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Finger Pointing in the Fab©

Introduction

The general public looks at vacuum as the absence of all matter. The hatch on the spaceship bursts open and the alien monster is sucked out, spinning off into nothingness. We can no longer hear an alarm clock ringing in the bell jar when it is evacuated with a mechanical pump. We conclude that this is because there is nothing left in the bell jar to conduct sound. We are greeted in the elevator of a hotel convention center with the tiring joke: "Ahah, much ado about nothing," when they see on our name tag the American Vacuum Society, or the Society of Vacuum Coaters. To the contrary, vacuum has much to do with our every day lives. But, the story is too lengthy to explain on the elevator.

A Little Mathematics Tells a Lot

The story of what is going on in a vacuum system starts with the basic equation of state first encountered in high school or freshman chemistry:

$$PV = n\mathrm{R}T, \tag{1}$$

where P = the pressure in torr,
V = the volume in liters,
n = the number of moles,
T = the temperature in degrees kelvin,
and R = the universal gas constant.

A mole of anything is 6.02×10^{23} of those things (i.e., boxcars, atoms, molecules, etc.). The universal gas constant R varies depending on the other units. This sounds like an oxymoron – that is, to say a constant varies depending ... But, we vacuum technicians have made a jumbled mess of the units of pressure, and the value of R varies depending on the unit of pressure used. Chemists use the unit *atmospheres*; physicists *Pascal* (newtons per square meter); Europeans adopted the *millibar*; engineers, pounds per square inch (*psi*); and, others mystified their work for decades using *mmHg* for the unit of pressure, and later changed this to *torr*.

Seeing the error of our ways, we all took a blood oath in the late 1980s, and swore to hence forth universally adopt the pressure unit of Pascal (Pa). Well, with the exception of the Japanese and others on the Pacific Rim, the world drifted back to its old habits. USA publications presently use the unit torr, with Pascal given parenthetically; Europeans almost exclusively use millibar; and, of course, we could never hope to change the chemists and engineers. It is suggested that before our children and grandchildren get a feel for torr, we start using the mks unit Pascal for pressure.

However, if you, like us old-timers, have trouble changing, the universal gas constant when using the unit torr for pressure is (please keep out of the reach of children):

$$R = 62.36 \text{ torr-liters/mole-degree K.}$$

So what, Kimo? Well, if you were to take a snapshot of what's going on in your vacuum system at any instant in time, you can actually count the number of molecules in the system using (1). Also, if the pressure in the vacuum system is $\sim 10^{-6}$ torr, molecules are impinging on every surface in that system at a rate of $\sim 10^{15}$ molecules/cm^2-sec. If all the molecules stuck to the surfaces, this would correspond to a monolayer build-up each second. Of course, they don't necessarily stick when they hit the surface, but they bombard the surface at that rate. Why is this important? Well, if the impinging molecules are chemically reactive with the surface, the surface may not have the chemical makeup you originally intended due to the reactions (e.g., "cloudy" films, etc.).

So the idea that there is nothing in the bell jar because we can't hear the alarm clock is nonsense. Processes going on in a vacuum system are dynamic and very active at even ulta-high vacuums (i.e., $\leq 10^{-9}$ torr).

Massaging Equation 1

Things become a little more interesting when we differentiate (1) with respect to time. Doing so, we obtain:

$$P\Delta V/\Delta t + V\Delta P/\Delta t = \Delta(n\mathrm{R}T)/\Delta t \qquad (2)$$

What the basic equation F = ma is to the physicist, (2) is of similar importance to we vacuum technicians. The term $\Delta V/\Delta t$ in (2) is given the symbol S, for speed. Pump speed might correspond to some chemisorption process when growing films in the chamber, to pumping on the chamber with some form of vacuum pump, or both. The term on the right of (2) is given the symbol Q_o. It is called the total throughput into the system. The total throughput may comprise any or all of: *i*) leaks into the system; *ii*) outgassing from surfaces; *iii*) diffusion of gas into the system; *iv*) gases introduced to create some process (e.g., CVD, PVD, etc.) in the system; or, *v*) gas byproducts created by a process.

