Forms of Energy

FIRST LAW OF THERMODYNAMICS

An expression of the principle of conservation of energy which states that energy cannot be created or destroyed but can only be transformed or changed from one form to another.

ENERGY

No one has clearly defined what energy is, but we can only know how to describe the characteristics of its manifestations. Work and Heat flow are means of which we can transfer or transform energies from one form to another. Without energy, there can be no work or heat flow that can happen.

For example, lifting a table against the force of gravity is considered work. A hot water poured in a cube of ice, the melting of ice manifests that there is an energy transfer through heat flow.

FORMS OF ENERGY

1. **Potential Energy, PE**
   The energy possessed by a body by virtue of its position.

$$PE_2 - PE_2 = m\frac{g_o}{g_c}\left(z_2 - z_1\right)$$

$$\Delta PE = m\frac{g_o}{g_c}\Delta z$$

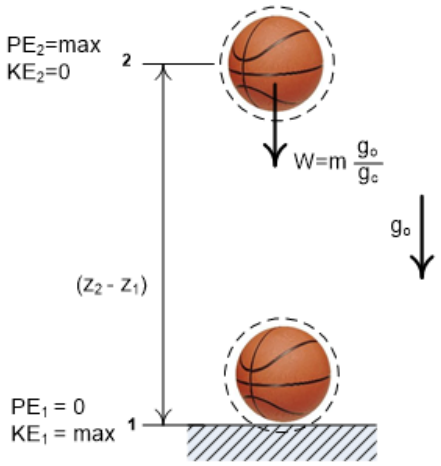


FIGURE 1: Energy transformation from PE to KE

2. **Kinetic Energy, KE**
   The energy possessed by a body by virtue of its motion.

$$KE_2 - KE_2 = \frac{1}{2}\frac{m}{g_c}\left[v_2^{\,2} - v_1^{\,2}\right]$$

$$\Delta KE = \frac{1}{2}\frac{m}{g_c}\left[v_2^{\,2} - v_1^{\,2}\right]$$

3. **Internal Energy, U**
   The energy stored in a system on a microscopic scale. It is associated with the random movement of molecules in a body, the sum of total kinetic energy due to the motion of molecules (vibration, translation and rotation) and the potential energy (binding energy) that holds the atoms together.

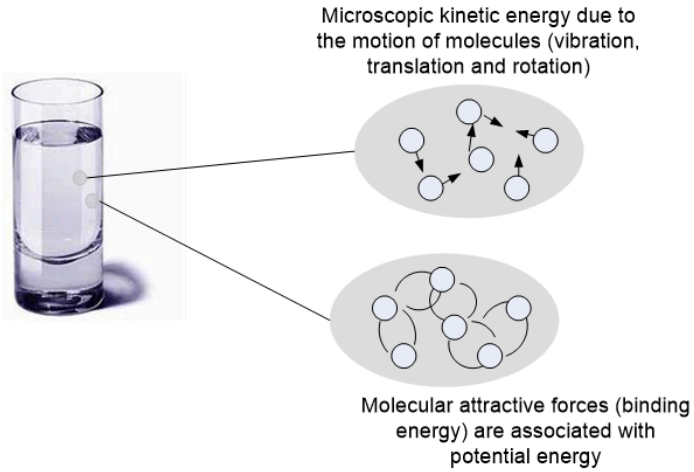


FIGURE 2: The internal energy in a glass of water

$$\Delta U = U_2 - U_1 = m\left(u_2 - u_1\right)$$

For example, consider a glass of water at room temperature, observing the glass of water using our naked eyes, we can see that there is no apparent energy, either potential or kinetic energy. But on its microscopic scale, there is a mass of high speed molecules moving at hundreds of meters per second.

4. **Flow Work, W_f**
   The flow work or also known as flow energy is the energy required to move a mass (thermodynamic substance) that enters a thermodynamic system from one point to another. This energy is needed to maintain a continuous flow of mass in the thermodynamic system.

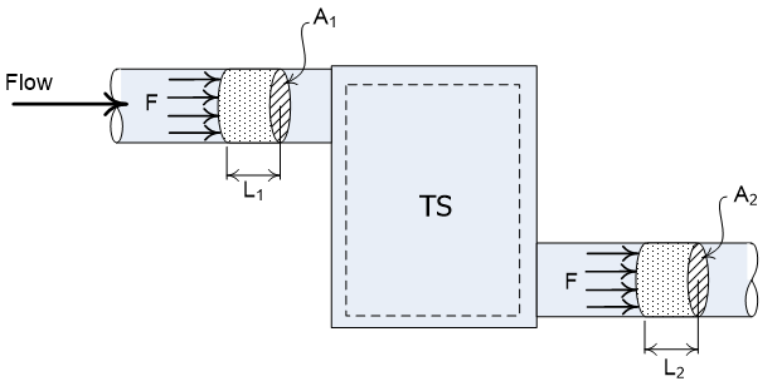


FIGURE 3: Flow work in a thermodynamic system

$$W_{f2} - W_{f1} = \left(P_2 V_2 - P_1 V_2\right)$$

$$\Delta W_f = m\left(P_2 \underline{v}_2 - P_1 \underline{v}_1\right)$$

The mass enters the thermodynamic system and is pushed by the surrounding against the resistance and local pressure in the thermodynamic system, providing the system with work in the process.

