmatrix} Total \quad mass \quad leaving \quad CV \end{pmatrix}$$

$$\sum m_i = \sum m_e \ \text{kg}$$

It can be expressed in rate form as:

$$\begin{pmatrix} Total \quad mass \quad entering \quad CV \\ \\ per \quad unit \quad time \end{pmatrix} = \begin{pmatrix} Total \quad mass \quad leaving \quad CV \\ \\ per \quad unit \quad time \end{pmatrix}$$

$$\sum \dot{m}_i = \sum \dot{m}_e \qquad kg/\sec$$

where the subscript ***i*** stand for inlet and ***e*** stand for outlet. For single stream, steady flow systems.

$$\dot{m} = \dot{m}_i = \dot{m}_e \quad \text{kg/sec}$$

$$\rho_i C_i A_i = \rho_e C_e A_e$$

$$\frac{C_i A_i}{\upsilon_i} = \frac{C_e A_e}{\upsilon_e}$$

Where:

ρ = density, kg/m^3.

$\upsilon =$ specific volume, m^3/kg ($= 1/\rho$).

C= average flow velocity in flow direction, m/sec.

A= cross- sectional area normal to flow direction, m^2.

Example 4.1

Steam enters a steady-flow device at 4MPa and 300^{o}C with a velocity of 160m/sec. The entrance area is 6cm^2, and the exit area is 21cm^2. If the outlet conditions are 0.15MPa and 150^{o}C. Determine (a) the mass flow rate in kg/sec, and (b) the exit velocity in m/sec

Solution: - Given water vapor ***P$_i$***=4MPa, ***T$_i$***=300^{o}C, ***A$_i$***=6cm^2=0.0006m^3 ,and ***C$_i$***=160m/sec, ***P$_e$***=.15MPa, ***T$_e$***=150^{o}C, and ***A$_e$***=21cm^2=0.0021m^3

At ***P$_i$***=4MPa, and ***T$_i$***= 300^{o}C, ***υ$_i$***= 0.05887m^3/kg

$$\dot{m} = \frac{C_i A_i}{\upsilon_i} = \frac{160 \times 0.0006}{0.05887} = 1.631 kg/\sec$$

At P$_e$=0.15MPa, and T$_e$=150^{o}C, $\upsilon_e = \dfrac{1.9367 + 0.95986}{2} = 1.448 m^3/kg$

$$\dot{m} = \dot{m}_i = \dot{m}_e \quad \text{kg/sec}$$

$$\dot{m} = \frac{C_e A_e}{\upsilon_e}$$

$$C_e = \frac{\dot{m}_e \upsilon_e}{A_e} = \frac{1.631 \times 1.448}{0.0021} = 1124.6 m/\sec$$

Example 4.2

Air initially at 1.7bar and 80^{o}C flows through a cross-sectional area of 100cm^2 at a rate of 50kg/min. Downstream at another position the pressure is 3.4bars, the temperature is 80^{o}C, and the velocity is 15m/sec. Determine (a) the inlet velocity in m/sec, and (b) the outlet area in square centimeters.

Solution: - Given Air ***P$_i$***=1.7bar=170kPa, ***T$_i$***=80^{o}C=353K, and ***A$_i$***=100cm^2=0.01m^2, $\dot{m} = 50 kg/\min = 0.8333 kg/\sec$, ***P$_e$***=3.4bar=340kPa, ***T$_e$***=80^{o}C=353K, and ***C$_e$***=15m/sec. For air ***R***=0.287 kJ/kg.K

To find the density, the ideal gas equation is used that

$$P = \rho R T$$

or $\rho = \dfrac{P}{RT}$

$$\rho_i = \frac{p_i}{RT} = \frac{170}{0.287 \times 353} = 1.678 kg/m^3$$

$$\rho_e = \frac{P_e}{RT_e} = \frac{340}{0.287 \times 353} = 3.356 kg/m^3$$

To find the inlet velocity and the exit cross sectional area, the conservation of mass principle relation is used

$$\dot{m} = \rho AC$$

$$C_i = \frac{\dot{m}}{\rho_i A_i} = \frac{0.8333}{1.678 \times 0.01} = 49.66 m/\sec$$

$$A_e = \frac{\dot{m}}{\rho_e C_e} = \frac{0.8333}{3.356 \times 15} = 0.01655 m^2 = 165.5 cm^2$$

4.2.2. Conservation of Energy

It was pointed out earlier that during a steady-flow process the total energy content of a control volume remains constant (***E***E_{CV}=constant). That is, the change in total energy of the control volume during such a process is zero ($\Delta E_{CV} = 0$). Thus, the amount of energy entering a control volume in all forms (heat, work, mass transfer) must be equal to the amount of energy leaving it for a steady-flow process.

The conservation of energy principle for a general steady-flow system with multiple inlets and exits can be expressed verbally as

$$\begin{pmatrix} Total \quad energy \\ crossing \quad boundary \\ as \quad heat \quad and \quad wark \\ per \quad unit \quad time \end{pmatrix} = \begin{pmatrix} Total \quad energy \\ transported \quad out \quad of \\ CV \quad with \quad mass \\ per \quad unit \quad time \end{pmatrix} - \begin{pmatrix} Total \quad energy \\ transported \quad into \\ CV \quad with \quad mass \\ per \quad unit \quad time \end{pmatrix}$$

or

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \theta_e - \sum \dot{m}_i \theta_i$$

Where θ is the total energy of the flowing fluid, including the flow work, per unit mass. It can also be expressed as

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \left(h_e + \frac{C_e^2}{2000} + \frac{gz_e}{1000} \right) - \sum \dot{m}_i \left(h_i + \frac{C_i^2}{2000} + \frac{gz_i}{1000} \right) \qquad \text{(kW)}$$

since $\theta = h + ke + pe$. The equation is the general form of the first law relation for steady flow processes. The first law for steady- flow systems first appeared in 1859 in German thermodynamics book written by Gustav Zeuner.

