Diffusion Pump System and Its Operation

Author

Hablanian, M. H.
Varian Vacuum Products,
Lexington, United States

Proceedings, Annual Technical Conference - Society of Vacuum Coaters 1994, pp. 340–343

Proceedings of the 37th Annual Technical Conference; Boston, MA, USA; 8 May 1994 through 13 May 1994

Abstract

This white paper is the last of a series of papers[1,2,3] primarily concerned with the issue of prevention of overloading high-vacuum pumps and the resulting adverse effects or malfunctions. For proper selection of pump size, it is necessary to consider different system requirements: the evacuation time to a given pressure, maintaining a certain pressure during a process, process cycle time, and maximum potential gas flow rate. In addition, for complex systems involving diffusion pumps, Roots blowers, and mechanical pumps, it is important to appreciate the transient events following abrupt changes of system pumping speed. The traditional display of vacuum pump performance in the form of pumping speed versus inlet pressure does not clearly distinguish between steady-state and transient sections of the performance and does not indicate overload conditions for the high-vacuum pump. For a full appreciation of high-gas-load vacuum system design and operation, it is instructive to restate the performance data in the form of the achieved or maintained vacuum versus the gas load evolving from the vacuum chamber. Such considerations are valuable for any vacuum pump, but they are particularly important for diffusion pumps because improper operation is often the cause of serious malfunctions such as the loss of pumping fluid and its back-streaming.

Introduction

Vacuum technology has made significant advances during the last 40 years. It is time for manufacturers of pumps and systems to relate the pump performance to specific system requirements, and it is time for users to clearly state the process needs throughout the entire range of process conditions, to specify not only process pressure but also the process gas flow rate requirement, to appreciate the transient and steady-state situations, and accommodate process operation to the limitations of the pumps. Very often, engineers designing vacuum systems use certain rules which may work well for certain conditions. For example, changeover (cross-over) from a roughing pump to a high-vacuum pump at 0.1 torr, or use half of the evacuation time for roughing and half for high-vacuum pumping, or first close the roughing valve and then open the high-vacuum valve. Depending on system design and operation requirements, most rules can be questioned. Cross-over pressure depends on matching the mass flow conditions as discussed in earlier papers.[1,2] Every system should have a different cross-over pressure depending on the ratio of pumping speeds of the pumps and the permissible maximum mass flow (throughput) for the high-vacuum pump. Even in the operation of the same system, cross-over pressure can be changed depending on the particular gas being pumped or change of the performance of the pumps involved. Some of these considerations may be thought to be secondary and, as such, they are rarely discussed in textbooks on vacuum technology. However, often the detail issues produce the difference between success and failure. In this white paper, an attempt is made to discuss certain topics related to common problems which occur frequently enough to merit attention.

Mass flow and volume flow

In engineering practice, one is often faced with a misconception of treating units such as sccm as volume flow. This occurs while establishing system design specifications for determining the required pump size and in leak detection practice. The units of “standard cubic centimeters per minute” are mass flow units. The word “standard” means that the gas density is atmospheric. If we assume that the process occurs near room temperature, and use the usual units of throughput (Q), the units of sccm can directly be converted to units of torr-liters per second.

$1 \text{ sccm} = (1 \times 760) / (1{,}000 \times 60) = 0.0127 \text{ torr-L/s}.$

To obtain the required pumping speed for maintainting a pressure of, for example, 1×10^{-3} torr with the process gas flow of 1 sccm, we use the relation:

$S = Q/P = (0.0127 \text{ torr L/s})/(1 \times 10^{-3} \text{ torr}) = 12.7 \text{ L/s}.$

If the required process pressure is ten times lower, the pumping speed must be ten times higher, etc. Therefore, when the flow rate is known, it is relatively easy to specify the net pumping speed required to maintain a given process pressure.

It is more difficult to specify a pumping speed for a required evacuation time because of uncertainties associated with outgassing. When baffles and traps are used at the inlet of the pump, the net pumping speed and the associated throughput are reduced but the maximum throughput value is unchanged. It should be noted that the ratio of the net pumping speed to the speed without baffles is not the same for different gases. Pump specifications usually provide data only for air. However, because the conductances are higher for lighter gases, the pumping speed for lighter gases will be reduced less than for air. As an example, if the conductance of a baffle for air is of the same magnitude as the pumping speed for air, the net speed for air will be 50% of the pump speed. But, in the case of helium, the pump speed may be 20% higher than air and the conductance 2.7 times higher. The net pumping speed for helium will be 83% of the pump speed (using the usual reciprocal addition method). For heavier gases, the effect is opposite.