We will come back to this equation numerous times in subsequent columns. But, for now, let's examine (2) assuming that the only source of throughput into the room-temperature system is a leak. Equation. 2 then takes the form:

$$PS + V\Delta P/\Delta t = Q_o \qquad (3)$$

Assume that we are leak checking the system, and that we spray helium on the leak at time $t = 0$. Solution of (3) takes the form:

$$P(\mathrm{t}) = (Q_o/S) \times (1 - e^{-S\,t/V}) \qquad (4)$$

That is, the helium partial pressure in the chamber as a function of time, $P(t)$, rises in direct proportion to the leak rate into the chamber, and is inversely proportional to the size of the pump pumping on the chamber. This finding may contradict the conventional wisdom of most who have poked around a vacuum system trying to find a leak. The value of S is of course the effective speed delivered to the chamber through various interposed conductances between pump and chamber.

Examination of (4) leads us to some logical conclusions. First, we know there are competing processes going on. A large volume, V, suggests that it will take a longer time before the helium pressure from the leak equilibrates in the volume, as there is much to fill, and the pump is pumping away some of the in-leaking gas. Secondly, it is obvious that the greater the leak, Q_o, the greater the leak signal in time (i.e., P(t)) in the chamber. We also see the trade-off of sensitivity v. response time in (4). It would be most instructive to the reader to enter the variables on a spreadsheet, and calculate response times, signal levels, etc., as a function of these variables. Let's go on to a more difficult problem; that is, determining if system difficulties in fact stem from some leak.

A Little Logic Goes a Long Way

Assume that we work in some fab, and that folks are arguing about why a system won't pump down (i.e., who did what and when). Rather than some fancy cluster tool system, it is simply a batch coater, with a 1,000 L volume, and planetary tooling such as shown in Fig. 1. The system today is basing out at a pressure of $\sim 2 \times 10^{-6}$ torr. The problem is that, though we don't keep system performance records (ugh), we recall that yesterday the system based out at $\sim 2 \times 10^{-7}$ torr.

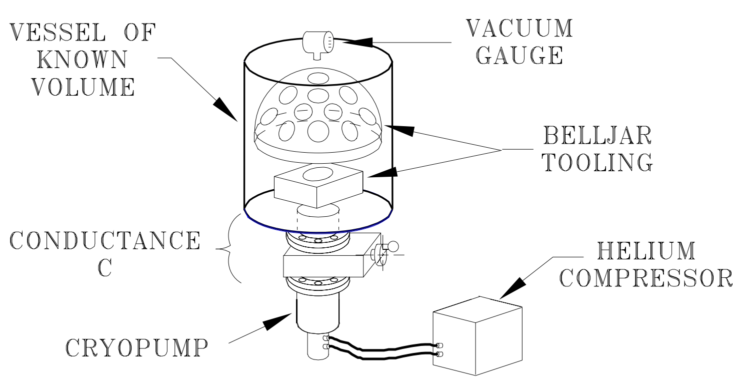

Figure 1. Coating system with problems in base pressure.

Last night the Production people put new tooling in the bell-jar. Also, the Maintenance people switched compressors on the cryopump. The compressor was due to have the adsorber changed. The maintenance people thoroughly leak checked the system today and found no leaks. They were able to valve-off the high vacuum pump when leak checking, so as to have the best possible sensitivity (i.e., see (4)). Also, the temperatures of the cryopump's first and second stages look OK.

The maintenance people say: "*The tooling is dirty or has a virtual leak*." The Production people say: "*The tooling if OK, but the Maintenance screwed up the pump*."

Formal logic has it that if one makes an assumption, legitimately tests the assumption, and reaches a contradiction, then the original assumption is proven wrong. As a trivial example, assume that we have nine (9) apples in a bowl. Claim that the apples weigh on average at least 0.25 pounds each. (This is your assumption.) You put the apples in a paper bag, measure their combined weight, and find it to be 2.1 pounds. (This is a legitimate measurement.) Next you divide the total measured weight by the number of apples to get the average weight. (This is a legitimate calculation.) The measurement and calculation indicates that the apples weigh on average ~0.23 pounds. This contradicts your original assumption. Therefore, your original assumption is incorrect.

Let's use the same technique to diagnose the above system problem. Assume that the speed of the pump, S_p is 1,500 L/s. This is based on the manufacturer's data sheet, and is probably correct, if the pump is not defective, to within ±20%. Calculate the effective speed delivered to the bell-jar, S_e, assuming an interposed conductance of C. The method of doing this can be found in any one of a dozen vacuum handbooks.[1-3]

Say the results of your (legitimate) calculation suggests a value of S_e of 1,000 L/s. We can now go back to (3), and plug in the value of $P \times S_e$ in that equation. Note also, the system has been pumped on overnight, and therefore the pressure is not changing in time. This means that the second term in the left part of (3) is zero. That is, $V \times \Delta P/\Delta t \equiv 0$. Then, (3) takes the form:

$$P \times S_e = Q_{1o} \qquad (5)$$

or, $$(2 \times 10^{-6} \text{ torr}) \times 1000 \text{ L/s} = 2 \times 10^{-3} \text{ torr-L/s}.$$

You've taken the measured pressure, and multiplied it times the calculated speed, and come up with an implied throughput, Q_{1o}, into the system. Don't worry about possible errors in gauge calibration just yet.