For single-stream (one inlet, one exit) systems the summation over the inlets and exits drop out, and the inlet and exit states in this case are denoted by the subscripts ***i*** and ***e***, also respectively. The mass flow rate through the entire control volume remains constant $(\dot{m}_i = \dot{m}_e)$ and is denoted as $\dot{m}$. Then the conservation of energy equation for single-stream steady-flow system can be derived as follows: (fig 4.7)

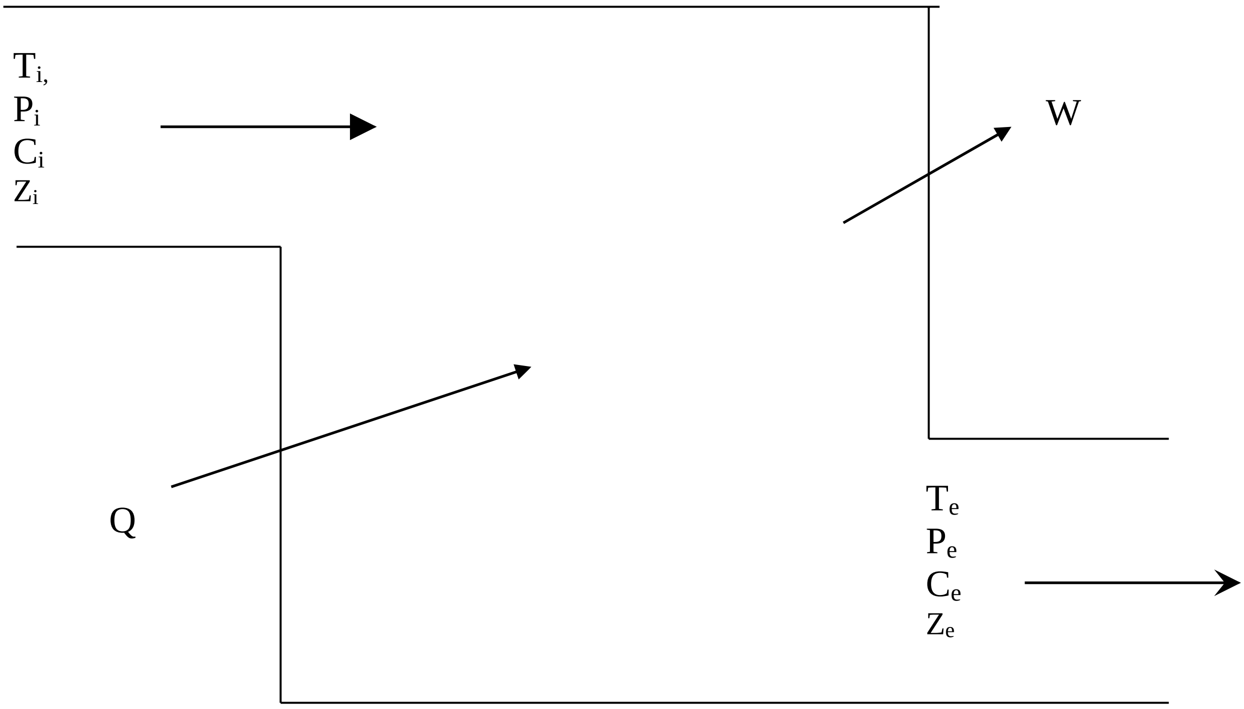


Fig. 4.7. single-stream steady flow system

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{C_e^2 - C_i^2}{2000} + \frac{g(z_e - z_i)}{1000}\right] \qquad \text{(kW)}$$

or $$\dot{Q} - \dot{W} = \dot{m}(\Delta h + \Delta ke + \Delta pe) \qquad \text{(kW)}$$

Dividing these equation by $\dot{m}$, we obtain the first –law relation on the unit mass basis as

$$q - w = h_e - h_i + \frac{C_e^2 - C_i^2}{2000} - g(z_e - z_i) \qquad \text{(kJ/kg)}$$

or $$q - w = \Delta h + \Delta ke + \Delta pe \qquad \text{(kJ/kg)}$$

where $q = \frac{\dot{Q}}{\dot{m}}$ (heat transfer per unit mass, kJ/kg)

$$w = \frac{\dot{W}}{\dot{m}} \quad \text{(work done per unit mass, kJ/kg)}$$

if the fluid experiences a negligible change in its kinetic and potential energies as it flows the control volume (that is $\Delta ke \cong 0,\ \Delta pe \cong 0$), then the energy equation for a single-stream steady-flow system reduces further to

$$q - w = \Delta h$$

4.3. Some steady-flow engineering devices

Steady-flow process is also called steady-state, steady-flow processes (SSSF) in which there is one fluid stream entering and one stream leaving the control volume, such that the first law can be written in the form known before

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{C_e^2 - C_i^2}{2000} + \frac{g(z_e - z_i)}{1000}\right] \quad \text{(kW)}$$

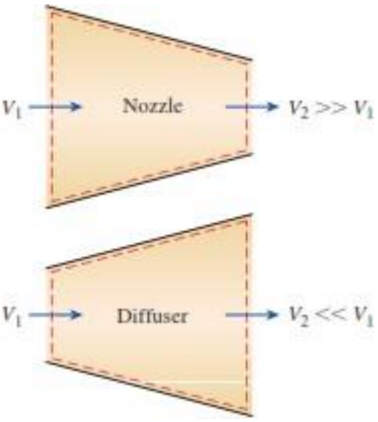
or

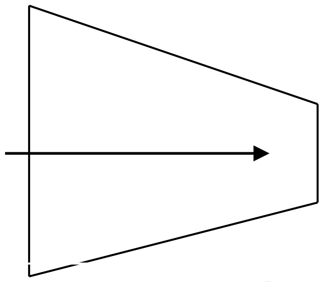
$$\dot{Q} - \dot{W} = \dot{m}(\Delta h + \Delta ke + \Delta pe) \quad \text{(kW)}$$

This equation has many application in engineering as a control volume with steady state steady flow process as following:

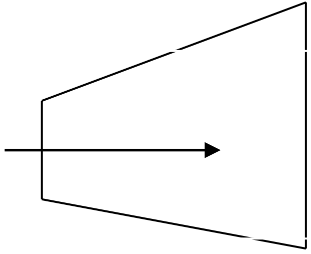
4.3.1. Nozzle and Diffuser

A nozzle is a device whose purpose is to increase the velocity of fluid at the expense of pressure. ***A diffuser*** is a device that increases the pressure of a fluid by slowing it down. That is, nozzle and diffuser perform opposite task. In general, the cross-section area of the nozzle and diffuser will different with the length of it. They are may be divergent, convergent, and convergent divergent as shown Fig. 4.8.

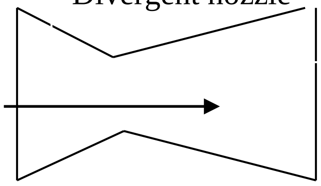




Convergent nozzle



Divergent nozzle



Convergent divergent nozzle

Fig.4.8 The nozzel

The relative importance of the terms appearing in the energy equation for nozzles and diffusers is as follows:

- $\dot{Q} = 0$. The rate of heat transfer between the fluid flowing through a nozzle or a diffuser and the surroundings is usually very small, even when these devices are not insulated.
- $\dot{W} = 0$. The work term for the nozzle and diffuser is zero. Since there is no shaft or electric work.
- $\Delta ke \neq 0$. Nozzle and diffuser usually involve very high velocities, and as the fluid passes through a nozzle or diffuser, it experiences large changes in its velocity.
- $\Delta pe = 0$. The fluid usually experiences little or no change in the in its elevation as it flows through the nozzle or diffuser.

