Vacuum systems

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References :

1. M Z Ahsan article july 2016
2. Hand book of vacuum science and technology by **Dorothy M. Hoffman , Bawa Singh & John H. Thomas, III**

Introduction

The vacuum system is not a single unit or machine rather it refers to an arrangement for producing vacuum in the vessel or chamber. This system has many applications that include vacuum impregnation, vacuum casting of metals, freeze drying of foods and pharmaceuticals, evaporation of metals, nuclear particle accelerators, research applications etc. The exact nature of the system depends on the applications. A principal distinction is the pressure range in which the system is to be operated. The objective of this assignment is to introduce related concepts and essentials of a vacuum system.

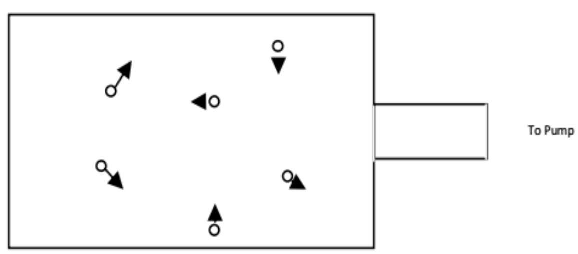
Related Concepts

Vacuum

The word vacuum is derived from the Greek word meaning empty. In practice, some type of vessel (vacuum enclosure, chamber, or container), which are open to the surrounding air is used. As air is removed some pumping means, a vacuum is obtained. Clearly, various degree of vacuum can be obtained, depending on how much air is removed from the enclosure. Practically, a vacuum vessel, which is empty i.e., free of all matter, is never obtained. If this were possible the vacuum would be called perfect or absolute.

Pressure

The word gas is often in vacuum practice to denote both *non-condensable gas* and *vapors*. The non-condensable gas cannot be compressed to liquid or solid form at the normal room temperature. Dry air is an example of non-condensable gas, and water vapor is an example of a vapor. In order to produce liquid air, it is necessary to use high degree of compression at low temperatures. The striking and rebounding of gas molecules results a push or force on the wall. The average force exerted on the wall per unit area at a given time is called pressure. This is the fundamental quantity in vacuum work. The pressure of a gas depends on how many molecules are striking at a given time and how fast they are moving. Consequently, the pressure will drop if air molecules are pumped out from the container and rise if the gas is heated up. The pressure is usually measured by U- tube mercury manometer and the basic unit of the pressure is *Torr* , where 1 mmHg = 1 Torr (1 atm = 760 mmHg). It has been stated that the pressure exerted on the wall inside a container. But, actually, the same pressure will be noticed at any point inside the container which will be evident when a plane sheet impressed inside the container, this pressure exerted vertically on both the plane of the sheet in opposite direction as shown in figure-1.



Figue-1:

Mean free path

A gas is made up of many tiny, invisible particles, which are moving about rapidly in all directions. They collide with each other and also strike the walls of the container and rebounded back in random directions as shown in figure-2. The distance, travelled by a gas molecule with another gas molecule is called free path. This distance or free path will be different from collision to collision in the gas of a container. So, the average distance travelled by a gas molecule in the gas of a container is called average mean free path.

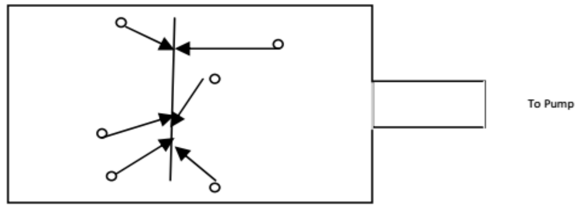


Figure-2 :

Effect of Pressure on a Gas

It is well known that when a gas is compressed it occupies less space. Conversely if the pressure on a gas is decreased, it will expand. This fact is governed by a law, which is known as Boyle's law and can be expressed as "the volume of a gas is inversely proportional to the pressure exerted on it at a constant pressure. If several gases are contained in a vessel, each gas will contribute its own pressure, and the total pressure will be the sum of the pressures of all gases. The pressure of each gas is its pressure when it occupies the vessel by itself. This is called the partial pressure of the gas. The pressure of each individual gas in a mixer obeys the Boyle's law. The term partial pressure has the same meaning in case of vapors. However, Boyle's la can be applied only when vapors are not near the temperature of liquefaction points. Often Boyle's law can be expressed as the volume of a gas times its pressure is constant the temperature remains unchanged.

Effect of Temperature on a Gas

It is well known that heating a gas causes it to expand, whereas cooling it causes to contract. The law governing this behavior is known as Charles' law and can be state as: The volume of a gas varies directly as the absolute temperature when the pressure is kept constant. Note that the temperature scale in this case will always be in Kelvin scale.