Enthalpy, H

Enthalpy is the sum of the internal energy and the workflow

$$\Delta H = H_2 - H_1 = m\left(h_2 - h_1\right)$$

$$\Delta H = \Delta U + \Delta W_f$$

$$\Delta H = m(\Delta u + \Delta P \underline{v})$$

Energies are transformed or transferred in two ways – by heat or work.

5. **Heat Energy, Q**

   Heat energy or also known as thermal energy is the transfer of energy between two bodies because of its temperature difference.

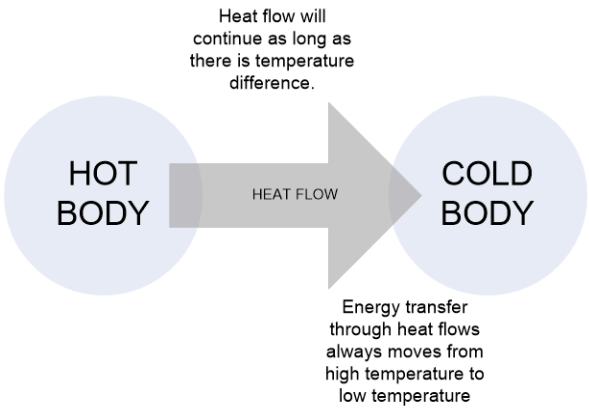


FIGURE 4: Heat flow from high temperature region to low temperature region

Heat transfer is denoted by: $$Q = \int_1^2 T\, ds$$

The sign convention of heat is that when Q carries a positive sign (+) it denotes that the heat is added on the system or the direction of heat is going into the system, however, when negative sign (-), it denotes that heat is rejected by the system or the direction of heat is going out of the system.

Entropy, S

- Entropy is defined as a measure of the amount of energy that is unavailable to do useful work in a closed system undergoing a change of state.
- It also describes the microscopic disorder or degree of randomness of molecules in a closed thermodynamic system.

Entropy is the subject in the Second Law of Thermodynamics, an expression of the Universal Law of Increasing Entropy. It states that the thermal energy in a closed system disperses over time until it reaches equilibrium. When energy disperses, the pressure, temperature and density evens out, therefore less energy is now available to do useful work. The greater the entropy, the less energy is available to do useful work.

$$dS = \int_1^2 \frac{dQ}{T} > 0$$

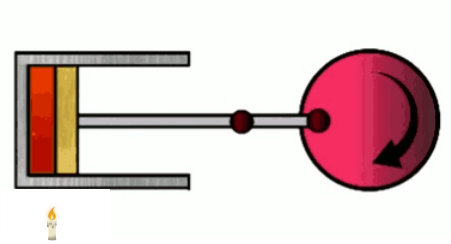
Melting of Ice: One example of the second law is the flow of heat from a hot body to a cold body. When you drop a cube of ice in a glass of warm water, the warm water will melt the cube of ice until both of them achieve the same temperature. When both the water and the ice reach equilibrium, energy stops flowing, and therefore less energy is now available to do useful work. During the process, the entropy of the system increases.

If we know the initial temperature of the cube of ice and the water, and its final temperature, we can quantify that the entropy increased in Joules per degree.

6. **Work, W**

Energy is transferred through work when force, F, is applied to a body that causes it to move or displaced at a distance, d.

$$W = F \cdot d$$



Knowing that Force = (Pressure)(cross-sectional area);

$$W = PA \cdot d$$

$$W = PV$$

Generally, work is denoted by: $W = \int_1^2 P\, dV$

The sign convention of work is that when W carries a positive sign (+) it denotes that the work is done **by** the system or the direction of work is going out the system, however, when negative sign (-), it denotes that work is done **on** the system or the direction of heat is going into the system.

Work can be work non-flow, W_{NF} or work steady-flow, W_{SF}, depending on the type of thermodynamic system involved.

Work non-flow: $W_{NF} = \int_1^2 P\, dV$

Work steady-flow: $W_{SF} = -\int_1^2 V\, dP$

Power, P

Power is the rate of doing work, expressed as amount of work per unit time or sometimes in horsepower.