Maximum throughput

Regarding the maximum allowed throughput for a particular pump, remember that the numerical value given for air is not applicable for other gases. For the same true mass flow (grams per second), the throughput value for the lighter gases (helium, water vapor) is higher, and for heavier gases (argon), it is lower. To convert the maximum throughput from air to another gas, the throughput must be adjusted according to the ratio of molecular weights and molecular velocities. If Q_1 is the maximum throughput of air, and Q_2 is the maximum throughput for another gas, and M_1 and M_2 are the molecular weights of the two gases, then, assuming roughly equal pumping speed:

$Q_2 = Q_1 (M_1 / M_2) (M_2 / M_1)^{1/2}$, or $Q_2 = Q_1 (M_1 / M_2)^{1/2}$

This formula may not apply in all cases, but it provides a good estimate for modern high-power diffusion pumps such as, for example, the Agilent HS-35, for which the helium pumping speed is approximately 20% higher than for air. Actual measurements show three times higher maximum throughput for helium and hydrogen compared to air.[4]

For proper steady-state operation of a diffusion pump, it is best not to exceed the maximum throughput of the top pumping stage, which is often 70% of the value given in commercial bulletins referred to an inlet pressure of 10 mtorr. There is no standard for measuring the maximum throughput. The old AVS tentative standard recommends plotting a curve for throughput and stating the size of the backing pump used during tests. However, no reference is made to the simple fact that the throughput values, given at the inlet pressure where the pumping speed is substantially reduced, are taken under conditions of nonfunctioning top vapor jet.

At high gas loads, the size of the backing pump begins to influence the pumping speed. To state the throughput value at 0.1 torr makes a comment about the backing pump rather than the diffusion pump. At that pressure, only the last stage at the foreline has some minimal pumping action but all the other jets are severely overloaded; the vapor condenses in space, without reaching the walls, and may pass into the backing pump producing a rapid oil loss.

Evacuation time

To demonstrate the performance of a vacuum system, designers and users often agree on the formula: “clean, dry, and empty”. This is understandable, but it only permits to show the performance of the pumps for noncondensable gases. The presence of water vapor at low pressures changes the performance of both rough pumps and high-vacuum pumps. In the high-vacuum section, the only choice is to estimate the outgassing from all sources and its reduction in time. The problem here is that outgassing data are uncertain because they depend on the prior history of the surfaces involved and because the outgassing data listed in vacuum texts do not clearly define zero time. It is particularly difficult to estimate the outgassing rates during short pumpdown cycles. In cases when the required pumping time is in seconds, an experimental determination becomes unavoidable. Outgassing effects are also important for the performance of the rough pumps. Outgassing of water vapor produces the deviaion from a straight line in usual evacuation plots (pressure versus time on a log-linear graph), at inlet pressures below approximately 1 torr. Textbooks usually list some multiplying factors for time of evacuation to lower pressures. However, these factors cannot be used in all situations because they depend on the ratio of the surface area of the vacuum system and on the condition of the pump in regard to its performance in the presence of water vapor. Figure 1 is an example: if the desired pressure is 10 mtorr, the smaller pump will not meet the expected correction factors and it may actually never get to 10 mtorr. The issue is the base pressure of the pump at the time of the test, not the base pressure listed in the pump specifications, which is particularly relevant to oil-sealed mechanical pumps.

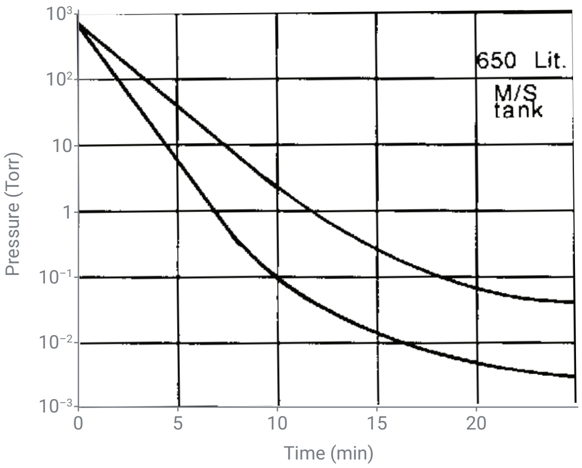

Figure 1. Pressure-time curves during evacuation with two different roughing pumps.