So, the control volume energy equation for nozzle and diffuser can be written as:

$$\Delta h+\frac{\Delta ke}{2000}=0$$

$$(h_e-h_i)+\frac{C_e^2-C_i^2}{2000}=0$$

Sometimes the heat transfer may not negligible and in this state, can be considered in the equation of energy.

Example 4.3

An adiabatic diffuser is employed to reduce the velocity of a stream of air from 250 m/sec to 35 m/sec. The inlet pressure is 100 kPa, and the inlet temperature is 300°C. Determine the required outlet area if the mass flow rate is 7 kg/sec and the final pressure is 117 kPa.

Solution: Given an adiabatic diffuser $\boldsymbol{C_i}$=250 m/sec, $\boldsymbol{C_e}$=35 m/sec, $\boldsymbol{P_i}$= 100kPa, $\boldsymbol{T_i}$= 300°C=573K, $\boldsymbol{P_e}$ =117kPa, $\dot{m}=7kg$

For diffuser $\dot{Q}=0,\ \ \dot{W}=0,\ \ \Delta pe=0$

The conservation of energy equation is:-

$$\left(h_e-h_i\right)+\frac{C_e^2-C_i^2}{2000}=0$$

$$Cp(T_e-T_i)+\frac{C_e^2-C_i^2}{2000}=0$$

From this equation, the value of the exit temperature can be found

$$1.005(T_e-573)+\frac{35^2-250^2}{2000}=0$$

$\boldsymbol{T_e}$=603K

To find the density of the exit air, the ideal equation of state is used.

$$\rho_e=\frac{P_e}{RT_e}=\frac{117}{0.287\times 603}=0.676kg/m^3$$

To find the outlet area the conservation of mass equation is used.

$$\dot{m}=\rho_e A_e C_e\rightarrow A_e=\frac{\dot{m}}{\rho_e C_e}=\frac{7}{0.676\times 35}=0.296m^2$$

Example 4.4

Steam enters a nozzle at 3MPa and 325°C and leaves at 1.4MPa with a velocity of 535m/sec. The mass flow rate is 8000kg/h. neglecting the inlet velocity and considering adiabatic flow, compute (a) the exit enthalpy in kJ/kg, (b) the exit temperature and (c) the nozzle exit area.

Solution:- Given at the inlet: $\boldsymbol{P_i}$=3MPa, $\boldsymbol{T_i}$= 325oC, $\boldsymbol{C_i}$=0.0, $\dot{m}=8000kg/h=2.222kg/\sec$,at exit $\boldsymbol{P_e}$=1.4MPa, $\boldsymbol{C_e}$=535m/sec, $\boldsymbol{h_e}$=?, $\boldsymbol{T_e}$=?, and $\boldsymbol{A_e}$=?

From water vapor superheated properties table it is found at 3MPa, and 325°C,

$$h_i = \frac{2993.5 + 3115.3}{2} = 3054.4 kJ/kg$$

By using the conservation of energy equation

$$(h_e - h_i) + \left(\frac{C_e^2 - C_i^2}{2000}\right) = 0$$

$$h_e = h_i - \left(\frac{C_e^2 - C_i^2}{2000}\right) = 3054.4 - \left(\frac{535^2 - 0}{2000}\right) = 2848.98 kJ/kg$$

From the table of sat. vapor water compare $\boldsymbol{h_e}$ with $\boldsymbol{h_g}$ at 1.5MPa it is found that $\boldsymbol{h_e > h_g}$ so it is still superheated and from super-heated properties table of water at 1.4MPa.

$$T_e = 200 + \frac{(2848.98 - 2803.3)}{(2927.2 - 2803.3)}(250 - 200) = 218.43^o C$$

$$v_e = 0.14302 + \frac{(2848.98 - 2803.3)}{(2927.2 - 2803.3)}(0.16350 - 0.14302) = 0.1506 m^3/kg$$

Now we can find the area of the exit that

$$A_e = \frac{\dot{m}\upsilon_e}{C_e} = \frac{2.222 \times 0.1506}{535} = 0.000625\, m^2 = 6.25 cm^2$$

4.3.2. Turbine and Compressor

In steam, gas or hydraulic power plants the device, that drives the electric generator is the turbine. 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. The work done in the turbine since it is done by the fluid (Fig. 4.9).

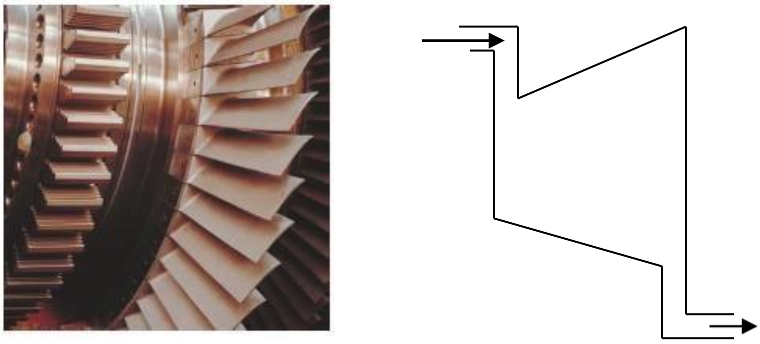


Fig.4.9 the turbine

Compressor, 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, the work term for compressor is negative since work is done on the fluid (Fig.4.10).

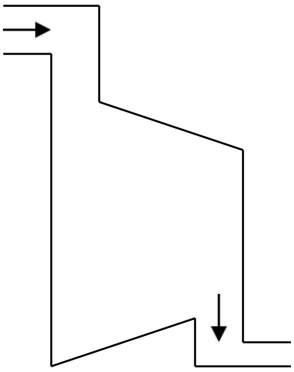


Fig. 4.10 the compressor

For turbines and compressors, the relative magnitudes of the various terms appearing in the energy equation are as follows:

- $\dot{Q} = 0$. The heat transfer for these devices is generally small relative to the shaft work unless there is intentional cooling (as for the case of a compressor).
- $\dot{W} \neq 0$. All these devices involve rotating shafts crossing their boundaries, therefore the work term is important.
- $\Delta pe \cong 0$. The potential energy change that a fluid experiences as it flows through the turbine, compressor, fun, and pump is usually very small and is normally neglected.
- $\Delta ke \cong 0$. The velocities of fluid involved with these devices is very small to cause any significant change in the kinetic energy.

Example 4.5:

Steam flows steadily through an adiabatic turbine the inlet conditions of the steam 10MPa, 450°C, and 80m/sec, and the exit conditions are 10kPa, 92 percent quality, and 50m/sec. The mass flow rate of the steam is 12kg/sec. Determine (a) the change in kinetic energy, (b)the power output, and (c) the turbine inlet area.