Conservation of Mass

In the First Law of Thermodynamics, we learned that energy cannot be created nor destroyed, but can only be transformed or changed from one form to another. That concept is the same with mass. Conservation of mass states that the mass going in the system is equal to the mass going out of the system.

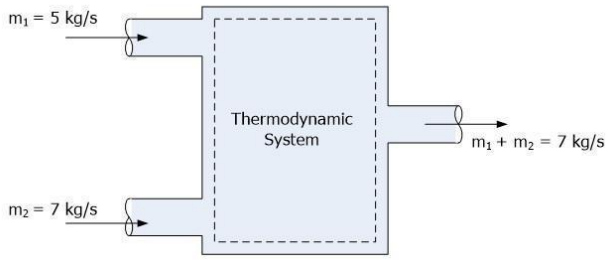


FIGURE 5: Conservation of mass in a two inlet and one exit thermodynamic system

In equation form:

$$mass\ flow\ rate\ going\ IN\ the\ system\ =\ mass\ flow\ rate\ going\ OUT\ of\ the\ system$$

The Continuity Equation

The continuity equation was derived from the law of conservation of mass.

$$\dot{m}_{in} = \dot{m}_{out}$$

$$\rho_1 \dot{V}_1 = \rho_2 \dot{V}_2$$

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2$$

For frictionless flow: $t_1 = t_2$, thus, $\rho_1 = \rho_2$;

$$A_1 v_1 = A_2 v_2$$

Where: A = cross sectional area normal to the flow, m^2
v = average flow velocity, m/s
$\dot{V}$ = volume flow rate, m^3/s

Thermodynamic System

Thermodynamic system or also known as control volume is defined as a region in space that is under consideration, it also contains mass or a thermodynamic substance. It has specific boundaries that separate it from the external effects of the environment.

A system can be anything, for example a piston, pump, blower, turbine, compressor etc.

Types of Thermodynamic System

1. **Open systems (Steady-flow Systems)** are able to exchange energy (heat and work) and mass across the system boundary.

First Law in an Open or Steady-Flow System:

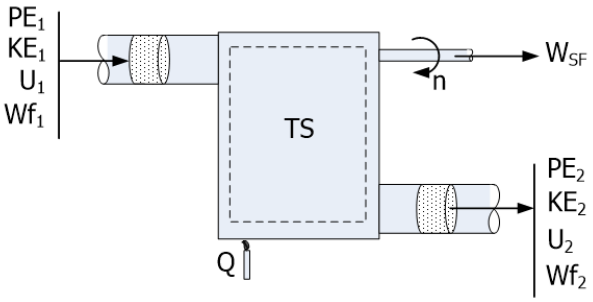


FIGURE 6: Energy balance in an open or steady-flow thermodynamic system

$$\left[E_{in} = E_{out}\right]$$

$$PE_1 + KE_1 + U_1 + W_{f1} + Q = W_{SF} + PE_2 + KE_2 + U_2 + W_{f2}$$

$$Q = W_{SF} + \Delta PE + \Delta KE + \Delta U + \Delta W_f$$

When: $z_1 \approx z_2$; $then\ \Delta PE \approx 0$

$v_1 \approx v_2$; $then\ \Delta KE \approx 0$

And: $\Delta H = \Delta U + \Delta W_f$

Therefore, the steady flow energy equation, SFEE is given by:

$$Q = W_{SF} + \Delta H$$

2. **Closed systems (Non-flow Systems)** are able to exchange energy (heat and work) across the system boundary but not mass.

First Law in a Closed or Non-Flow System:

