A Journal of Practical and Useful Vacuum Technology

From THE VACUUM LAB

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Understanding Pressure and Measurement

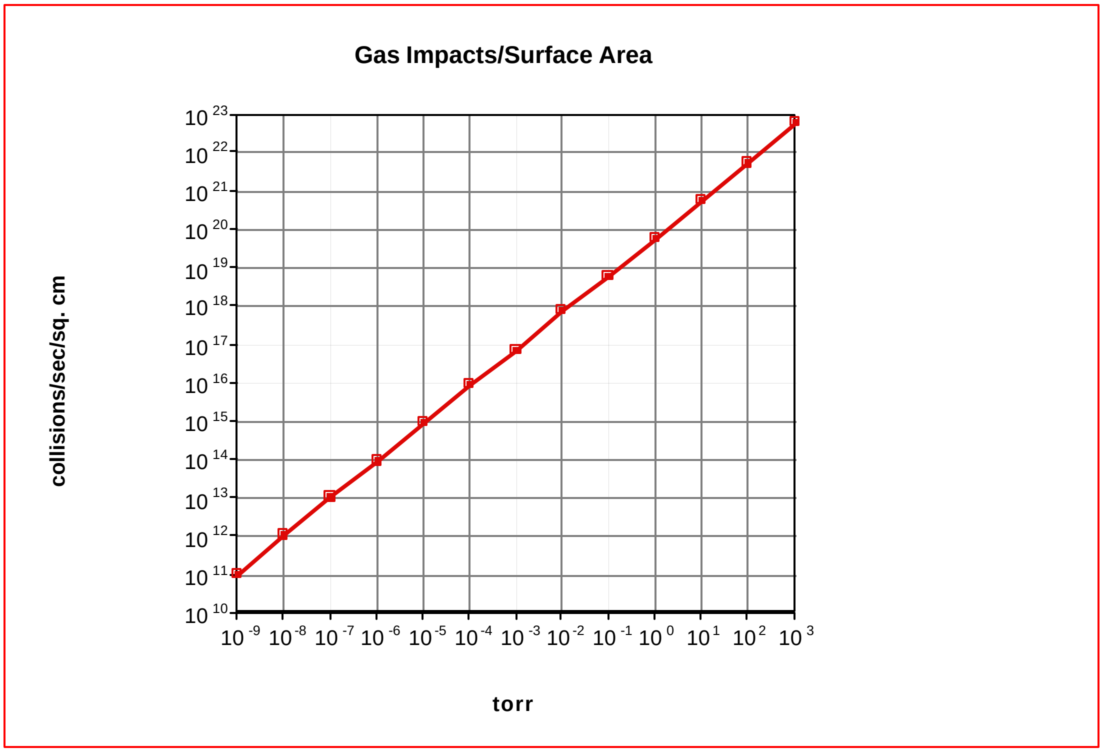
Pressure is an important component of the Q=SP fundamental vacuum relationship, but it means much more in practice and application.

Pressure is one of the three main quantities that make up the fundamental relationship that governs the behavior of all vacuum systems. This relationship is expressed in the formula Q (Gas Load) = S (Pumping Speed) x P (Pressure). In many cases, achieving a certain pressure is taken as the main end in vacuum technology. Under these conditions the P in the formula can become merely a number in the mind of the vacuum practitioner. There are, however, many ways to look at the concept of pressure, and how you look at it will depend upon what you're trying to do. Pressure is defined as force per unit area. In this case, the force is exerted by the impact of the gas molecules with the surface where their impact energy is transferred. The more impacts, the more force, and the higher the pressure. Since all molecules, at any given temperature, have the same energy, it doesn't matter what the gas is. This is true for any pure gas or gas mixture such as air. Lighter molecules, such as helium (He) will be moving faster than a heavier gas such as argon (Ar), and the energy transfer at impact will be the same. The concept of the force exerted by air pressure opened the door to vacuum technology when Torricelli discovered that air pressure would support a column of mercury (Hg) in a closed-end tube in 1644. Today, a standard atmosphere is defined as a Hg column of 760 mm (760 torr) as measured by a Hg manometer. That's right, torr comes from Torricelli.

A large and important segment of vacuum technology depends upon using the concept of force. The designer of a vacuum chamber has to take this into account. As gas molecules are pumped out of a container, there will be fewer molecular collisions with the inside of the container while the air outside the container will still provide a higher, and fixed, number of collisions. This difference results in a pressure differential that is also a force differential on the walls of the container. This accounts for the occasionally heard grunts and groans, pings and pops, or the oil can sound of a large flat area deflecting as a vacuum chamber is being evacuated. This effect was first demonstrated by von Guericke in 1650 when he joined two hemispheres together and pumped out some of the air in the resulting sphere. Two teams of horses couldn't pull them apart, but they fell apart when the sphere was airreleased. As more and more molecules are removed from the container, the pressure and force differentials increase. This continues until the pressure inside the vessel has been reduced to a few torr. At lower pressures, the differential forces are too small to have any practical effect or concern.