Solution:- Given steam at inlet to the turbine $\boldsymbol{P_i}$=10MPa, $\boldsymbol{T_i}$=450°C, and $\boldsymbol{C_i}$=80m/sec. At exit $\boldsymbol{P_e}$=10kPa, $\boldsymbol{x_e}$=0.92, $\boldsymbol{C_e}$=50m/sec. $\dot{m} = 12kg/\sec$

A. The change kinetic energy $\Delta ke = \dfrac{C_e^2 - C_i^2}{2000} = \dfrac{50^2 - 80^2}{2000} = -1.95kJ/kg$

power output,

For the turbine $\dot{Q} = 0, \quad adiabatic, \quad \Delta pe \cong 0$

From conservation of energy equation

$$-\dot{W} = \dot{m}(h_e - h_i) + \dot{m}(\Delta ke)$$

h_i= 3242.4kJ/kg, ***v_i***=0.029782m^3/kg

h_e=191.81+0.92 x 2392.1= 2392.5421kJ/kg

B. $\dot{W} = -12(2392.542 - 3240.9) - 12(-1.95) = 12521.29 kW$

C. The area at inlet

$$A_i = \frac{\dot{m}\upsilon_i}{C_i} = \frac{12 \times 0.029782}{80} = 0.0044673\, m^3$$

Example 4.6;

Calculate the power required by a compressor if air flowing at a rate of 0.8kg/sec enters at 100kPa, 7°C, with a velocity of 70m/sec, and leaves at 200kPa, 77°C, with a velocity of 120m/sec. Heat transferred from the air amounts to 15kJ/kg.

Solution:- Given: Air compressor, $\dot{m} = 0.8 kg/\text{sec}$, at inlet ***$P_i$***=100kPa, ***$T_i$***=7°C=280K, and ***$C_i$***=70m/sec, at exit ***$P_e$***=200kPa, ***$T_e$***=77°C=350K, ***$C_e$***=120m/sec, heat transfer ***q***=-15kJ/kg

Change in kinetic energy $\Delta ke = \dfrac{C_e^2 - C_i^2}{2000} = \dfrac{120^2 - 70^2}{2000} = 4.75 kJ/kg$

Change in enthalpy

$$\Delta h = h_e - h_i = Cp(T_e - T_i) = 1.005(350 - 280) = 70.35 kJ/kg$$

By using the energy conservation equation

$$\dot{m}q - \dot{W} = \dot{m}(\Delta h + \Delta ke)$$

$$0.8 \times (-15) - \dot{W} = 0.8(70.35 + 4.75)$$

$$-\dot{W} = 70.08 kW$$

$$or\ \dot{W} = -70.08 kW$$

The compressor work is negative

4.3.3. Throttling Valves

Throttling valves are any kind of flow- restricting devices that causes a significant pressure drop in the fluid. Throttling valves are usually small device fig. 4.11.

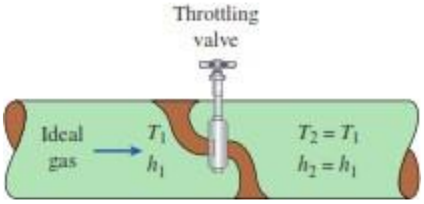


Fig. 4.11. Throttling valve

- $(q = 0)$, The flow through them may be assumed to be ***adiabatic***. since there is neither sufficient time nor large enough area for any effective heat transfer to take place.
- $(W = 0)$, There is no work done.
- $(\Delta pe = 0)$, The no change in potential energy.
- $(\Delta ke = 0)$, The increase in kinetic is insignificant.

Then the conservation of energy equation for this single-stream steady-flow device reduces to

$h_1 \cong h_2$ (kJ/kg)

Example 4.7;

Steam is throttled from 4MPa to 50kPa and 150°C. What is the quality of the steam entering the throttling process? If the inlet and exit velocities are essentially the same, what is the ratio of exit to inlet area for the device?

Solution: - Given throttling process at inlet $\boldsymbol{P_i}$=4MPa, $\boldsymbol{x_i}$=?, and at outlet $\boldsymbol{P_e}$=50kPa, $\boldsymbol{T_e}$=150°C, $\boldsymbol{C_i}=\boldsymbol{C_e}$

At outlet, $\boldsymbol{h_e}$=2780.1kJ/kg, $\upsilon_e = 3.148 m^3/kg$

$\boldsymbol{h_i}=\boldsymbol{h_e}$=2780.2kJ/kg at $\boldsymbol{P_i}$=4MPa

it is found that $\boldsymbol{h_i}$ is smaller than $\boldsymbol{h_g}$ at 4MPa so it is mixture and,

$$x_i = \frac{h_i - h_f}{h_{fg}} = \frac{2780.2 - 1087.4}{1713.5} = 0.988$$

$$\upsilon_i = \upsilon_f + x_i(\upsilon_g - \upsilon_f) = 0.001252 + 0.988(0.049779 - 0.001252) = 0.0492 m^3/kg$$

$$\dot{m} = \frac{A_i C_i}{\upsilon_i} = \frac{A_e C_e}{\upsilon_e} \text{ Continuity equation}$$

$$\frac{A_e}{A_i} = \frac{\upsilon_e}{\upsilon_i} = \frac{3.148}{0.04978} = 63.24$$

4.3.4. Mixing Chamber

In engineering applications, mixing two streams of fluids is not a rare occurrence. The section where the mixing process takes place is commonly referred to as a ***mixing chamber*** (Fig. 4.12).

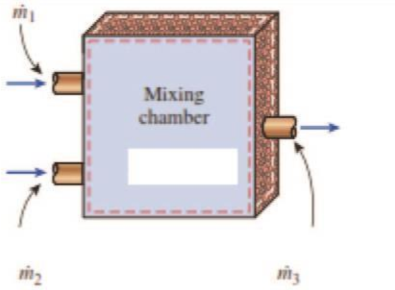


Fig.4.12 mixing chamber

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

- $(q = 0)$, Mixing chambers are usually well insulated.
- $(W = 0)$, do not involve any kind of work.
- $(ke = 0)$, the kinetic energy of fluid stream is usually negligible.
- $(pe = 0)$, the potential energy of fluid stream is usually negligible.

The conservation of mass and energy equations for mixing chamber can be written as following: -

$$m_1 + m_2 = m_3$$

$$m_3 h_3 - (m_1 h_1 + m_2 h_2) = 0$$

If the heat transfer is considered in the equation, then it can be added to the energy equation instead of zero. And they also can be written in form of rate.