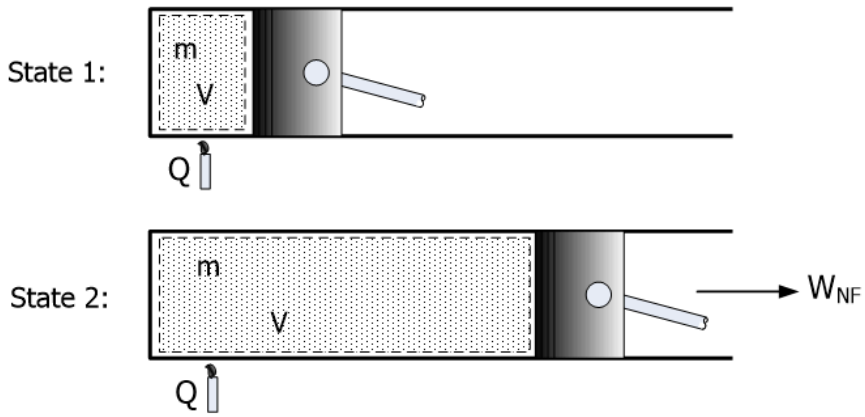


FIGURE 7: Energy balance in a closed or non-flow thermodynamic system

$$\left[E_{in} = E_{out}\right]$$

$$PE_1 + KE_1 + U_1 + Q = W_{NF} + PE_1 + KE_1 + U_1$$

$$Q = W_{NF} + \Delta PE + \Delta KE + \Delta U$$

When: $z_1 \approx z_2$; $then\ \Delta PE \approx 0$

$v_1 \approx v_2$; $then\ \Delta KE \approx 0$

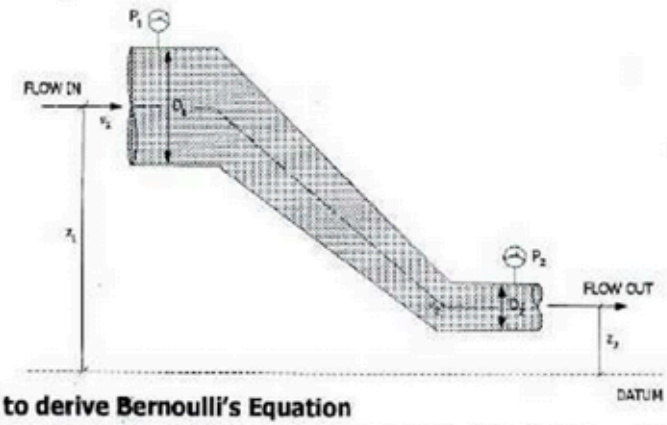
Therefore, the non-flow energy equation, NFEE is given by:

$$Q = W_{NF} + \Delta U$$

Bernoulli's Principle

In fluid dynamics that describes the conservation of energy in a flowing fluid. It states that for an ideal flow of fluid, the total energy along the streamline remains constant. This total energy consists of three components: pressure energy, kinetic energy, and potential energy.

Illustration:



Assumptions used to derive Bernoulli's Equation

1. We have incompressible flow, and thus the specific weight of the fluid is constant.
2. The fluid is ideal (no viscosity), and thus there are no energy losses due to friction.
3. There are no mechanical devices such as pumps or turbines between point 1 to point 2 to add or remove energy from the fluid.
4. The flow is steady.
5. No heat transferred (added or removed) to or from the fluid between point 1 and point 2 via devices called heat exchangers.

Applying law of conservation of energy

$$[E_{in} = E_{out}]$$

$$PE_1 + KE_1 + U_1 + W_{f1} = PE_2 + KE_2 + U_2 + W_{f2}$$

Since $t_1 = t_2$, then U_1 and U_2 is equal to zero

$$\dot{m}_W\left[\frac{g_o}{g_c}\right]z_1 + \frac{1}{2}\left[\frac{\dot{m}_W}{g_c}\right]v_1^2 + P_1\dot{V}_1 = \dot{m}_W\left[\frac{g_o}{g_c}\right]z_2 + \frac{1}{2}\left[\frac{\dot{m}_W}{g_c}\right]v_2^2 + P_2\dot{V}_2$$

$$z_1 + \frac{1}{2}\frac{v_1^2}{g_o} + \frac{P_1\dot{V}_1 g_c}{\dot{m}_W g_o} = z_2 + \frac{1}{2}\frac{v_2^2}{g_o} + \frac{P_2\dot{V}_2 g_c}{\dot{m}_W g_o}$$

$$z_1 + \frac{1}{2}\frac{v_1^2}{g_o} + \frac{P_1}{\frac{\dot{m}_W g_o}{\dot{V}_1 g_c}} = z_2 + \frac{1}{2}\frac{v_2^2}{g_o} + \frac{P_2}{\frac{\dot{m}_W g_o}{\dot{V}_2 g_c}}$$

$$\boxed{z_1 + \frac{1}{2}\frac{v_1^2}{g_o} + \frac{P_1}{\gamma_W} = z_2 + \frac{1}{2}\frac{v_2^2}{g_o} + \frac{P_2}{\gamma_W}}$$

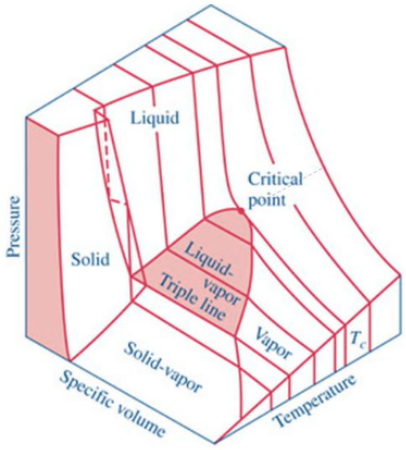
Daniel Bernoulli, an 18th-century Swiss mathematician and physicist, is credited with formulating Bernoulli's Principle, which is one of his most famous contributions to fluid dynamics. His principle is derived from the conservation of energy in a fluid flow system