Cross-over pressure

The amount of water vapor can also affect the cross-over condition. A minor effect is due to the higher maximum throughput of the diffusion pump for water vapor (compared to air, for which it is stated in the specifications). A more important issue is the base pressure of the roughing pump for water vapor at that time. For best results, during evacuation, the switch from the roughing pump to the diffusion pump should be made at a gas load (throughput) from the vacuum chamber, which is lower than the maximum permissible throughput of the diffusion pump with fully functioning top jet. The gas load is created by the vacuum chamber (not by the pump) and, at pressures below 0.1 torr, assume for practical purposes to be independent of the pressure. Then, the gas load immediately before and immediately after opening the high-vacuum valve is the same.

To find the appropriate cross-over pressure, estimate the gas load at the end of the roughing period. One way to do this is to measure the rate-of-rise of pressure of the fully loaded system after a certain period of pumping. The other way is to obtain the expected throughput (after cross-over) by multiplying the net pumping speed of the roughing pump by the chamber pressure. The difficulty arises because the net pumping speed depends on the base pressure for water vapor at that particular time.

Figure 2 demonstrates the possible changes in the net pumping speed of the roughing pump, which can affect the choice of the cross-over pressure when the gas content of the system shifts from mainly air to mainly water vapor. As the base pressure shifts to higher values, the effect is to decrease the net speed at pressures normally encountered. Remember that the slope of the evacuation curve represents the pumping speed and, whenever the evacuation curve becomes nearly horizontal, the pumping speed is nearly zero. When, after the initial evacuation, a high-vacuum pump is engaged, not only the pumping speed increases but also the overall compression ratio. This can explain why the inlet pressure, after cross-over, often drops in seconds by 1,000 or 10,000 times rather than according to the increase of the pumping speed. An example of this behavior is shown in Figure 3, where the drop of pressure is nearly four orders of magnitude while the ratio of pumping speeds is only about four. Figure 3 also clearly demonstrates that in nonsteady state situations, evacuation time does not have a simple inverse relationship with time.

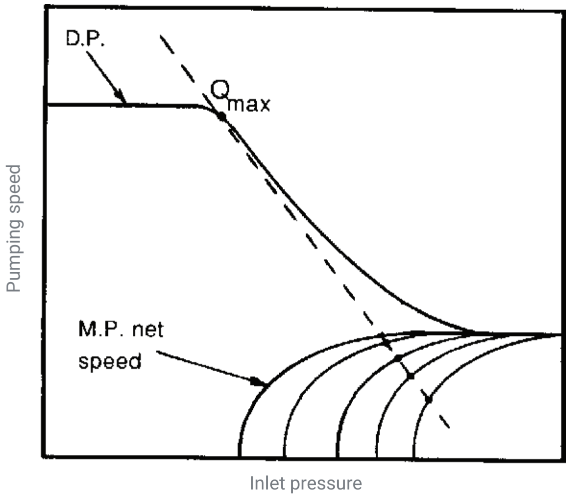

Figure 2. Effect of changing rough pump base pressure on the cross-over point.

Despite the large difference between the two high-vacuum pumps, the initial evacuation time is not very different. This is because in this phase the process of evacuation is influenced more by the outgassing rate transient rather than by the density decay from a constant volume and with a constant pumping speed. In addition, the transient gas flow velocity after opening the high-vacuum valve is usually much higher than the velocity which corresponds to a given pumping speed at steady-state conditions.

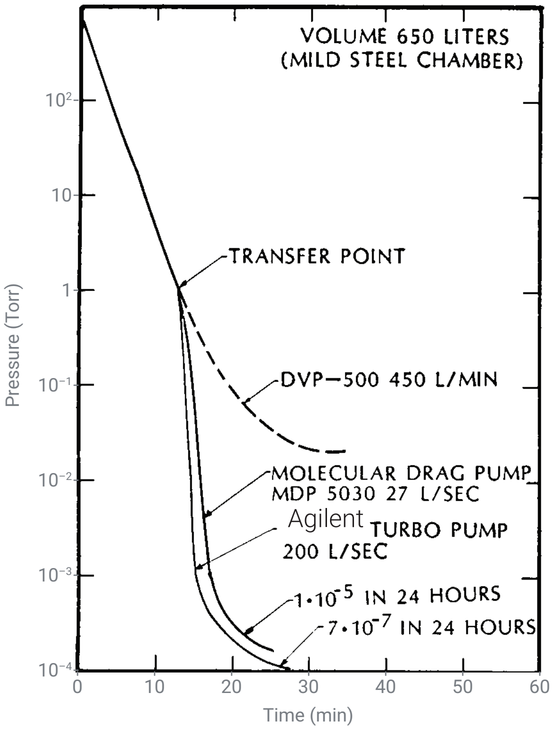

Figure 3. Typical pumpdown curves of a chamber with two different high-vacuum pumps.