Example 4.8:

Water is fed into a pipe line from two different sources. One source delivers steam of 90percent quality at a rate of 2000kg/h. the second source delivers steam at a rate of 1750kg/h at a temperature of 300°C. If the mixing process is adiabatic and at a constant pressure of 1MPa, determine the state of the mixture at equilibrium downstream.

Solution: mixing process at state (1) $\boldsymbol{P_1}$=1MPa, and $\boldsymbol{x_1}$=0.9 $\dot{m}_1 = 2000 kg/h$ at second state (2) $\boldsymbol{P_2}$ =1MPa, $\boldsymbol{T_2}$=300°C, $\dot{m}_2 = 1750 kg/h$.

By using the principle of conservation of mass

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 2000 + 1750 = 3750 kg/h$$

$$h_1 = 762.51 + 0.9 \times 2014.6 = 2575.65 kJ/kg$$

$$h_2 = 3051.6 kJ/kg$$

By using the principle of conservation of energy

$$\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$$

$$h_3 = \frac{\dot{m}_1 h_1 + \dot{m}_2 h_2}{\dot{m}_3} = \frac{2575.65 \times 2000 + 1750 \times 3051.6}{3750} = 2797.76 kJ/kg$$

$\boldsymbol{h_3} > \boldsymbol{h_g}$ at 1MPa then it is superheated

now to find its temperature by using interpolation

T	H
179.88	2778.1
T=?	2797.76
200	2828.3

T_3=185.84°C.

4.3.5. Heat Exchanger

Heat exchanger are devices where two moving fluid streams exchanges heat without mixing. Heat exchangers are widely used in various industries.

The simplest form of a heat exchanger is a double-tube (also called tube-and-shell) heat exchanger, shown in Fig. 4.13. 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 mixing chambers discussed earlier are sometimes classified as direct-contact heat exchangers.

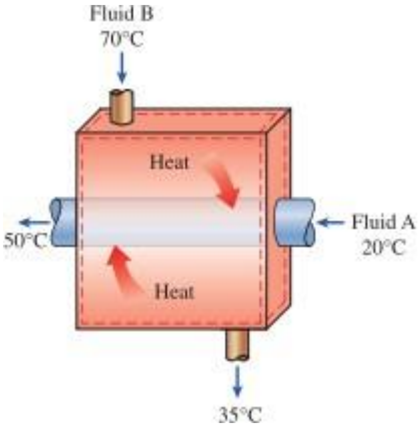
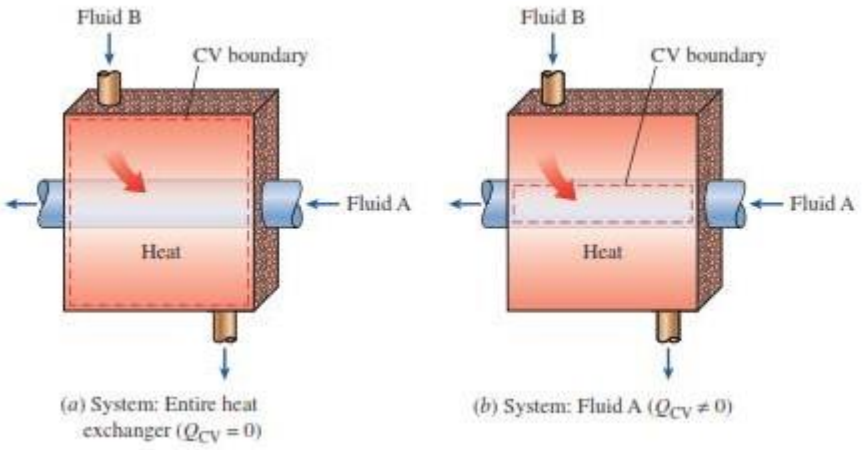


Fig. 4.13. Heat exchanger

- $(W = 0)$, Heat exchangers typically involve no work interactions.
- $(\Delta pe = 0)$, negligible potential energy change for each fluid.
- $(\Delta ke = 0)$, negligible kinetic energy change for each fluid.

When the entire heat exchanger is selected as the control volume, $\dot{Q}$ becomes zero, since the boundary for this case lies just beneath the insulation and little or no heat crosses the boundary (Fig. 4–14). If, however, only one of the fluids is selected as the control volume, then heat will cross this boundary as it flows from one fluid to the other and $\dot{Q}$ will not be zero. In fact, $\dot{Q}$ in this case will be the rate of heat transfer between the two fluids.



(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

(*b*) System: Fluid A ($Q_{CV} \neq 0$)

Fig.4.14. The heat transfer associated with a heat exchanger may be zero or nonzero depending on how the control volume is selected.

The conservation of energy equation can be written as:-

$$\dot{Q} = \dot{m}_a \left(h_{a2} - h_{a1}\right) + \dot{m}_b \left(h_{b2} - h_{1b}\right)$$

For adiabatic heat exchanger, the term of heat transfer rate can be equal to zero. Heat exchanger is like the condenser, evaporator, boiler, feed water heater, radiator, and so on.

Example 4.9:

Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (a) the mass flow rate of the cooling water required and (b) the heat transfer rate from the refrigerant to water.

Solution: Given: For water, P_1=300 kPa, T_1=15°C, T_2=25°C. For R-134a, P_3=1MPa and T_3=70°C $\dot{m}_R = 6 kg/\text{min}$, T_4=35°C

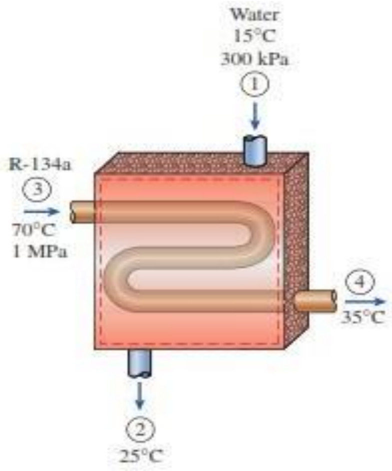


Fig. 4.15. Schematic for Example4–9.

Mass balance:

$$\dot{m}_{in} = \dot{m}_{out}$$

For each fluid stream since there is no mixing. Thus,

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

For no heat transfer the conservation of energy equation is

$$\Delta H = 0$$

$$\dot{m}_w\left(h_2 - h_1\right) + \dot{m}_R\left(h_4 - h_3\right) = 0$$

$$\dot{m}_w\left(h_1 - h_2\right) = \dot{m}_R\left(h_4 - h_3\right)$$

Now we need to determine the enthalpies at all four states. Water exists as a compressed liquid at both the inlet and the exit since the temperatures at both locations are below the saturation temperature of water at 300 kPa.