Properties of Pure Substance

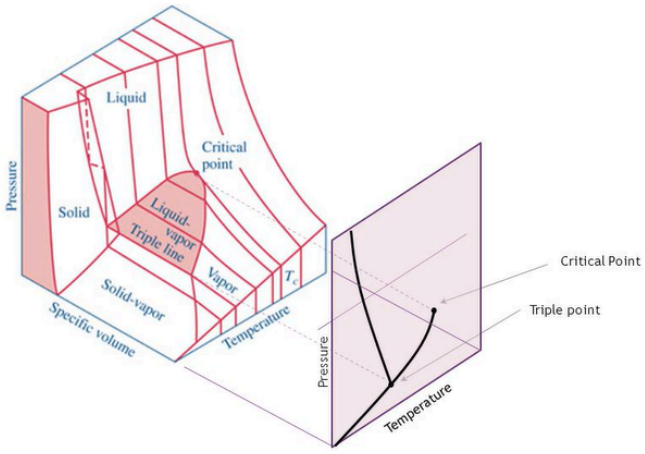
Pure substances are substances that have uniform and consistent chemical composition and retain their distinct properties regardless of the conditions or phases it may undergo. Pure substances can exist in different phases, such as solid, liquid, or gas, depending on the temperature and pressure conditions.

3D P-V-T Surface Model

The 3D P-V-T surface model provides a visual representation of how pressure, volume, and temperature influence the behavior of a substance. It is also known as the phase diagram or phase space diagram.



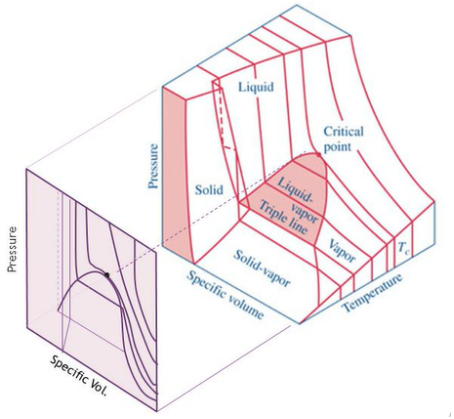
The *Phase Diagram* is given by the Pressure – Temperature, PT projection:



The Triple Point is the state at which solid, liquid and gas coexist. For water, the Triple Point is at t = 0.01°C and P = 0.611657 kPa

The Critical Point is where the saturated liquid and saturated vapor lines meet. For water, the Critical Point is at t = 374.13°C and P = 22,090 kPa

The *Ice-Water-Water Vapor System* is given by the Pressure – Specific Volume, PV projection:



The *Lines of Constant Pressure* is shown in Temperature-Specific Volume, TV projection:

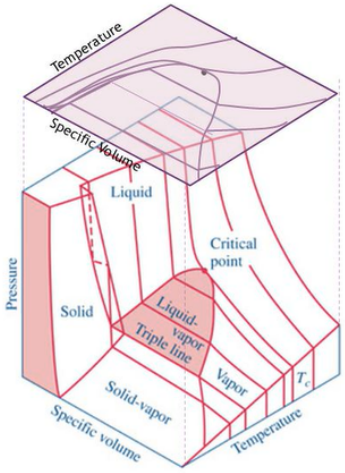


Illustration: Change of water from subcooled liquid state to a superheated vapor state by constant pressure heat addition

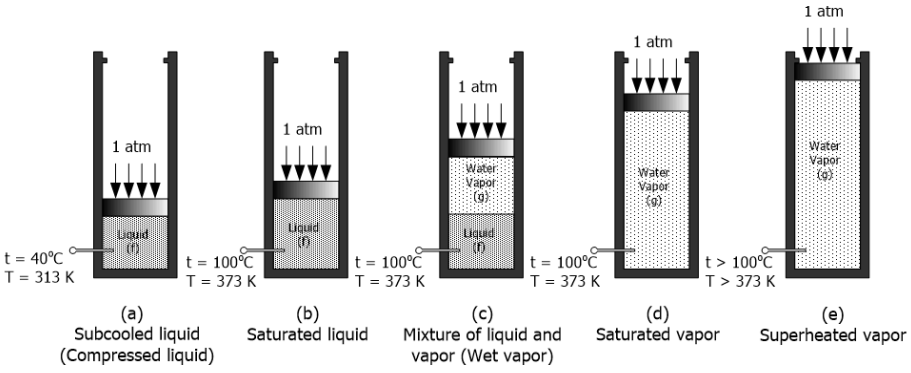


FIGURE 8: A change of phase of water from subcooled liquid to superheated vapor

The change of phase of water illustrated in Temperature – Specific Volume diagram

