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Selection of Appropriate Equipment for Designing Effective Vacuum System

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ABSTRACT
Vacuum systems are designed for a variety of research activities and industrial performs for different vacuum ranges depending upon the process prerequisite. It is very essential that these systems should be designed by selecting the vacuum equipment for proper vacuum generation, precise vacuum measurement and particular vacuum control for immense contribution to the process effectiveness, operational ease, working efficiency and quality product. In this paper effort has been made to clarify the physical concepts to use variety of vacuum pumps, gauges and valves to design different vacuum systems with diverse vacuum ranges for their up to mark effectiveness.

Keywords: Physical concepts, Vacuum equipment, System designing.

Contribution/ Originality
As far as the contribution of the study of this paper is concerned, it is one of very few studies which have investigated. It surely contributes in the existing literature with trustworthy methodology. It also contributes the first logical analysis. The paper's primary contribution is finding the true solution.

1. INTRODUCTION
A convenient and approximate rule for work in a vacuum system is to specify its ultimate pressure, which should be 10 times lower than the desired process environment. Consequently, selection of suitable vacuum equipment for vacuum generation, measurement, and control to design the vacuum system for a particular vacuum range is of prime importance. Here the physical concepts of using different vacuum pumps, gauges and valves for diverse vacuum ranges to design the vacuum systems have been enlightened from vacuum physics point of view.

2. VACUUM GENERATION
For all vacuum concern modern and sophisticated technologies, the appropriate vacuum generations are as essential as these technologies themselves. So the proper vacuum generation of

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broad vacuum range is of prime interest and need of the hour. For this purpose, a vacuum pump plays the major role, selection of which is an important and questionable issue.

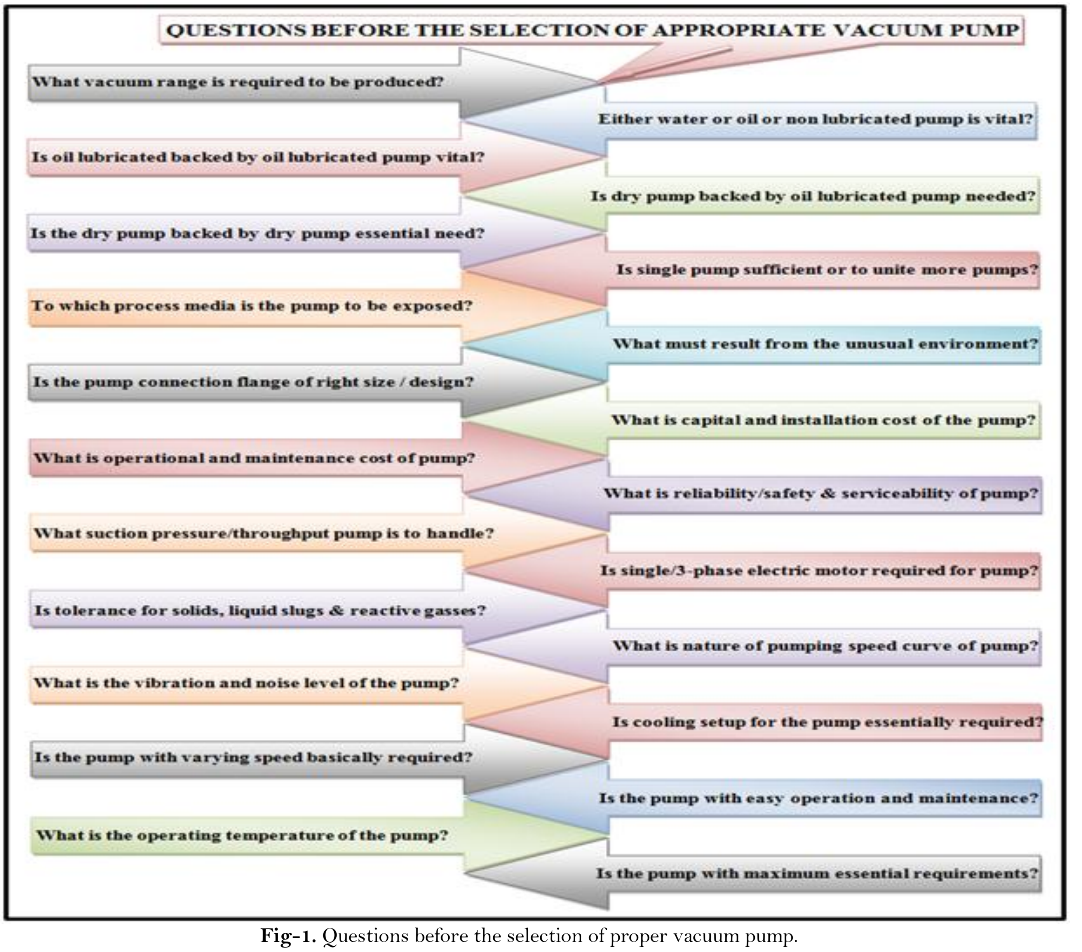

Fig-1. Questions before the selection of proper vacuum pump.