Approximating the compressed liquid as a saturated liquid at the given temperatures, (Table A-4) we have

$$h_1 = h_{f\,@15^\circ c} = 62.982\ kJ\ /\ kg$$

$$h_2 = h_{f\,@25^\circ c} = 104.83\ kJ\ /\ kg$$

The refrigerant enters the condenser as a superheated vapor and leaves as a compressed liquid at 35°C. From refrigerant-134a tables,

$$h_3 = 303.87\ kJ\ /\ kg$$

$$h_4 = h_{f\,@35^\circ c} = 100.88\ kJ\ /\ kg$$

$$\dot{m}_w\left(62.982 - 104.83\right) = 6\left(100.88 - 303.87\right)$$

$$\dot{m}_w = 29.1\ kg\,/\,\mathrm{min}$$

To determine the heat transfer from the refrigerant to the water, we have to choose a control volume whose boundary lies on the path of heat transfer. We can choose the volume occupied by either fluid as our control volume. For no particular reason, we choose the volume occupied by the water. All the assumptions stated earlier apply, except that the heat transfer is no longer zero. Then assuming heat to be transferred to water, the energy balance for this single-stream steady-flow system reduces to

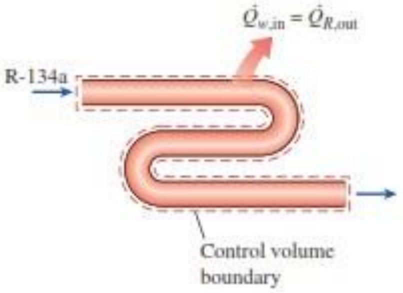


Fig. 4.16. In a heat exchanger, the heat transfer depends on the choice of the control volume.

$$\dot{Q}_{w,in} = \dot{m}_w(h_2 - h_1) = 29.1(104.83 - 62.982) = 1218 kJ/kg$$

4.3.6. Pipe and Duct Flow

The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications. Flow through a pipe or a duct usually satisfies the steady-flow conditions and thus can be analyzed as a steady-flow process.

When the flow through pipes or ducts is analyzed, the following points should be considered:

- $\dot{Q} \neq 0$, Under normal conditions, the amount of heat gained or lost by the fluid may be very significant.
- $\dot{W} \neq 0$, If the control volume involves a heating section (electric wires), a fan, or a pump(shaft), the work term interactions should be considered.
- $\Delta ke \cong 0$, The velocities involved in pipe and duct flow are relatively, same, so the change in kinetic energy is negligible.
- $\Delta pe \neq 0$, In pipe and duct, the fluid may undergo a considerable elevation change. Thus, the potential energy term may be significant. This is particularly true for flow through insulated pipes and ducts where the heat transfer does not overshadow other effects.

Example 4.10:

A house has an electric heating system that consists of 300W fan and an electric resistance heating element placed in a duct. Air flows steadily through the duct at a rate of 0.6kg/sec and experiences a temperature rice of 5°C. the rate of heat loss from the air in the duct is estimated to be 400W. determine the power rating of the electric resistance heating element.

Solution: - Given duct With Air flow rate $\dot{m} = 0.6 kg/\sec, \Delta T = 5^o C$ temperature rice, Fan with power, $\dot{W}_f = -300W$ and heat loss of $\dot{Q} = -400W$. from conservation of energy equation

$$\dot{Q} - \dot{W}_f - \dot{W}_e = \dot{m}Cp\Delta T$$

$$-400 - (-300) - \dot{W}_e = 0.6 \times 1005 \times 5$$

$$\dot{W}_e = -3115W$$

$$or \quad the \quad electric \quad element \quad power \quad rating = 3.115kW$$

4.4. Uniform-state, uniform-flow process

Many processes of interest in thermodynamics involve unsteady flow and do not fit into category. A certain group of these-for example, filling closed tanks with gas or liquid, or discharge from closed vessels- can be reasonably represented to a first approximation by another simplified model. We call process the uniform-state, uniform-flow process, or for convenience, the USUF process. The basic assumptions are as follows:-

- The control volume remains constant relative to the coordinate frame.
- The state of the mass within the control volume may change with time, but at any instant of time the state is uniform throughout the entire control volume (or over several identifiable regions that make up the entire control volume.
- The state of the mass crossing each of the areas of flow on the control surface is constant with time although the mass flow rates may be time varying.

4.4.1. Conservation of mass

Unlike the case of steady flow process, the amount of the mass within the control volume does change with time during unsteady-flow process. The degree of change depends on the amount of mass that enters and leaves the control volume during the process. Thus, the conservation of mass principle for a control volume (***CV***) undergoing any unsteady-flow process for time interval Δt can be expressed

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

or $$\sum m_i - \sum m_e = \Delta m_{CV}$$

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

Where the subscripts are ***i***=inlet, ***e***=exit, ***1***=initial state of CV, ***2***=final state of CV

For single inlet and exit system

$$m_i - m_e = m_2 - m_1$$

4.4.2. Conservation of energy

Unlike the case of steady-state processes, the energy content of a control volume changes with time during an unsteady-flow process. The degree of change depends on the amount of energy transfer across the system boundaries as heat and work as well as on the amount of energy transferred into and out of the control volume by mass during the process. Thus, the conservation of energy principle for a control volume undergoing any unsteady-flow process for a time interval Δt can be expressed as

$$\begin{pmatrix} \text{Total energy} \\ \text{crossing boundary} \\ \text{as heat and work} \end{pmatrix} + \begin{pmatrix} \text{Total energy} \\ \text{transported by} \\ \text{mass into CV} \\ \text{during } \Delta t \end{pmatrix} - \begin{pmatrix} \text{Total energy} \\ \text{transported by} \\ \text{mass out of CV} \\ \text{during CV} \end{pmatrix} = \begin{pmatrix} \text{Net change} \\ \text{in energy} \\ \text{of CV} \\ \text{during } \Delta t \end{pmatrix}$$

OR

$$Q - W + \sum \theta_i - \sum \theta_e = \Delta U_{CV} \text{ kJ}$$

Where θ represents the total energy transported by mass into or out of a control volume through an inlet or exit during the process. The energy equation can also have expressed in the rate form as follows

$$\dot{Q} - \dot{W} + \sum \dot{\theta}_i - \sum \dot{\theta}_e = \frac{dU_{CV}}{dt} \quad \text{(kW)}$$

The energy equation for uniform-state, uniform-flow process

$$Q - W = \sum m_e \left(h_e + \frac{C_e^2}{2000} + \frac{g z_e}{1000} \right) - \sum m_i \left(h_i + \frac{C_i^2}{2000} + \frac{g z_i}{1000} \right) + \left(m_2 u_2 - m_1 u_1 \right)$$

Q= Total heat transfer between the control volume and the surrounding during the process

W= total work associated with the control volume.

