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How To Use the Q=SP Fundamental Vacuum Relationship

Vacuum technology, like most other complex technologies, can be approached either as an assembly of small and discrete segments or as an overall concept that can be broken into smaller concepts. Although both approaches can be used successfully, a combination is often the most effective. The trick is obviously found in picking the right mix. The complexity of vacuum technology can be bewildering to the beginner, but it is especially bewildering to the normally technically competent person who expects to follow a learning path that uses thinking techniques learned in mastering other technologies. One of the first barriers, and vacuum isn't alone in this, is to discover that the complexity of a system is greater than the sum of the complexity its own component parts. This comes right down to facing up to the interaction of each component with all the others. If, as is often the case, early understanding is based on a series of single observations, the use of reasonable logic seems to disappear and bewilderment descends. Single observations, rules, and lessons are extremely important, but attempts to utilize single bits of information can cause more problems than they can solve. Still, how can you use those valid and accurate single bits? You hold them up against an overall concept that governs the entire assemblage of the technology, and this lets the bits and pieces fit together to help form a clear understanding. The overall concept that encompasses all vacuum systems and processes is easiest to understand when written as the equation Q (Gas Load) = S (Pumping Speed) x P (Pressure). This equation can be used in both a qualitative and quantitative sense.

Qualitatively, the equation can be used for understanding a vacuum system's behavior by mentally changing any one of the three

Making Quantitative Vacuum Calculations

Mixing units is one of the simplest traps to fall into when making quantitative calculations, since various performance parameters are often taken from different sources, such as published literature data, catalogs, or Web pages. For example, a pumping speed (s) in m**3**/min will need to be converted to L/sec if the gas load (Q) is given in torr L/sec with pressure in torr. Practical and useable units for Q and S can be obtained from other articles:

Q

1. "Improve Your Vacuum System Performance and Behavior"
2. "Reduce Water Vapor in Vacuum Systems"
3. Assessing Gas Loads in Vacuum System Design"

S

1. "How to Match Pumping Speed to Gas Load"

variables and letting the formula tell you what the effect might be on the other two. For example, a sudden increase in gas load would result in an attendant increase in pressure. Reversing the thinking process, an increase in pressure might be due to an increase in gas load. Although this sort of thinking is extremely simplistic, it can provide a powerful and quickly applied tool for either zeroing in on a problem with an existing system or preventing a future problem when in the design phase for a new system. The process of absorbing the simplicity of the Q = SP relationship can easily advance to a “gut feel” ability to watch a pumpdown proceed by monitoring the gauges and knowing what’s happening within the system at all times. Although this ability is commonly developed by vacuum practitioners in regard to a system that they use frequently, it can be taken to the next level by constantly keeping the fundamental relationship in mind. That next level is achieving the same, almost instinctual, feel for any and all vacuum systems’ behavior and performance, familiar or unfamiliar. If, for example, you attempt to foresee the roughing cycle pumpdown performance of an unfamiliar system, you might picture the roughing curve of a well-known system and try to mentally extrapolate a pumpdown curve based on that single example. If the chamber is larger than the example while the roughing pumps speed is the same, applying the Q = SP relationship will help estimate the additional time required to pump down the larger chamber. A higher level ability, though, would easily allow the performance to be estimated when both the chamber volume and the speed of the roughing pump were different than the known example. Useful as this technique is, it’s only good enough to determine differences in performance within the qualitative limits of a little or a lot. Going beyond these rough estimates requires that the relationship be used quantitatively.

Quantitative consideration of a system’s performance requires a shift in thinking. Qualitative thinking can be applied effectively both during a systems’ pumpdown and at its ultimate pressure without going deeper into the Q = SP equation, but quantitatively, the step to actual numbers comes into play. In a quantitative sense, the formula only applies within an infinitely narrow slice of time. If you think of watching a pumpdown progress on either an analog or a digital gauge, the difference becomes clearer. The analog gauge’s needle might be showing the pressure moving down fairly steadily with only an occasional twitch to a slightly higher or lower pressure. In this case, it’s easy to observe the pumpdown’s progress in terms of time and pressure. The readout on a digital gauge will present an entirely different interpretational problem. The digits will be constantly changing during the pumpdown, and the observer’s mind will be almost unable to damp out any short-term pressure twitches. Although both types of gauge are equally useful, the analog gauge tends to lend itself to more qualitative understanding since trends are easy to spot while the digital gauge tends to lend itself to more quantitative understanding. The difference, then, is traceable to the particular gauge’s readout being a function of time, and here we get back to the slice of time concept. The Q = SP formula allows you to compute either Q, S, or P only as long as you know the other two variables. During a roughing cycle, all three variables can be changing constantly. This makes the use of the relationship to look almost impossible at first, but pumping speed at a given pressure can be gotten from the pump manufacturer's literature and a systems gas load (Q) can be easily calculated if a quantitative number is required. In a practical sense, qualitative thinking will probably be more useful in a roughing cycle situation.