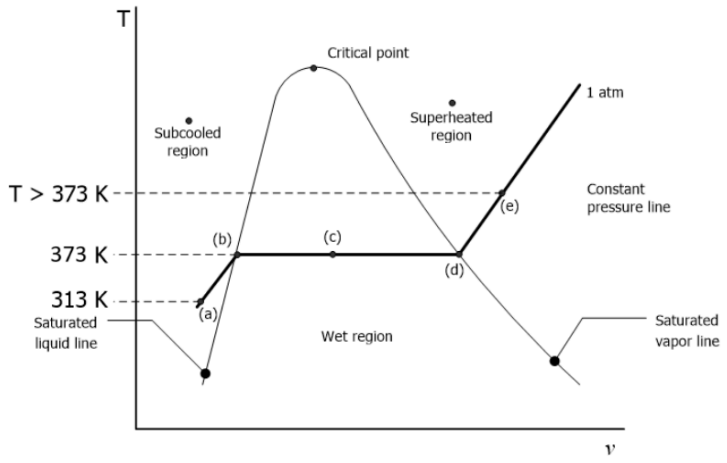


FIGURE 9: The change of phase of water illustrated in temperature-volume diagram

The Steam Table

Steam tables are tables widely used by engineers and scientists in design and operation of equipment where steam is used as a working substance in thermodynamic processes and cycles. It gives an idea about the phase of steam at various temperatures and pressure.

QUALITY OF STEAM, x

Steam quality is the proportion by mass of vapor in a liquid-vapor mixture. A quality of zero (0) indicates 100% water while a quality of one (1) indicates 100% steam.

$$x = \frac{mass\ of\ vapor}{total\ mass} = \frac{m - m_f}{m}$$

Where: m = total mass = $m_g + m_f$
m_f = mass of liquid = (1 – x)(m)
m_g = mass of vapor = xm

m_f = (1 – x)m and m_g = xm

If we let ϵ be any specific thermodynamic property, in kJ/kg and deriving an equation that will relate the property ϵ_{mix} of a liquid-vapor mixture to the properties ϵ_f and ϵ_g, we can apply the concept of conservation of energy, thus:

$$m\epsilon_{mix} = m_f\epsilon_f + m_g\epsilon_g$$

$$m\epsilon_{mix} = (1 - x)m\epsilon_f + xm\epsilon_g$$

$$\epsilon_{mix} = (1 - x)\epsilon_f + x\epsilon_g$$

$$\epsilon_{mix} = \epsilon_f + x(\epsilon_g - \epsilon_f)$$

$\epsilon_{fg} = \epsilon_g - \epsilon_f$ = change in vaporization

For specific enthalpy: $h = h_f + x(h_g - h_f)$

$h = h_f + xh_{fg}$

For specific entropy: $s = s_f + x(s_g - s_f)$

$s = s_f + xs_{fg}$

For specific internal energy: $u = u_f + x(u_g - u_f)$

$u = u_f + xu_{fg}$

For specific volume: $v = v_f + x(v_g - v_f)$

$v = v_f + xv_{fg}$

General Gas Law (Ideal Gas Law)

General gas law is the equation of state of an ideal gas. It is a good approximation of the behavior of gasses in relation to its pressure, volume and temperature.

In terms of mass: $PV = mRT$

In terms of moles: $PV = n\overline{R}T$

Where:

P = absolute pressure of the gas, kPa_a

V = volume of the gas, m^3

m = mass of the gas, kg

n = number of moles of gas, mols

R = ideal gas constant, kJ/kg-K

each gas has unique value of ideal gas constant

$\overline{R}$ = universal gas constant, kJ/kg_{mol}-K

T = absolute temperature, K

The General Gas Law behaves according to various Laws:

Charles's Law

If the pressure remains constant within a closed system, the volume of the gas varies directly with the temperature during the change of state.

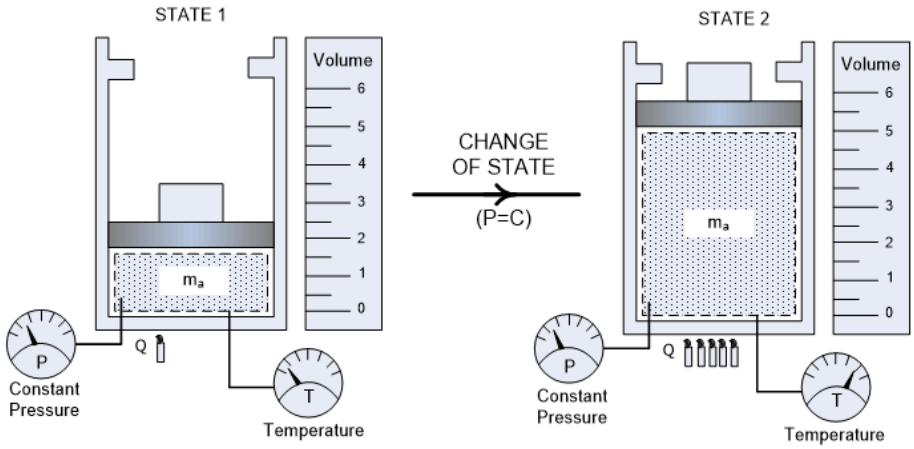


FIGURE 10: An ideal gas undergoing a change of state at a constant pressure

Gay-Lussac's Law

The pressure of an ideal gas if held at a constant volume is directly proportional to its temperature at any change of state.