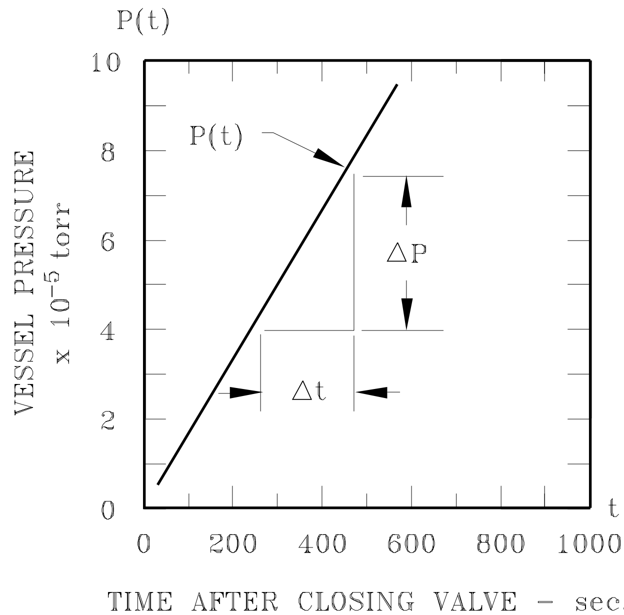

Figure 2. Determining the outgassing or leak rate into a 1000 liter vessel by measuring the rate-of-pressure-rise

Now, let's close the high vacuum valve at the pump inlet. This results in the pressure rising in time. In fact, returning to (3), we determine that the volume of the system times the rate at which the pressure rises is just another means of determining Q. Note that by closing the high vacuum valve you have forced S_e in (3) to become zero. You monitor pressure as a function of time in the valved-off bell-jar, and plot the results of this (legitimate) measurement in Fig. 2. The pressure rises at a rate of 10^{-4} torr/600s. That is:

$$V \times \Delta P/\Delta t \quad = \quad Q_{2o} \qquad (6)$$

or, $$1{,}000\text{ L} \times 10^{-4}\text{ torr/600s} = 1.7 \times 10^{-4}\text{ torr-L/s.} \qquad \rightarrow\leftarrow$$

The symbol "→←" means you have reached a contradiction**.** Note that you have used the same gauge to make the rate-of-pressure rise measurement as was used to previously measure the based-out pressure of the system. Therefore, gauge calibration is not an issue. Also the results when plugging the numbers into (5) and (6) contradict each other by more than a factor of ten (10).

The results of all of your calculations might cause a disparity in the two results of perhaps 30%-40%, but not 1,000%. Therefore, this can mean only one thing: your original assumption about the effective speed delivered to the bell-jar, S_e, being 1,000 L/s, was erroneous. This finding can result from only two possibilities: *i*) the pump is defective; or, *ii*) there is some obstruction between the bell-jar and pump.

What if the results of the two calculations agreed to within 30%-40%? This would mean that the pump is not defective, there is no obstruction between the pump and chamber, and there is probably a virtual leak somewhere in the system.

The power of this simple analytical tool often escapes even those who manufacture systems. By your use of this logic you have been led to an obvious result, and thus eliminated finger pointing in the fab.

On publication of this article in the magazine Vacuum Technology & Coating, I was critiqued by a friend and colleague Phil Lessard. Phil pointed out that if there is a lot of surface pumping in the vacuum system, or the "leak" into the system happens to be water vapor, the pressure rise may not be linear in time. This is a most important comment. Indeed, we must be wary of any pat solutions when diagnosing system problems. Thanks, Phil, for the comment.

References

[1]John F. O'Hanlon, A User's Guide to Vacuum Technology, 2nd Ed. (John Wiley & Sons, New York, 1989).

[2]Marsbed H. Hablanian, High-Vacuum Technology, A Practical Guide, 2nd Ed. (Marcel Decker, Inc., New York, 1997).

[3]Kimo M. Welch, Capture Pumping Technology, 2nd Edition (Elsevier Science, Amsterdam, 2001).