The General Gas Law

In practice changes might occur in all the tree quantities – temperature, pressure and volume. Hence, there is a relationship governing the changes in these quantities which is known as General gas law. This law states that the product of pressure and the volume of a certain amount of gas divided by the absolute temperature gives a quantity which is always constant. Accordingly, the product of initial pressure and initial volume divided by initial absolute temperature equals the product of final pressure and final volume divided by final absolute temperature of the same amount of gas.

Characteristics of gas

There are some other characteristics quite important in certain circumstance in vacuum work. These are diffusion, viscosity and thermal conductivity.

1. *Diffusion*. In vacuum work, where the pressure is analogously low, gases and molecules will diffuse quite rapidly because there are fewer collisions. This fact is known as diffusion of gas.

2. *Viscosity*. If a stream of gas moves through a stationary gas, the moving gas tends to drag along some of the stationary gas. At the same time the moving gas is slowed down. The amount of drag involved is

expressed in terms of a quantity called viscosity, which is the characteristic of each gas and vapor. This property of a gas or vapor is important in leak detection since it determines the ease with which the gas or vapor will pass through a small leak.

3. *Thermal Conductivity*. It is well known that copper is a better conductor of heat that is wood. Similarly gases and vapors differ in their ability to conduct heat. It is possible to speak of the thermal conductivity of a particular gas or vapor. In the micron range of pressure, the conductivity of a gas or vapor depends on the pressure, so this property becomes the basis on which certain classes of vacuum gauges work for example Pirani and thermocouple gauges.

Degrees of Vacuum

Vacuum systems are often classified according to their operating pressure. One method of classifying which is being widely accepted is as the following:

1.	Low vacuum	-	760mmHg to 25 mmHg
2.	Rough Vacuum	-	760 mmHg to 1 mmHg
3.	Medium Vacuum	-	25 mmHg to 10^{-3} mmHg
4.	Fine Vacuum	-	1 mmHg to 10^{-3} mmHg
5.	High Vacuum	-	10^{-3} to 10^{-6} mmHg
6.	Very High Vacuum	-	10^{-6} to 10^{-9} mmHg
7.	Ultra high vacuum	-	10^{-9} mmHg and less.

Essential of Vacuum System

Typical vacuum system

In spite of large differences among various vacuum systems, all of them possess certain elements in common. Figure-3 shows a vacuum system intended for operation in 10^{-6} mmHg or Torr range. The actual lower limit of pressure which will be reached with such a system will depend on the choice and design of components as well as the care taken in fabrication and cleaning. The major components involved in this system are the vacuum vessel, the pumps, and the piping connecting the vessel and pumps. Other components include vacuum gauge, valves, baffle, a cold trap, and miscellaneous hardware including seals, protective devices etc.

The vacuum vessel and the various pumping lines are constructed of glass and metals. The use of glass is confined to relatively small system because of its fragility, cost and difficulty in fabrication of large glass parts. Either glass tubing or piping can be used for pumping lines. Metals commonly used are copper, brass, steel, aluminum, and stainless steel. The tubing is commonly used for small system whereas the piping in large system. The vapor pump can be an oil or mercury pump, although sometimes ejector stages are used either separately or in a combination diffusion-ejector pump. If a mercury pump is used then a cold trap should be used between this pump and the mechanical pump so that the mercury does not get into the mechanical pump or air. The type of mechanical pump used for a system operating this pressure range is usually a rotary-oil sealed pump.

With reference to the figure-3, it is noted that two vacuum gauges are used in the system – vacuum gauge No.1 for measuring the pressure of the vacuum vessel and vacuum gauge No. in the fore-line for measuring the fore-pressure. Gauge No.1 should be more sensitive than gauge No.2 because it measures low pressures. It is desirable to include a roughing line so that the vessel can be pumped down without the vapor pump having to be cooled down.

CHARACTERISTICS OF A GAS—BASIC DEFINITIONS

A low-pressure sample of gas can be completely described if at least three of the four quantities that relate to it are known. These quantities are its *pressure, volume, temperature,* and the *amount* of gas in the sample.

Pressure: Pressure is defined as the force per unit area that a gas exerts on the walls of its container. In the MKS system of units, pressure is expressed as newton per square meter, or newton/m^2 or newton m^{-2}. The MKS unit is the pascal, where 1 torr =133 pascal and 1 pascal = 7.5 torr.

Volume: The volume is simply a measure of the space a gas takes up; it is usually set by the dimensions of the enclosure. The MKS unit of volume is the m^3 but liters are extensively employed to refer to pumping rates, gas flow measurements, etc. The pumping speed of mechanical pumps is often expressed in cfm (cubic feet per minute).