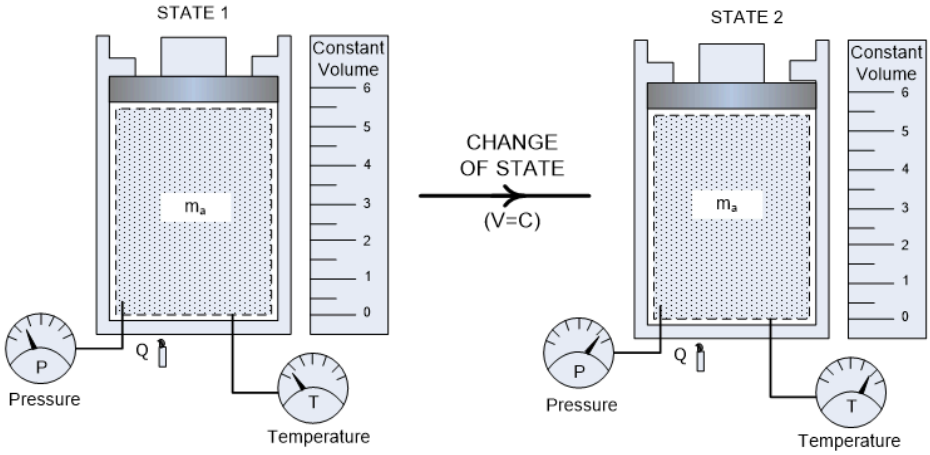


FIGURE 11: An ideal gas undergoing a change of state at a constant volume

$$P \, \alpha \, T$$

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

Boyle's Law

If the temperature remains constant within a closed system, the volume of the gas varies inversely with the pressure during the change of state.

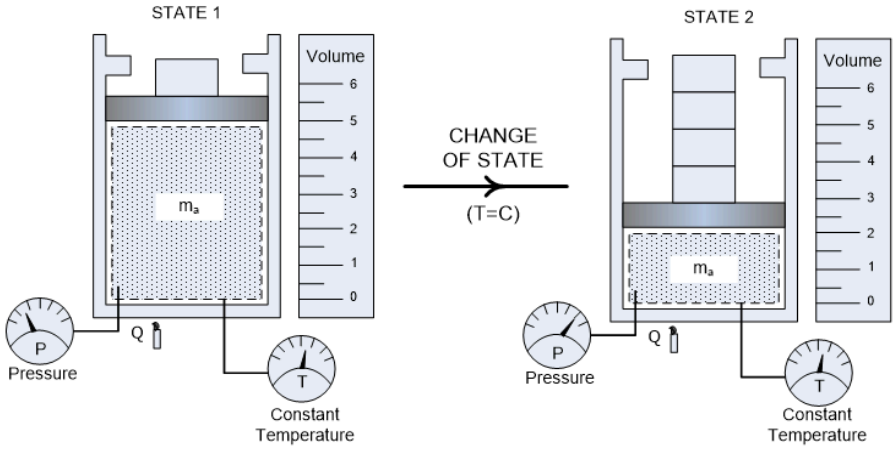


FIGURE 12: An ideal gas undergoing a change of state at a constant temperature

$$V \alpha \frac{1}{P}$$

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

$$V \, \alpha \, T$$

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

Combined Gas Laws

Let us consider an ideal gas undergoing a change of state at random from state 1 to state 2 as shown in Figure 13.

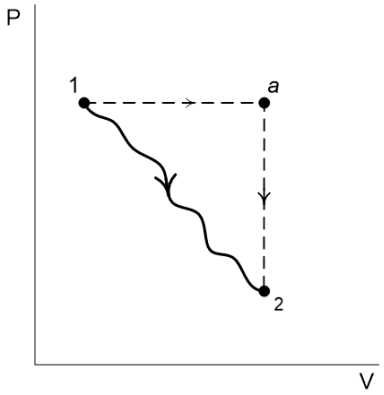


FIGURE 13: An ideal gas undergoing a change of state from state 1 to state 2.