The physical force exerted by pressure differentials can have a large number of practical applications. Pneumatic tubes used to transfer materials, vacuum chucks or hold-downs, or even the venerable suction cup are prime examples. In fact, the first American subway used this technique in New York to move cars a single block in 1870. These forces can also be used to operate vacuum/pressure gauges. As a chamber is evacuated, the diminishing pressure will exert a smaller force differential on a thin-walled diaphragm or closed-end Bourdon tube that will result in motion that is proportional to the pressure differential between the chamber and the ambient atmosphere. This motion can be coupled to a dial through mechanical linkages to produce a readout of the pressure within the chamber. Commonly, these gauges respond only down to pressures of a few torr since the pressure differential will produce little force differential below these pressures, but there are some gauges of this type that reach lower pressures. Capacitance manometers where subtle sensing techniques are used to measure tiny differences are a notable example.

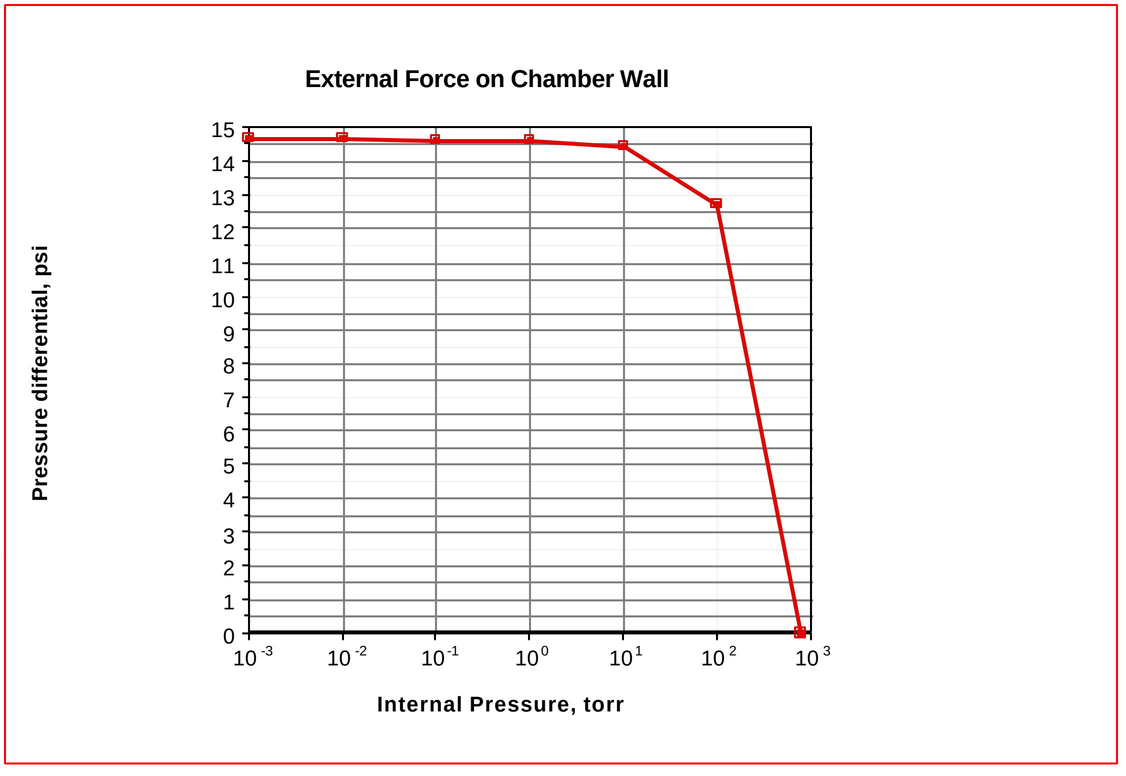
The use of mechanical gauges has led into a potentially confusing situation that often plagues the communication of specifications and references. We have both absolute pressure and gauge pressure to contend with. Absolute pressure uses a perfect vacuum as zero while gauge pressure uses atmospheric pressure as zero. This means that a mechanical gauge, usually calibrated in English units, might have a dial reading from zero to something called 30 inches of vacuum. What they mean



As the pressure is reduced, the number of impacts/unit area are reduced as well.

here is pretty confusing to many vacuum practitioners unless it is converted, usually mentally, into absolute pressure equivalents. For example, a gauge reading of 29.5 inches of vacuum is actually 11 torr in absolute pressure. The use of gauge pressure is usually confined to some particular application areas, but some confusion still exists. For example, a vacuum practitioner might be interested in a diaphragm pump that is only capable of producing vacuum levels of a few torr, and would then find the manufacturer's specifications listed in inches of vacuum. In fact, many of these manufacturers tend to refer to anything below a few torr as "deep vacuum" which is obviously not a term deeply appreciated by practitioners operating at lower pressures.