Temperature: The temperature of a gas at pressure below 1 torr is determined mainly by the temperature of the surfaces with which the gas comes in contact. Typically the gas is at room temperature. In deriving the equations that describe the behavior of gases, the unit of temperature is K or Kelvin.

Amount of gas: The amount or mass of gas in a given sample is measured in molar gram units or moles.

Gram molecule or mole: Defined as that quantity of gas (or any substance) having a mass equal to its molecular weight in grams. A gram molecule contains 6×10^{23} molecules. One mole of any gas at 0°C and a pressure of 760 torr, occupies 22.4 liters of volume. The mass of 1 mole of gas is exactly equivalent to its molecular weight in grams.

Gram molecular volume: The volume occupied by a gram molecule of gas is a universal constant; it is found experimentally to be 22.414 liters at 760 torr and 0°C. As 1 mole of any gas, at a temperature of 0°C and a pressure of 760 torr occupies a volume of 22.4 liters, it is possible from this relationship to calculate the molecular density of any volume of gas if its temperature and pressure are known. For example, 1 cubic centimeter of air at 760 torr and 0°C contains 2.7×10^{19} molecules; whereas at a pressure of 1 torr and a temperature of 0°C, 1 cubic centimeter of air contains 3.54×10^{16} molecules

GAS LAWS

The gas laws (Boyle's, Charles's, Gay-Lussac's) lead to relationships of the bulk physical quantities of the gas, such as pressure, volume, temperature, and the amount of gas to one another. These relationships describe the behavior of a given quantity of an "ideal" gas; an ideal gas is one where the volume of all the molecules is negligible compared to the volume of the gas, and the energy of attraction between the molecules is negligible compared to their mean thermal energy. This means that the sample of gas is dilute and is at a temperature that is not low enough to condense it. Gases that are ideal at room temperature include O2, Ne, Ar, CO, H2, N2, and NO. A summary of the relationships that result from apphcations of the gas laws to an ideal gas is provided here:

Boyle's law: States that the product of pressure and volume, *pW,* is constant for a given mass of gas at constant temperature.

Charles's law: States that *W/T* is constant for a given mass of gas at a constant pressure, where 1/is the gas volume and *T* = the absolute temperature.

Avogadro's law: States that equal volumes of gas at any gas at the same temperature and pressure contain the same number of molecules. From this law can be obtained an important relationship between the number of moles in a sample and the pressure the gas exerts.

General gas law: The general gas law relates all four quantities needed to describe the state of a gas. The general law states that *PV=nRT ....* (1)
for a given mass of gas, where R = universal gas constant (constant of proportionality) with a value of 62.4 torr-liter/mole°K, and *n* is the number of moles in volume *V.*
This law is known as the "ideal" gas law, because it is exactly true for ideal gases; most gases at reduced pressures behave as ideal gases.

Dalton's law of partial pressures: The total pressure exerted by a mixture of gases is equal to the sum of the partial pressures exerted by the individual components.

Partial pressure: The partial pressure exerted by any one component of a mixture of gases is the pressure exerted by that component if it occupied that volume alone.

Avogadro's law: Equal volumes of all ideal gases measured at the same temperature and pressure contain the same number of molecules.

Avogadro's number: The number of molecules in a gram molecule of gas or any substance is a universal constant and is 6.023 X 10^{23}.

Loschmidt's number: The number of molecules per cm3 of gas at 760 torr and 0°C is a universal constant equal to 2.637 X 10^{19}.
For 1 mole at standard temperature and pressure (STP), *P* = 760 torr = 1,013,250 dynes/cm2, *V* = 22.414 liters, and *T* = 273.2°K, whence R = 8.31 X 107 ergs per gram molecule or in thermal units R/J = 1.99 cal per °K (J = mechanical equivalent of heat = 4.182 joules cal ^). In more tangible terms, therefore, 1.99 cal will raise the temperature of 1 mole of any ideal gas 1°K. Alternatively, having raised the temperature of 1 mole of any ideal gas by 1°K, the increase in energy of the gas amounts to 8.31 joules.

MOLECULAR MEAN FREE PATH

The average distance a molecule moves before colliding with another (collisions with chamber walls being excluded) is called the *mean free path* (*mfp*) and is given by

$$\lambda = \frac{1}{\sqrt{2}} \cdot \frac{1}{(\pi n d_0^2)} = \frac{\mathrm{k}T}{\sqrt{2}\pi d_0{}^2 P} \tag{22}$$

where d_0 = molecular diameter ($\sim 10^{-8}$ cm)
n = number of molecules per unit volume

Example:

At 760 torr, mfp for air at 20°C = 6.4×10^{-6} cm
At 10^{-6} torr, mfp for air at 20°C = 49 m