Pressure fluctuations

Often, inlet pressures above the Q_{max} point become unstable, exhibiting large fluctuations that then subside above approximately 25 mtorr. This is usually caused by the interruption of the function of the top pumping jet, because of overloading. In general, whenever a curve representing a variable (on a linear rectangular plot) becomes horizontal or vertical, it cannot be controlled. As a result, a small variation of the independent variable will cause large variations of the dependent variable. In the operation of the diffusion pump, we cannot control the pumping speed or the pressure; what we can control is the gas flow (mass flow) by doing something in the chamber or, perhaps, by throttling the inlet valve.

Between inlet pressures of approximately 1 to 20 mtorr (depending on pump size and design), the mass flow capacity tends to become constant, producing a horizontal throughput versus pressure curve (or, more correctly, a vertical pressure versus throughput curve), so that a small variation of the gas load produces large fluctuations of the inlet pressure. To prevent this, the pump designer has little choice. To produce a less steep slope, it is necessary, for each successive pumping stage, to have a substantially higher throughput capacity. In such a case, the available total power must be redistributed such that the first (inlet) stage would become weaker. This is hardly a desirable design direction. Typically, for safety, we try to have each next stage to have approximately 10% more throughput capacity than the previous stage. In large pumps, which sometimes have five or six stages, this already produces 20 or 30% of "wasted" power. The other way of increasing the slope of the throughput versus inlet pressure curve is to use large backing pumps, but this is also not a good design direction. An overloaded diffusion pump with a large backing pump will tend to lose pumping fluid because the denser gas passing through the diffusion pump will tend to sweep a part of the pumping fluid vapor into the backing pump. Above approximately 30 mtorr, the pressure becomes stable, but then the major portion of the pumping action is due to the backing pump. For proper operation, at chamber process pressures above approximately 1 mtorr, it is best to limit the gas flow to the Q_{max} (of the first stage) and throttle the inlet valve. Otherwise, we can use smaller valves, baffles, or traps and save a considerable expense, or we can bypass the diffusion pump, after the initial evacuation, and continue pumping with the backing or roughing pump. In systems that are exposed to air every half an hour, it is a waste to use enlarged valves, traps, etc., to increase the net pumping speed. The 20% higher speed obtained by the use of enlarged (high-conductance) components can hardly improve the pumpdown time, as can be seen by comparing the two curves in Figure 3, but the higher impedance of smaller components will produce a desired throttling effect.

Conclusion

Designers and users of vacuum systems must cooperate in choosing the right pump size with a required maximum throughput, and a proper inlet duct configuration to reflect all process conditions. High-vacuum pumps should be matched not only with backing pumps but also with roughing pumps. The cross-over point from roughing to high-vacuum pumping must be based on the maximum mass flow (throughput) capability of the high-vacuum pump. Each vacuum system may require a different cross-over point, and even the same vacuum system may sometimes require a different cross-over point depending on the condition of the roughing pump. Vacuum system design should be made remembering that after the initial evacuation from atmosphere to approximately 0.1 torr, the remaining gas in the chamber is primarily water vapor. This affects base pressure, pumping speed, and throughput for roughing, high-vacuum, and backing pumps. A distinction should be made between systems that are often exposed to atmosphere and that are pumped continuously. To optimize the initial cost of the vacuum system and the cost of its operation, the size of various pumps must be chosen accordingly. A reasonably good estimate of various gas loads during all phases of the system operation is unavoidable. Overload conditions for high-vacuum pumps must be understood, identified, and be clearly measurable with reliable and accurate instruments. Diffusion pump systems, in particular, should not be designed to be used at mass flow conditions exceeding the maximum throughput capability of the first (inlet) vapor jet.

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DE44239.4713773148

Printed in the USA, February 16, 2021
5994-2037EN

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