Selecting the right vacuum pump or pumping system for a vacuum process is a complex and challenging task with the realization that no single type of vacuum pump is likely to provide all the characteristics necessary to meet all the process requirements. Before the selection of an appropriate vacuum pump for a particular vacuum application, one has to come across a variety of questions which are planned in figure-1 [1]. Vacuum pumps are used for vacuum generation in the broad vacuum range from atmospheric pressure to Extremely High Vacuum (XHV). Due to some physical reasons, it is not possible to construct a vacuum pump which can generate the vacuums of entire vacuum range. Consequently, a series of vacuum pumps is available, each of which has a characteristic vacuum generation range that usually extends over several orders of magnitudes. A variety of pumps have to employ to generate vacuum, depending on the needed range. These pumps generally fall into three different main groups: positive displace pumps, momentum transfer pumps and local entrapment pumps. A graph of molecular density versus vacuum quality, gives up a straight line, consequently defining different vacuum levels: 'Low

Vacuum', 'Medium Vacuum', 'High Vacuum', Ultra High Vacuum' & 'Extremely Ultra High Vacuum' and corresponding pump operation regions: 'positive displacement region', 'momentum transfer region' and 'local entrapment region', as shown in figure-2 [1]. Due to the diversity of vacuum ranges and pump regions, selection of appropriate pump for a particular region is critical. Selection of vacuum pumps, gauges and valves for different vacuum ranges is briefly discussed in the subsequent sections.

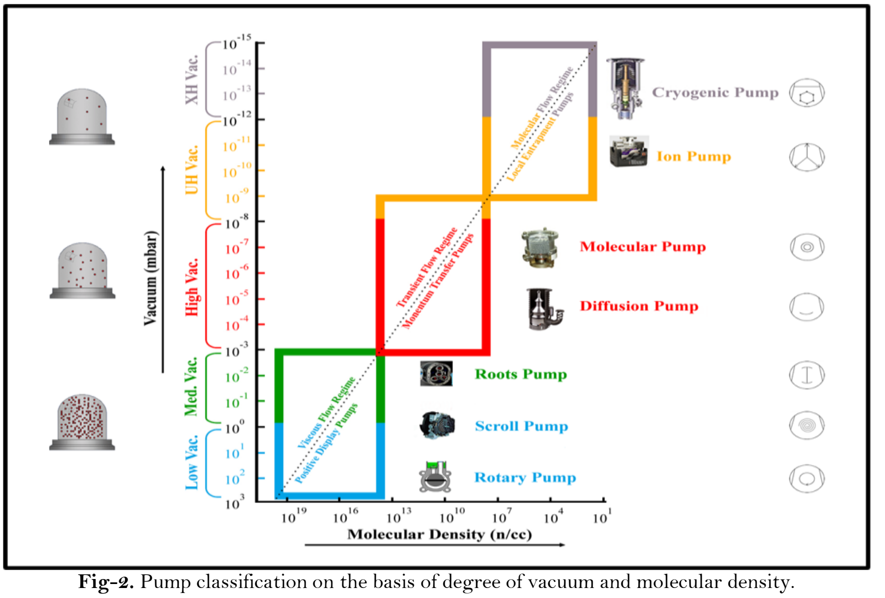

Fig-2. Pump classification on the basis of degree of vacuum and molecular density.

2.1. Selection of Vacuum Pumps

Vacuum pumps can be grouped by the pressure range they measure. Categorically**,** a pump has to generate the vacuum of specific range for a particular vacuum system. For this purpose, it is essential to select the pump according to the process vacuum range of the system. For all vacuum applications, pumps are selected that are more suitable for these applications. Selection criteria of various pumps for varied vacuum ranges are briefly discussed on basis of the concept given in the graph of figure-2 as well as taking into consideration other relevant parameters and requirements of specific vacuum systems.