m_e =mass leaving the control volume

m_i =mass entering the control volume

m_1=initial mass in the control volume

m_2= final volume in the control volume

$U_1 = m_1 u_1$= total initial internal energy of the control volume

$U_2 = m_2 u_2$= Total final internal energy of the control volume

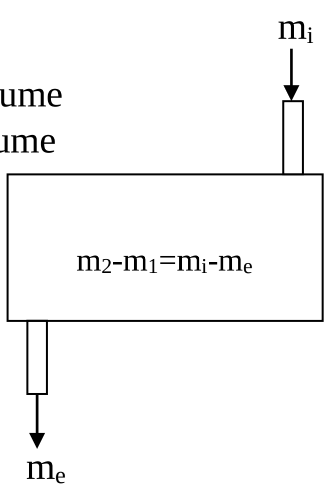


Fig.4.17. uniform flow uniform state process

Example 4.11

Steam at a pressure of 1.4MPa, 300°C is flowing in a pipe. Connected to this pipe through a valve is an evacuated tank. The valve is opened and the tank fills with steam until the pressure is 1.4MPa, and then the valve is closed. The process takes place adiabatically and kinetic energies and potential energies are negligible. Determine the final temperature of the steam.

Solution: uniform state, uniform flow process.

Pipe line with steam P_i=1.4MPa, T_i=300°C, from steam table at this condition, h_i=3040.4kJ/kg.

The tank is evacuated initially. m_1=0

Finally it become at the pressure of 1.4MPa so P_2=1.4MPa

There is charging only so m_e=0

From conservation of mass principle

$$m_2 - m_1 = m_i - m_e$$

$$m_2 = m_i$$

from the conservation of energy principle

$$Q - W = (m_2 u_2 - m_1 u_1) + (m_e h_e - m_i h_i) + (m_e ke_e - m_i ke_i) + (m_e pe_e - m_i pe_i)$$

for adiabatic and rigid tank **Q**=0, **W**=0

for neglecting potential and kinetic energy

$$0 = m_2 u_2 - m_i h_i$$

$u_2 = h_i = 3040.4 kJ/kg$ at 1.4MPa

from steam table at **P**=1.MPa, and **u**=3040.4

$$T_2 = 400 + (500 - 400)\frac{3040.4 - 2952.5}{3121.1 - 2952.5} = 452.13^o C$$

Example 4.12

A pressurized tank contains 1.5kg of air at 200kPa and 60°C. Mass is allowed to flow from the tank until the pressure reaches 100kPa. However, during the process heat is added to air within the tank to keep the temperature constant. How much heat is transferred during the process? Assume constant specific heats.

Solution: Tank contains air with initial state P_1=200kPa, T_1=60°C= 333K, m_1=1.5kg

The final state P_2=100kPa, T_2=333K, V_2=V_1,

T_e=333K

By using the ideal gas equation

$$V = \frac{m_1 RT}{P_1} = \frac{1.5 \times 0.287 \times 333}{200} = 0.717 m^3$$

to find the final mass in the tank

$$m_2 = \frac{P_2 V}{RT} = \frac{100 \times 0.717}{0.287 \times 333} = 0.75 kg$$

The mass of that leaves the tank can be calculated from the principle of mass conservation

$$m_i - m_e = m_2 - m_1$$

$$m_i = 0$$

$$m_e = m_1 - m_2 = 1.5 - 0.75 = 0.75kg$$

to find the heat transfer from or to the tank, we can use the conservation of energy equation for uniform-state, uniform flow process, where **W**=0.0,

$$\Delta pe = 0.0, \ \Delta ke = 0.0$$

$$Q = \left(m_2 u_2 - m_1 u_1\right) + \left(m_e h_e - m_i h_i\right)$$

$$T_1 = T_2 = T_e = 333K, \quad m_i = 0.0, \quad ideal \quad gas$$

$$Q = (0.75 \times 0.718 \times 333 - 1.5 \times 0.718 \times 333) + (0.75 \times 1.005 \times 333 - 0)$$

$$Q = 0.75 \times 333 \times (1.005 - 0.718) = 71.678kJ$$

Example 4.13

A vertical piston cylinder device initially contains 0.01m^3 of steam at 200°C. The mass of the frictionless piston is such that it maintains a constant volume of 500kPa inside. Now steam at 1MPa and 350°C is allowed to enter the cylinder from a supply line until the volume inside doubles. Neglecting any heat transfer that may have taken place during the process, determine (a) the final temperature of the steam in the cylinder and (b) the amount of mass that has entered.

Solution: piston/cylinder device , Steam,

Initial state **V_1**=0.01m^3, **T_1**=200°C, **P_1**= 500kPa, from steam table at this state, υ_1=0.4249m^3/kg, **u_1**=2642.9kJ/kg, **h_1**=2855.4kJ/kg

At the final state **V_2** =2**V_1**=0.02m^3, **P_2**= **P_1**=500kPa,

The inlet steam condition **P_i**=1MPa, **T_i** =350°C, **h_i**=3157.7kJ/kg

By using the uniform-state, uniform-flow equation of energy

$$m_1 = \frac{V_1}{\upsilon_1} = \frac{0.01}{0.4249} = 0.0235kg$$

$$-W = (m_2 u_2 - m_1 u_1) + (m_e h_e - m_i h_i)$$

$$-(P_2 V_2 - P_1 V_1) - (U_2 - U_1) = -m_i h_i \qquad where \quad m_e = 0$$

$$H_2 - H_1 = m_i h_i$$

$$m_2 h_2 - m_1 h_1 = m_2 h_i - m_1 h_i$$

$$\frac{V_2}{\upsilon_2} h_2 - m_1 h_1 = \frac{V_2}{\upsilon_2} h_i - m_1 h_1$$

$$\frac{0.02}{\upsilon_2}h_2 - 0.0235\times 2855.4 = \frac{0.02}{\upsilon_2}\times 3157.7 - 0.0235\times 3157.7$$

$$\frac{1}{\upsilon_2}(h_2 - 3157.7) = -355.2$$

$$\upsilon_2 = \frac{(h_2 - 3157.7)}{-355.2}$$

This equation contains two dependent variables, so can be solved by trials and errors. The initial state is superheated and the steam inters the piston cylinder is also superheated so the so we can estimate that the steam in the cylinder in the final state is also superheated.

By taking h_2=2985kJ/kg, at P_2=500kPa, it is found from the table that $\upsilon_2 = 0.4857 m^3/kg$

$T_2 = 261.71^o C$

And from the relation written before it is found that $\upsilon_2 = 0.4862 m^3/kg$ which less error from that of the table so T_2=261.71°C. And

$$m_2 = \frac{V_2}{\upsilon_2} = \frac{0.02}{0.4862} = 0.0411 kg$$

$$m_i = m_2 - m_1 = 0.0411 - 0.0235 = 0.0176 kg$$

Example 4.14:

A vertical piston –cylinder device contains 0.2m^3 of air at 20°C. The mass of the piston is such that it maintains a constant pressure of 300kPa inside. Now a valve connected to the cylinder is opened, and air is allowed to escape until the volume inside the cylinder is decreased by one half. Heat transfer takes place during the process, so that the temperature of the air in the cylinder remains constant. Determine (a) the amount of air that has left the cylinder, and (b) the amount of heat transfer.