Vacuum practitioners that operate at pressures below a few torr will tend to think in terms of absolute pressure in a logarithmic sense, using units of torr, millibar (mbar), or Pascal (Pa). Pascal expanded Torricelli's work to prove that a Hg column changed with altitude, and for this, he deserves his own unit. All three of these unit systems have diminishing numbers that refer to the diminishing numbers of molecules within a chamber as the chamber is evacuated.



As the pressure within the vacuum chamber is reduced, the ambient pressure increases the force on the chamber wall, but the increase in force is negligible below a few torr.

Although the mechanical considerations of pressure down to a few torr don't need to take the actual gas species into account, this is not true for a number of applications that require evacuating a chamber to a sufficiently low pressure to remove atmospheric gases before backfilling the chamber with specific gases to some higher pressure. In these cases, the actual gas, or gas mixture, is of extreme importance. On the other hand, though, processes that require only a pumpdown tend to ignore the gas makeup at pressures above the few torr level where most mechanical gauges bottom out. A welcome change has occurred here with the introduction of thermal conductivity gauges with convection enhancement that allow readings all the way from atmospheric pressure, or slightly above, to a few millitorr. This allows the same logarithmic units to be used throughout the pumpdown and process cycles. Still, the differences in the actual gas makeup come into play even though we have been considering only total pressure.

To the vacuum practitioner, total pressure is the sum of the partial pressures of the various gases making up the vacuum environment. Attempting to work only in total pressure can cause some problems. A good example is using thermal conductivity gauges where the various gases used or encountered might have widely differing thermal conductivity. If you attempt to backfill a chamber to atmospheric pressure using a gauge calibrated in nitrogen (N_2) with Ar, the gauge will read so low that you chance overpressuring the chamber before you reach an atmospheric pressure reading. This can result in a very dangerous and expensive method of disassembling a vacuum system. Perhaps more importantly, the partial pressures within the chamber can have crucial effects on the process.

Total pressure gauges, calibrated in N_2 equivalents can have widely differing partial pressures of residual gases while still indicating the same total pressure. Since water vapor is usually the main gas species in the chamber at pressures below 10^{-3} torr, many process specifications will require a particular total pressure reading before the process is initiated, but this will often assume that water vapor is always the main constituent. A small air leak can change this makeup, but the total pressure read on a hot or cold cathode ion gauge might show the same reading. This can kill a process. Since each gas will have a different sensitivity for ion gauges, total pressure measurements can always be misleading. Residual gas analyzers (RGA) can provide a solution to this problem. They measure and display the partial pressures of all the residual gases that lie within their particular pressure ranges. Usually, a range of 1 to 50 atomic mass units (AMU) is sufficient unless heavy hydrocarbon contamination is expected. The use of an RGA will not stave off vacuum or process problems, but it will certainly help to head them off before process problems occur.

The concept of pressure in terms of the force exerted by molecular impacts changes to really consider the effects of the impacts. For example, a growing thin film of reactive metal will react with the impacting active gas molecules in proportion to the number of impacts per unit time, and this is proportional to pressure.

The actual units that you use are not important as long as they're consistent. Torr is arguably the most commonly used in the US, but mbar is usually used in Europe while Pa is common in Japan. For rough work, it's possible to use torr and mbar interchangeably, but for fine work you just multiply mbar by 0.75 to get torr and multiply torr by 1.33 to get mbar. Pa is a little trickier, and this might explain the resistance to its use in many cases even though one of the most common vacuum books, **A Users Guide to Vacuum Technology** by John O'Hanlon. uses Pa throughout the text. Conversion isn't all that difficult though; multiply torr by 1.33 or mbar by 10^2 to get Pa.

The concept of pressure is of obvious importance in vacuum technology, but it's always necessary to consider what the term really implies for your process or application. The differences between total and partial pressure always need to be kept in mind, and this is especially important for cross-communication between vacuum practitioners. Maintaining consistent units are equally important. And, always remember that really experienced vacuum folk always refer to particular exponential numbers with "ten'a'minus."