2.1.1. Low /Medium Vacuum Pumps

The pumps used to generate the low / medium vacuum in the viscous flow regime are usually positive displacement mechanical vacuum pumps. Viscous flow is feasible only when there is a bulk of gas molecules, and if one part of the bulk is removed, the remaining one comes to fill its space. During the evacuation process when the bulk of gas molecules reduces, the pumping speed of the pump decreases simultaneously and ultimately becomes almost zero at the further reduced pressure. To focus the stepwise discussion firstly, the focus is mainly on vacuum pumps capable of producing low vacuum from atmospheric pressure to 1 torr and medium vacuum from 1 torr to

10^{-3} torr. The mechanical rotary vacuum pumps are positive displacement pumps that move fluids by means of the motion of rotors, cams, pistons, screws, vanes, etc. or mechanical elements in a fixed casing. The mechanical vacuum pump, historically the work horse of the industry is the oil sealed rotary piston vacuum pump. Therefore, the mostly focus is on choosing oil sealed rotary mechanical vacuum pumps. However, some oil-free vacuum pumps can be considered as suitable due to the absence of oil in their design [2]. Good examples of such dry pumps are scroll vacuum pumps. Sometime rapid evacuation of the system is essentially required in the medium vacuum range. For this purpose, a roots vacuum pump in series with suitable mechanical vacuum pumps is essential. Another class of positive displacement pumps commonly known as liquid ring vacuum pumps is constantly becoming more important in modern plant production processes. Their design and principle of operation offers many advantages over other types of rotary vacuum pumps. Liquid Ring Vacuum Pumps can be used on a very large scale for widely divergent applications. The schematics of some of the positive displacement pumps are shown in figure-3 [1].

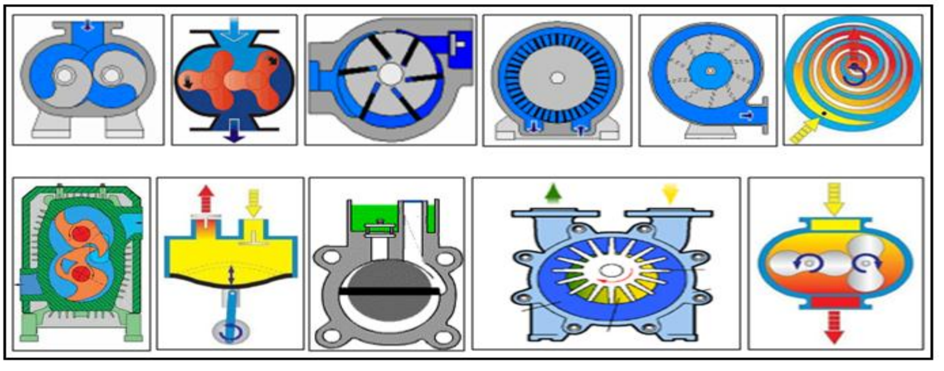

Fig-3. Schematic of working principle of some positive displacement pumps.

2.1.2. High / Ultrahigh Vacuum Pumps

The transient flow regime is with somewhat lesser molecular density and molecules do not behave like a bulk but act as individual particles that need to be removed individually through the process of momentum transfer. The pumps utilizing this process are called momentum transfer pumps. Two pumps in this low density region are of prime interest and are mostly used. First, the oldest one is the oil diffusion pump-DP (backed by rotary pump), with oil or mercury as working fluid, encountering the main problems of back streaming, back migration and contamination. A good alternative, free from all these problems, with better performance, and producing clean vacuum is turbo-molecular pump-TMP (backed by dry scroll pump). The momentum transfer is the governing principle in both diffusion and turbo molecular pumps, used for various purposes in high and ultrahigh vacuum range. The schematic showing working principle of oil diffusion pump and turbo molecular pump is given in figure-4 and figure-5 respectively.

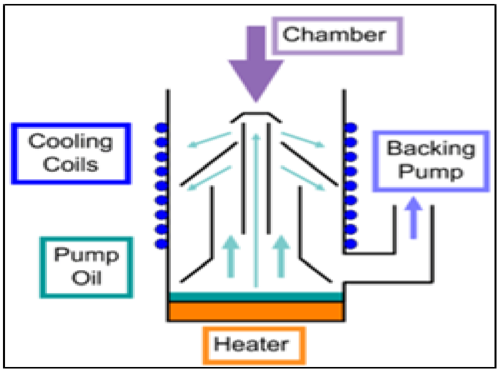

Fig-4. Schematic of DP working principle.

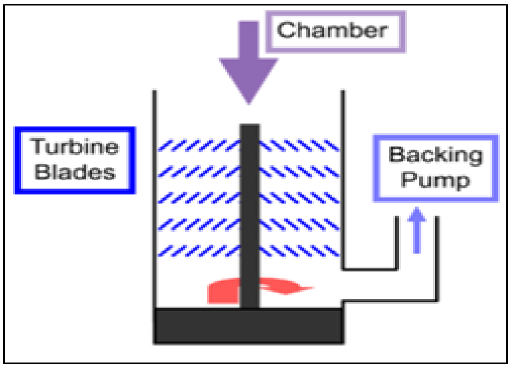

Fig-5. Schematic of TMP working principle.