Solution: the initial state of the cylinder T_1=20°C=293K, P_1=300kPa, V_1=0.2m^3 air R=0.287kJ/kg.K

From ideal gas equation

$$m_1 = \frac{P_1V_1}{RT_1} = \frac{300\times 0.2}{0.287\times 293} = 0.7135 kg$$

the final state, T_2=20°C=293K, P_2=300kPa, V_2=0.1m^3,

$$m_2 = \frac{P_2V_2}{RT_2} = \frac{300\times 0.1}{0.287\times 293} = 0.3568 kg$$

m_i=0.

$$m_e = m_1 - m_2 = 0.7135 - 0.3568 = 0.3567 kg$$

in this process, there is a work at constant pressure

$$W = P(V_2 - V_1) = 300\times(0.1 - 0.2) = -30 kJ$$

there is no potential and kinetic energies so the energy equation can be written as

$$Q - W = (m_2 u_2 - m_1 u_1) + (m_e h_e - m_i h_i)$$

$$Q = W + Cv(m_2 T_2 - m_1 T_1) + m_e Cp T_e$$

$$T_e = T_1 = T_2 = 293K, \quad m_i = 0.0$$

$$Q = -30 + 0.718(0.3568 - 0.7135) \times 293 + 0.3567 \times 1.005 \times 293 = 0.0kJ$$

4.5. A systematic approach to problem solving:

To this point we have concentrated our efforts on understanding the basic of thermodynamic. Armed with this knowledge, we are now in a position to tackle significant engineering problems.

Our problem analysis and solution technique is contained within the framework of the following set of questions that must be answered in the process of an orderly solution of a thermodynamic problem.

What is the control mass or control volume? Is it useful, or necessary, to choose more than one? It may helpful to draw a sketch of the system at this point, illustrating all heat and work flows, and indicating forces such as external pressures and gravitation.

What do we know about the initial state (Which properties)?

What do we know about the final state?

What do we know about the process that takes place? Is anything constant or zero? Is there some known functional relation between two properties?

Is it helpful to draw a diagram of the information in steps 2 to 4 (for an example, a ***T-v***, or ***P-v*** diagram)?

What is our thermodynamic model for the behavior of the substance (for example steam table, ideal gas, and so on)?

What is our analysis of the problem (examine control surfaces for various work modes, first law, conservation of mass)?

What is our solution technique (in other words, form what we have done so far in steps 1-7, how do we proceed to find whatever it is that is desired)? Is a trial-and-error solution being necessary?

Sample problem

A rigid tank containing 0.4m^3 of air at 400kPa, 30°C is connected by a valve to a piston-cylinder device with zero clearance. The mass of the piston is such that a pressure of 200kPa is required to raise the piston. The valve is now opened slightly, and air is allowed to flow into the cylinder until the pressure in the tank drops to 200kPa. During the process, heat is exchanged with the surrounding such that the temperature of air remains at 30°C at all times. Determine the heat transfer for this process.

Solution:

It is a control mass (closed system)

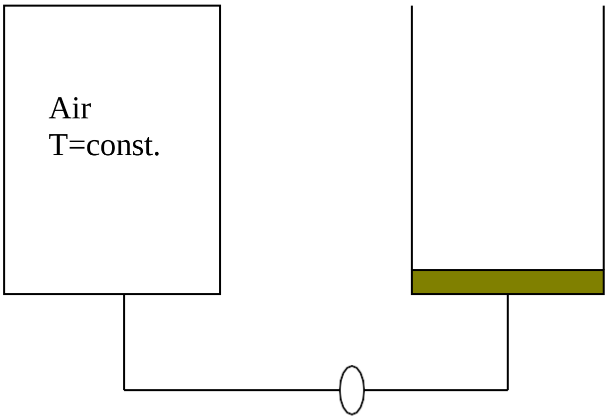


Fig. 4.18. The sketch of problem.

the initial state

In tank $\boldsymbol{V_t}$ =0.4m^3, $\boldsymbol{T_t}$=30°C, $\boldsymbol{P_t}$=400kPa

In the cylinder, there is no initial mass and the piston with constant pressure of $\boldsymbol{P_c}$=200kPa, $\boldsymbol{V_{c1}}$=0.0

the final state

the pressure in the tank $\boldsymbol{P_{t2}}$=200kPa=$\boldsymbol{P_c}$

the process in the tank is constant volume with change in mass

$\boldsymbol{W_t}$=0.0

the process in the cylinder is constant pressure

$\boldsymbol{W_c}=\boldsymbol{P_c}(\boldsymbol{V_{c2}}-\boldsymbol{V_{c1}})$

$\boldsymbol{T}$=constant

for this problem, the P-v diagram for the cylinder can be shown in fig. 4.19.

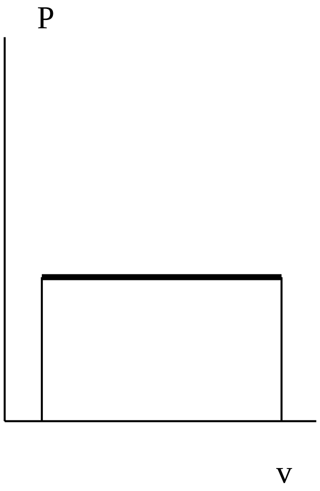


Fig. 4.19. P-v diagram for the problem

The substance used is air (ideal gas) with $\boldsymbol{R}$=0.287kJ/kg.K by using the conservation of mass

m_1=m_2

in the initial state $m_1 = m_t = \frac{P_t V_t}{RT} = \frac{400 \times 0.4}{0.287 \times 303} = 1.84kg$

the total volume in the final state

$$V_2 = \frac{m_2 RT}{P_2} = \frac{1.84 \times 0.287 \times 303}{200} = 0.8m^3$$

$$V_{c2} = V_2 - V_t = 0.8 - 0.4 = 0.4m^3$$

Now the work in the cylinder can be calculated

$$W_c = P_c (V_{c2} - V_{c1}) = 200 \times (0.4 - 0.) = 80kJ$$

by using the first law of thermodynamics for closed system

$$Q - W = \Delta U$$

$$Q - (W_t + W_c) = \Delta U_T$$

where $\Delta U_T = mCv(T_2 - T_1) = 0.0$ for constant temperature

$$Q = W_c = 80kJ$$

the technique used is simple solution for the first law equation to find the heat transfer.