Considering the initial state of the ideal gas at point 1, we can also say that this ideal gas can go to state 2 by first undergoing a constant process (P=C) from state 1 going to state *a* and then a constant volume process (V=C) from state a to state 2.

Process 1-a: From Charles's Law (P = C)

$$\frac{V_1}{V_a} = \frac{T_1}{T_a}$$

$$T_a = T_1 \frac{V_1}{V_a} \qquad \text{eq. (1)}$$

Process a-2: Gay-Lussac's Law (V = C)

$$\frac{P_2}{P_a} = \frac{T_2}{T_a}$$

$$T_a = T_2 \frac{P_2}{P_a} \qquad \text{eq. (2)}$$

Equating equation (1) and (2),

$$T_1 \frac{V_1}{V_a} = T_2 \frac{P_2}{P_a}$$

But: $P_a = P_1$ and $V_a = V_2$

Hence;

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

The Ideal Gas Constant or the Specific Gas Constant, R

The ideal gas constant or the specific gas constant of a gas or a mixture of gases is given by the Universal Gas Constant over the Molar Mass.

From: $\frac{PV}{T} = mR$ and $\frac{PV}{T} = n\overline{R}$

Equating: $mR = n\overline{R}$

$$R = \frac{\overline{R}}{\frac{m}{n}}$$

Where: $M = molecular\ mass = \frac{m}{n}$; $\frac{kg}{kg_{mol}}$; $\frac{lb_m}{lb_{mol}}$

$$M = (standard\ atomic\ weights)(number\ of\ atoms)$$

$$R = \frac{\overline{R}}{M}$$

$$\overline{R} = universal\ gas\ constant = 8.314\ \frac{kJ}{kg_{mol}-K}$$

$$= 1545 \frac{ft-lb_f}{lb_{mol}-°R}$$

$$= 1.9859 \frac{Btu}{lb_{mol}-°R}$$

Avogadro's Law

The principle that states 1 mole of any ideal gas always occupies the same volume at a constant pressure and temperature.

One mole of an ideal gas occupies 22.4 m^3 (359 ft^3) at standard ambient temperature and pressure.

n	V	t	P
1 lb_{mol}	359 ft^3	32 °F	14.7 psi_a
1 kg_{mol}	22.4 m^3	0 °C	101.325 kPa_a

From: $PV = n\overline{R}T$

$$\left(101.325\ kPa_a\right)\left(22.4\ m^3\right) = \left(1\ kg_{mol}\right)(\overline{R})(0\ +\ 273)K$$

$$\overline{R} = universal\ gas\ constant = 8.314\ \frac{kJ}{kg_{mol}-K}$$

Specific Heat

Specific heat is a thermal property that measures the heat required to increase the temperature of one unit of thermodynamic substance by one degree.

The equation relating heat energy to specific heat: $C = \frac{Q}{m \cdot \Delta T}$

Where: Q = heat transfer, in Joules, J
C = specific heat, J/kg-K
m = mass, in kg
ΔT = temperature difference

There are two specific heats for gasses:

Specific heat constant at constant volume, C_v:

If you heat up a gas in a rigid container, the volume remains constant, and you use the constant-volume specific heat, C_v.

The constant-volume specific heat relates a temperature change in a process to the change in internal energy in the following equations:

$$Q = U_2 - U_1 = mC_v\Delta T$$

This assumes the specific heat remains constant during a process.

Specific heat constant at constant pressure, C_p:

If you heat up a gas in a process that has a constant pressure, you use the constant-pressure specific heat, C_p.

For a constant-pressure process, the enthalpy ($H_2 – H_1$) of the gas changes because the gas must do work in addition to changing internal energy. The constant-pressure specific heat relates a temperature change in a process to the change in enthalpy in the following equations:

$$Q = H_2 - H_1 = mC_p\Delta T$$

This assumes the specific heat remains constant during a process.

When a gas is heated at constant volume, the whole heat supplied to gas is used up in raising its temperature. While in the second case, since the gas is allowed to expand under constant pressure, heat is used up in raising the temperature as well as doing external work against expansion. Therefore, the specific heat of a gas at constant pressure is greater than the specific heat at constant volume ($C_p > C_v$) by the amount equal to the thermal equivalent of external work done by the gas.

The two specific heats are related to each other by the gas constant (R).

$$R = C_p - C_v$$

Specific Heat Ratio, k

Specific heat ratio or also known as isentropic expansion factor is the ratio of specific heat at constant pressure and constant volume. This ratio is used for evaluating thermodynamic processes of turbines, compressors and reciprocating engines:

$$k = \frac{C_p}{C_v}$$

For air: $k = 1.4$

$$C_p = 1.0062\ \frac{kJ}{kg-K}$$

$$C_v = 0.7192\ \frac{kJ}{kg-K}$$