2.1.3. Ultrahigh / Extreme High Vacuum Pumps

The molecular flow regime the least molecular density one, is the region of high, ultra high and extreme ultra high vacuum. The principle of entrapment of the residual molecules is used for the evacuation in this region. The pumps operating on this principle are called entrapment pumps. In this least molecular density region, the residual molecules are either wiped out by the process of ionization or condensed cryogenically. Consequently, two types of vacuum pumps namely ion pumps and cryogenic pumps are used for the production of high / ultrahigh vacuum and ultrahigh / extreme high vacuum respectively. In an ion pump the residual molecules in the working vacuum chamber are vanished through the process of ionization. In a cryogenic pump, gas molecules are condensed on the cold surface by some suitable refrigeration arrangement. As long as the surface remains cold, the gas molecules will remain on the cold surface, creating required vacuum in the rest of the chamber. The schematic showing working principle of ion pump and cryogenic pump is given in figure-6 and figure-7 respectively.

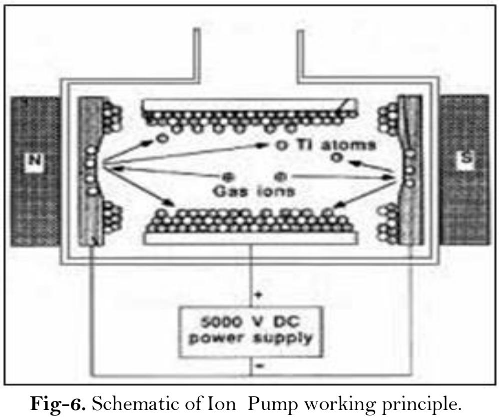

Fig-6. Schematic of Ion Pump working principle.

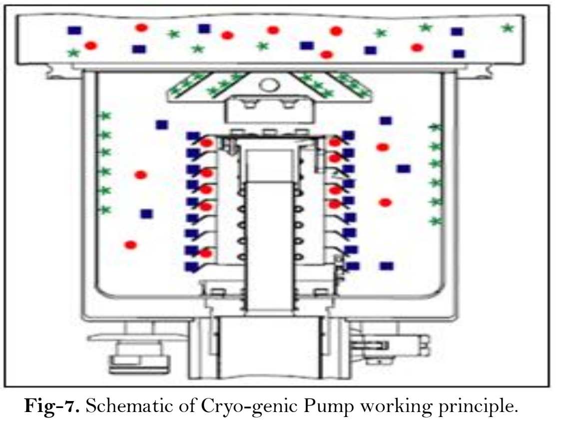
Fig-7. Schematic of Cryo-genic Pump working principle.

It is worth mentioning that in case of high, ultra-high and extreme-high vacuum, initial evacuation is done with positive displacement mechanical vacuum pump followed by other discussed pumps: diffusion, turbo-molecular, ion, cryogenic pump, etc. Usually parallel or series arrangements of these pumps are used as per requirement to achieve the essential vacuum.

3. VACUUM MEASUREMENT

It is very important that the generated vacuum should be measured accurately. Similar to vacuum pumps, there is not a single vacuum gauge that can measure the vacuum of entire ranges. Therefore, various gauges have to employ to measure vacuum, depending on the needed range [3]. Before the selection of an appropriate vacuum gauge for a particular vacuum application, one has to come across a variety of questions which are listed in figure-8.