Actual quantitative calculations become more and more useful as the system's pressure drops into the high vacuum region or merely approaches its ultimate vacuum. As this happens, the slice of time becomes bigger in a practical sense merely because the changes, with time, of the three variables become smaller and smaller. When making quantitative calculations, you have to constantly remind yourself that the slice of time concept is in play. That's why it's tricky to make calculations during a pumpdown. Once you've completed the calculation, the system's variables have changed and your calculational results are now old news. This means that you are taking snapshots only, but when you string those snapshots together, you have a movie. As the changes with time become smaller and smaller, it's tempting to assume that you are reaching some sort of equilibrium. You'll never reach it because tiny changes will always occur within the system even though they might be too small to show up on a gauge's readout. You will reach a quasi-equilibrium, though, and in a practical sense, you can assume that you are in equilibrium for the sake of calculation.

An apparent equilibrium situation would be when you've pumped the system down to its ultimate pressure and the pressure reading doesn't seem to be changing. Since you are most likely seeing a gas load from surface desorption of water vapor where the desorption rate is decreasing very slowly, you might think that you are in a condition of true equilibrium. Although this is still a quasi-equilibrium condition, it's a safe place to momentarily assume a constant gas load (Q). If you know the pumping speed (P) at the chamber by calculations based on speed of the pump and the conductance of the connecting tubulation, it's easy to make a quick calculation for Q. Once you have a number for Q, it's a simple matter to compare the total gas load you might expect from Q numbers based on published gas load vs. pumping time curves. The expected total Q would usually be an addition of the gas loads expected from water desorption from surfaces and from O-rings at the same pumping time as in the original Q calculation. At this point, the power of making simple Q=SP quantitative calculations becomes apparent because you've got two number to compare. If, as is often the case, the actual Q is an order of magnitude or more higher than expected, there's a problem. The problem might lie with any one or more of the equations three variables; Q,S, or P. Whether the apparent problem is big or small depends on the system and the process, but you've now got some numbers to work with.

With quantitative numbers in hand and a problem suspected, you can use the same Q = SP relationship in a search for the cause of the apparent problem. You can stand the relationship on its head by valving off the pump which results in reducing its pumping speed (S) to an infinitely small quantity. Since the pump is no longer removing a measurable amount gas from the chamber, the pressure (P) will begin to increase because the gas molecules emanating from the source of the gas load will remain within the chamber. Following the pressure rise over a period of time is a diagnostic technique known as a rate-of-rise curve. In a qualitative sense, this technique can differentiate between desorption gas loads such as outgassing and a real vacuum leak. If the source of the gas load in question is desorption, the pressure will begin to stabilize at some point in time as a new desorption/resorption equilibrium is achieved. If the pressure continues to rise, a real leak is present. The rate-of-rise technique's practical value can easily be appreciated by the amount of time that could be fruitlessly expended in leak checking a system when the actual source of the higher gas load was actually desorption. The most useful tool to use for this technique is a simple pressure vs. time graph. Vacuum gauges that display both pumpdown curves and rate-of-rise curves directly on the instrument's readout as time vs pressure histograms are commercially available.

Quantitative applications of the rate-of-rise technique are also useful. If you know the system volume, it's a simple matter to arrive at numbers that can be correlated to the Q that was calculated originally when the system was under quasi-equilibrium conditions. Since no gas is being pumped away from the chamber, it will expand into the known volume. The quantity of gas per unit time can be taken from the pressure rise per unit time on any part of the graph. The most commonly used units are torr liters/sec, but any units reflecting pressure difference and volume can be used to calculate rates. For example: a pressure rise of 1×10^{-6} torr to 1×10^{-3} torr in one minute within a 100 liter chamber will be a rate of 9.99×10^{-4} torr per minute or 9.99×10^{-2} torr liters/min. Dividing by 60, we get a Q of 1.66×10^{-3} torr liters/sec. Comparing this number with the original Q, and the probable differences can be further applied toward gaining an understanding the system's behavior.

These are only a few of the many examples of using the Q = SP relationship either in a qualitative or quantitative fashion. With the constant application in both observation and calculation, a deep and basic understanding of vacuum technology will emerge that will far surpass the advantages of merely attempting to memorize a large number of single and discrete facts and observations.