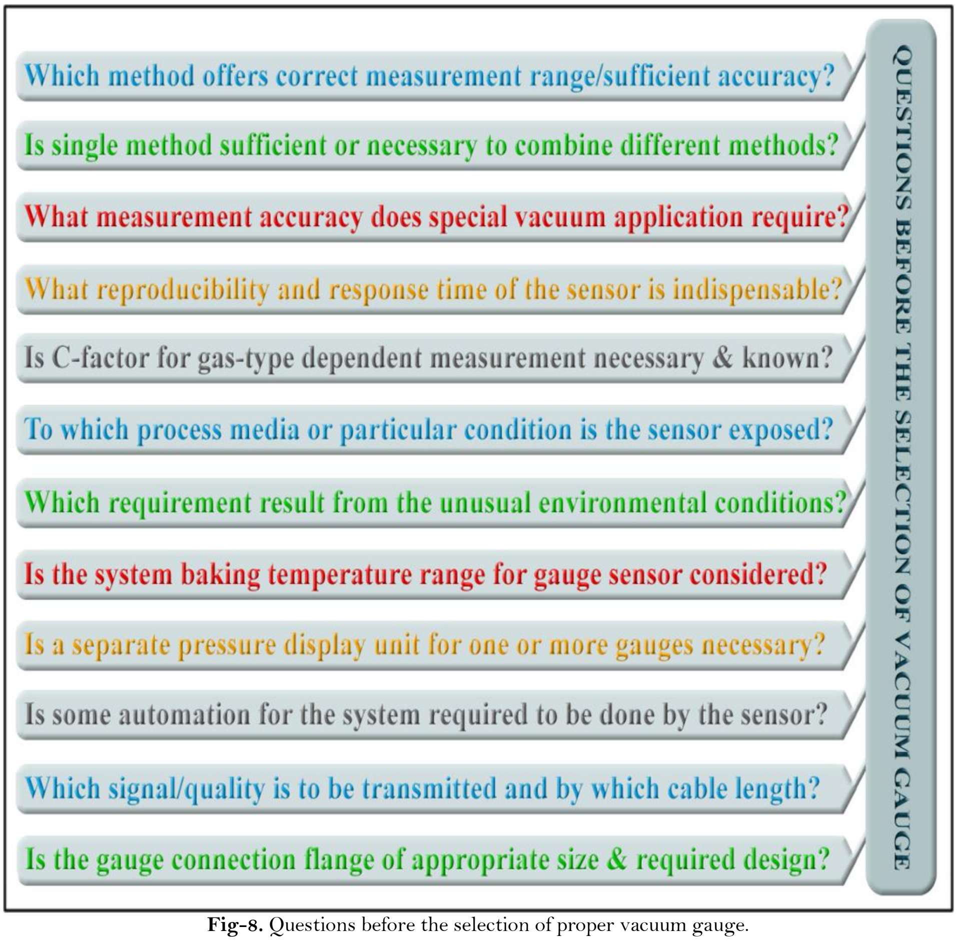

Fig-8. Questions before the selection of proper vacuum gauge.

3.1. Selection of Vacuum Gauges

Generally Vacuum gauges fall into different main groups: mechanical phenomena gauges, transport phenomena gauges, ionization phenomena gauges, analyzing phenomena gauges, etc [4]. A graph of molecular density versus vacuum, gives up a straight line, consequently defining different vacuum levels and corresponding gauge regions: pressure exertion region, thermal conductivity region, ionization region, enhanced ionization region, and gas analyzing region as shown in figure-9 [4]. Due to the diversity of vacuum regions, selection of appropriate gauge for a particular vacuum region is critical.

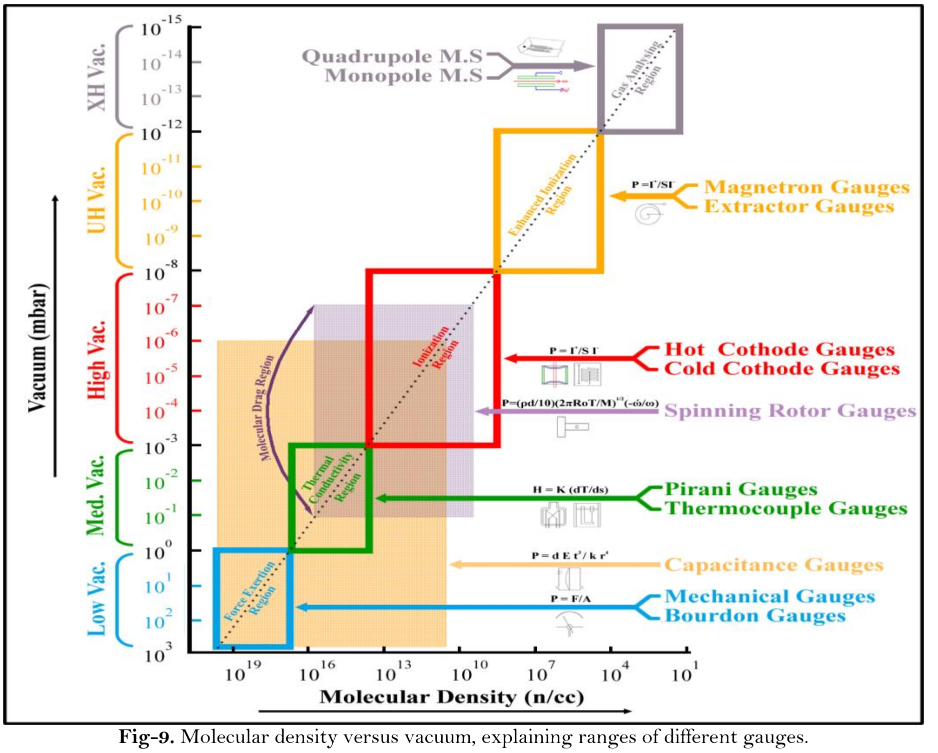

Fig-9. Molecular density versus vacuum, explaining ranges of different gauges.

3.1.1. Low Vacuum Gauges

The gauges that are used to measure the low vacuum, are usually mechanical vacuum gauges which measure pressure P by recording the force F exerted by the gas molecules per unit area **A** on the walls of the gauge sensing element [5]. A variety of gauges can be used for low

$$P = F / A \qquad (1)$$

Vacuum systems. Two of them are significant and mostly used. One is Bourdon Gauge and other is Capacitance Diaphragm Gauge (CDG). Normally, for industrial low vacuum measurements, Bourdon gauges are preferred while for high accuracy and R&D work CDGs are essentially selected. While selecting Bourdon gauges thought is given to a number of parameters which have an effect on gauge accuracy, safety, and utility. These gauges are usually mechanically operated rugged sensors, having installed flexible tubes inside, which are of suitable material with proper geometry sensitive to pressure changes.

Capacitance Diaphragm Gauge is used in clean vacuum systems because of its ease of use, potential accuracy, fine resolution and quick response [6]. It is used as a transfer gauge because its accuracy, reliability and stability have long been proved to be high in international comparison of vacuum gauges [7]. In this gauge a thin diaphragm (membrane) is used as a sensing element. The use of this thin diaphragm, makes the gauge highly sensitive to space changes of the capacitance technique. This makes CDG superior to most of the other mechanical deflection gauges. If d is the deflection of a uniformly loaded circular membrane (diaphragm) tightly attached around its periphery, the pressure P measured by this gauge [6] is given by

$$P = d\,E\,t^3 / k\,r^4 \qquad (2)$$

Where **P** is pressure across the diaphragm, E is the elastic constant of the diaphragm material, **r** & **t** are the diameter and thickness of the diaphragm and **k** is constant. It is obvious that the deflection of the diaphragm is linearly related to the pressure. Therefore, the response of this gauge is linear with reasonable accuracy of vacuum measurement.

3.1.2. Medium Vacuum Gauges

In medium vacuum range, the molecular density is too less to exert mechanical force. Therefore, direct measuring mechanical gauges cannot be used in this range. Consequently, some other physically observable phenomena using certain property of gas is employed in medium vacuum gauges, which is thermal conductivity of gases. Thermal conductivity is defined as the amount of heat transfer per unit time across the unit area of small plane located perpendicular to the direction of heat flow divided by the temperature gradient. The thermal conductivity **K** of a substance is defined by the expression [8].

$$H = K\,(dT/ds) \qquad (3)$$

In which **H** is the amount of heat flowing per unit area per second in the direction parallel to **s**, and **dT/ds** is the temperature gradient in the same direction.

The Pirani gauge is constant filament temperature thermal conductivity gauge used for the measurement of the pressures in medium vacuum systems [9]. It was invented in 1906 by Marcello Pirani [6]. This gauge measures the pressure by determining the filament temperature through a measure of filament resistance which is given by Akram and Fasih [6].

$$R_T = R_0\,(1+\alpha T) \qquad (4)$$

Where R_T is the filament resistance at T°C, R_0 is Resistance at 0°C and α is the temperature co-efficient of resistance for the filament wire. Therefore, if the temperature of the filament is measured, this can be related to its resistance then supply voltage and ultimately to the pressure. So in thermal conductivity gauges, there is relation between the pressure of a gas and its ability to transfer heat. Different gauges are used for this range but two of them: thermocouple gauges and Pirani gauges are important. CDG has also the potential to measure vacuum accurately in medium range and is employed successfully.

3.1.3. High Vacuum Gauges

High vacuum range is basically a regime of molecular flow, in which molecular density is too low to conduct thermally. Therefore, neither the mechanical nor thermal conductivity gauges can be used in this region. The physical principle employed for the gauges of this region is the ionization of gases. This is one of the largest, most important and most widely used class of vacuum gauges. In such gauges, the positively charged molecules are attracted by ion collector, indicating positive-ion current which is ultimately calibrated in pressure **P**, which is give by the relation [10].

$$P = I^+ / S\,I^- \qquad (5)$$

Where I^+ is positive-ion current to the ion collector, I^- is electron-emission current to the anode and **S** is the proportionality constant known as the gauge head sensitivity. Thus if **S** and I^- are kept constant, I^+ will be directly proportionally to pressure **P**. Two types of ionization gauges generally employed are cold cathode ionization gauges and hot cathode ionization gauges, utilizing the application of high voltage and high current respectively used for ionization.

Another important gauge, which is also used for high vacuum work is Spinning Rotor Gauge (SRG). It is used for consistent vacuum measurements as well as reliable secondary standard because it is an internationally recognized reliable transfer standard from 10^{-2} mbar to 10^{-6} mbar [11]. This gauge operates by virtue of the viscous or frictional forces that gas molecules exert on the moving surface which is a small stainless steel ball. The collisions of the gas molecules with the surface of the ball impart a drag to it which decelerates the ball, measured by the pickup coils. This force is dependent upon molecular density of the gas and temperature. For this gauge, taking different factors into account, the pressure **P** [12].

is given by

$$P = (\rho d/10)(2\pi R_o T/M)^{1/2}\,(-\acute{\omega}/\omega) \qquad (6)$$

Where **T** & **M** is absolute temperature and the molar mass of the gas, **d** & **ρ** is diameter and density of the ball respectively, $\acute{\omega}$ is the measured rate of change of ball s' rotation rate and R_o is universal gas constant.

3.1.4. Ultra High Vacuum Gauges

In Ultra High Vacuum (UHV) range, the molecular density is further reduced as compared to high vacuum region. Special ionization gauges are commonly used for vacuum measurements in this range. The lower density gas present in the chamber is ionized and the subsequent measurement of the ion current gives gas pressure information [6, 13, 14]. Doubtlessly, the most widely used ionization gauge with some special design, more supportive for ionization in this range, is Extractor gauge by Redhead [15]. This gauge measures pressures between 10^{-4} and 10^{-12} mbar].

3.1.5. Extreme High Vacuum Gauges

For Extreme High Vacuum (XHV) range, the molecular density is the least one. In such a region the partial pressures of small amounts of gases present are analyzed by mass spectrometer and total pressure is found by making the use of Dalton law of partial pressures. Monopole and quadrupole mass spectrometers are used for this least particle density region. In mass spectrometer, the present gases are ionized, produced ions are accelerated, tuned mass selected, magnetically deflected, detected, measured and finally displayed as partial pressures.

It is also noteworthy that in case of high, ultra-high and extreme-high vacuum, initial vacuum is measured with rough/medium vacuum gauges while other vacuums are measured by different deliberated vacuum gauges.

4. VACUUM CONTROL

Vacuum valves are basically mechanical devices constructed by different materials. These are installed in the vacuum system for multiple control purposes like isolation, air-admittance, throttling, adjust & maintain the required vacuum levels as well as for accurate flow rates of the process fluid in the vacuum system. As for as the construction of a conventional valve is concerned, it comprises the housing or body that encloses the valves' mechanism vacuum leak tight as well as contains inlet and outlet ports, the bonnet, through which the motion from the external atmospheric side is transmitted, and the stem which transfers this motion to the valve disc that opens or closes the flow passage depending on its position [16]. There is diversity of vacuum valves available. Some commonly used valves in the vacuum systems are shown in figure-10.

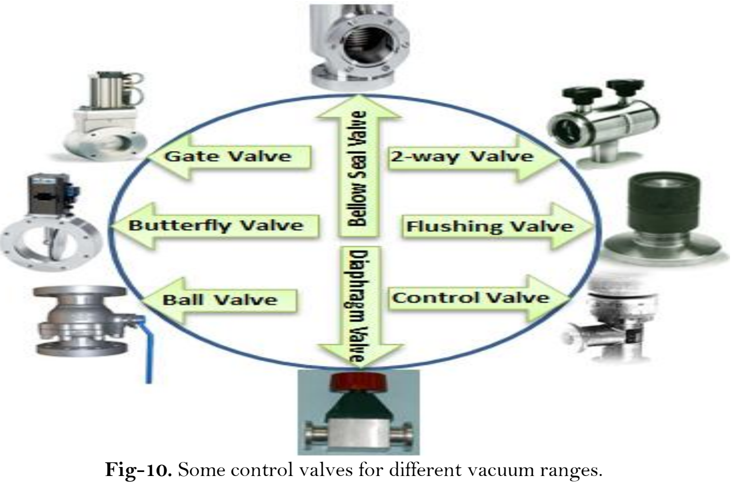

Fig-10. Some control valves for different vacuum ranges.

4.1. Selection of Vacuum Valves

Since the valves are important part of the vacuum system, consequently care should be taken to ensure that the precise valve is selected for a specific vacuum range to ease the required process. In case of improper selection, valves can cause operational problems, including poor control, cavitation consequence, reduced conductance, and hydraulic transients that result the effects like poor performance, accelerated wear, repair, and replacement of the valve [17]. The vacuum valves are classified on the basis of operating system. Classification of the systems forming a valve is shown in figure-11 [18].

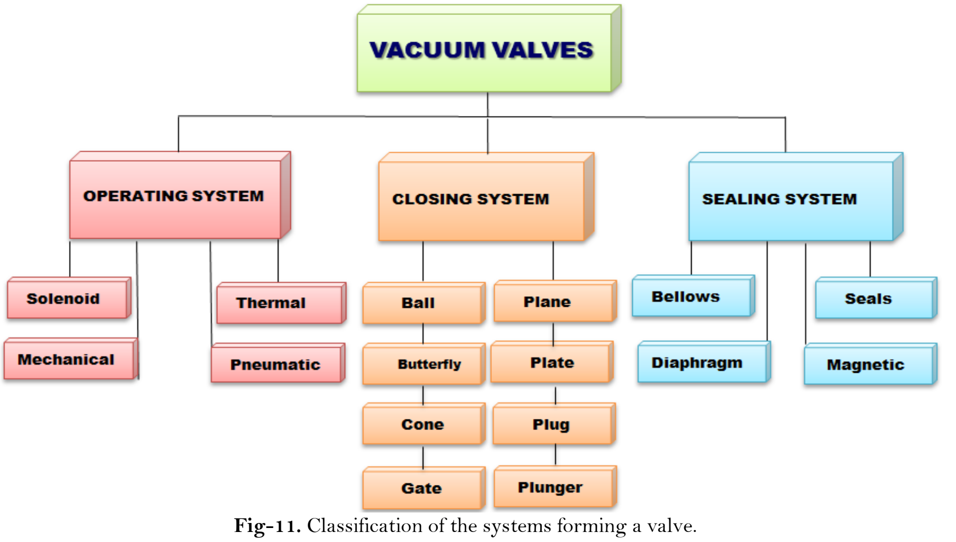

Fig-11. Classification of the systems forming a valve.

4.1.1. Low and Medium Vacuum Valves

Good quality commercial valves intended for pressure service are almost practically satisfactory for low vacuum range applications. Caste valves are acceptable for use in these ranges because outgassing and other sources of virtual leaks do not contribute significantly to the observed leakage rate. Moreover permeation is not a consideration in these vacuum ranges [10]. Therefore, the normal valves like ball valves, diaphragm valves, butterfly valves, gate valves, bellow sealed valves etc. can be used for these ranges.

4.1.2. High and Very High Vacuum Valves

Normally conventional valves are not acceptable for high and very high vacuum applications. Fine quality valves are used for these vacuum ranges. Interior surfaces of valves for such ranges must be properly machined and polished to minimize outgassing. Also the use of metal bellows to seal the shaft stem is standard, and the metal gaskets are used for the bonnet-to-body sealing. For high and very high vacuum ranges, fine quality high performance butterfly valves, gate valves, bellow sealed valves with some added features are used. They are installed in the vacuum system with metallic seals as elastomeric seals are avoided for such vacuum ranges due to their high outgassing rate.

4.1.3. Ultra High and Extreme High Valves

For Ultra High Vacuum (UHV) and Extreme High Vacuum (XHV) ranges, specially made all metal valves are used. These valves are usually fabricated systematically from fine quality Stainless Steel or other suitable material having low outgassing rate. The internal surfaces of these valves are finished to the best quality and polished. Furthermore, these are with Conflate Flange (CF) and installed in the vacuum system with Oxygen Free High Conductivity (OFHC) Copper gasket using proper sealing torque, which is great enough to deform the Copper gasket on the valve CF knife-edge conical seat to make this joint properly leak tight [10]. The main reason that these valves are used in UHV and XHV with OFCS is to minimize the outgassing rate from these components which is the essential requirement for such uppermost quality vacuum ranges. Due to all metal assembly, these valves can be baked to high temperature for further reducing outgassing rate. These valves have different port geometry like straight through ports, right angled and 45 degree ports for simple system designing with maximum conductance. Excellent material gate valves are also used in this vacuum range as per requirement of the system.

From the above discussion it is quite obvious that there are various types of vacuum valves available for putting into practice in the vacuum systems. But an ideal valve should be selected. An ideal valve should meet specific requirements that have been briefly listed in figure-12 [19].

Fig-12. Requirements of an Ideal Vacuum Valve.

Unfortunately no valve can meet all these requirements. Consequently, in selecting a valve for a specific application a compromise should be made, insisting on the most significant requirements for the desired particular purpose.

5. CONCLUSION

Effective vacuum system designing is basically a technical concern to select appropriate equipment for vacuum generation, measurement and control. In this regard, all the equipment has systematically been deliberated keeping in view the perceptions of vacuum physics. Thoughtfully designed vacuum system on the basis of these deliberations, surely contribute to the process effectiveness, operational ease, working efficiency and quality product.

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