White Paper

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The Overload Conditions in High-Vacuum Pumps

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Proceedings of the 34th Annual Technical Conference of the Society of Vacuum Coaters, SVC publications, 1991, p.253.

Abstract

High-vacuum pumps have a limiting inlet pressure above which they cannot function. Recognizing and dealing with the approaching overload conditions is an important aspect of vacuum system operation. This white paper outlines the basic considerations for selecting the pressure at which the high-vacuum pumps are started, emphasizing the importance of mass flow (throughput) limits rather than the pressure as such. Some basic parameters, such as the ratio of pumping speeds of the roughing pump and the high-vacuum pump are associated with the choice of the cross-over pressure. Practical engineering recommendations are offered for system design and operation. Adverse system effects resulting from pump overload (for example, backstreaming and oil loss in diffusion pumps) are noted for momentum transfer pumps (diffusion pumps and turbomolecular pumps) and capture pumps such as sputter-ion pumps and cryogenic pumps. To prevent any adverse effect, normally, the transient pressure rise during switching should not be longer than a few seconds. To reduce the magnitude of the pressure rise during cross-over, the high-vacuum valve should be opened slowly.

Introduction

High-vacuum pumps, like other compressors, have two basic limitations, flow rate and pressure. Because high-vacuum pumps usually discharge into another pump rather than directly into the atmosphere, their discharge pressure must be associated with the performance of the backing pump. In addition, it is necessary to coordinate the performance of the high-vacuum pump with the performance of pumps used for pre-evacuation of the vacuum system or roughing pumps.

Both of the basic limits are associated with the power used to operate the pump. Depending on design and power used, a pump or a compressor will have a maximum mass flow (and volume flow) capacity and a maximum achieved pressure difference, which is called "tolerable forepressure" in the jargon of high-vacuum technology. In some high-vacuum pumps, this maximum achievable pressure difference (between discharge and inlet) must not be exceeded under any circumstances if some very significant malfunctions are to be avoided. This is one of the most important conditions of overload.

The other most important overload condition is due to exceeding the maximum mass flow rate for which the particular pump has been designed, commonly called "maximum throughput". The degree and types of malfunctions that result from this overloading vary with different pumps, and they must be understood for correct system design and operation. The mass flow overload often occurs during switching from the process of pre-evacuation to high-vacuum pumping. It is unfortunate that, historically, the performance presentations of high-vacuum pumps in the form of pumping speed versus inlet pressure do not clearly identify the overload region. This is a cause of common misunderstandings in design and operation of vacuum systems. Most high-vacuum technologists have a convenient singular value for the cross-over pressure applied to all vacuum systems. This is fundamentally incorrect because the value must be different for each particular case, the most important parameters being the ratio of pumping speeds of the high-vacuum pump and the rough vacuum pump and the maximum permissible mass flow or the maximum throughput capacity of the high-vacuum pump.

The cross-over conditon

The basic condition for cross-over is very simple: it must occur when the gas flow from the system is below the maximum throughput capacity of the particular high-vacuum pump. This condition can easily be established for a given system. The basic consideration is illustrated in Figure 1. The gas flow rate emanating from the system is the same immediately before and after the moment of switching from pre-evacuation to high-vacuum pumping. Just before the cross-over, the pressure in the vacuum chamber is given by the outgassing rate in the chamber divided by the net pumping speed of the rough vacuum pump. Immediately after cross-over, the pressure is given by the same outgassing rate divided by the net pumping speed of the high-vacuum pump. Therefore, the system gas load just before the cross-over can be estimated from the pressure in the chamber multiplied by the net pumping speed of the roughing pump at the chamber. In many typical vacuum systems and for the pressure range considered here, it will be nearly half of the nominal pumping speed.

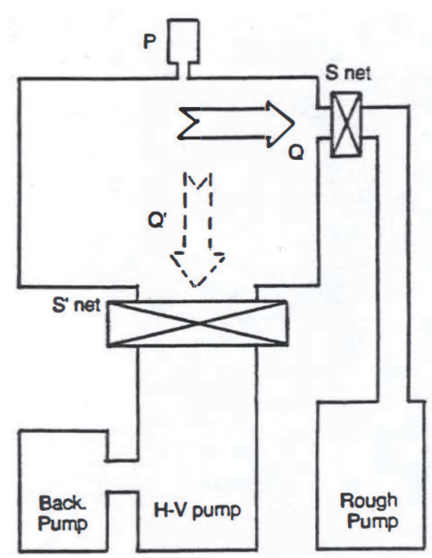

Figure 1. Illustrating relationships immediately before and after cross-over; Q = p Snet = Q' = p' S'net.

For a cross-over condition that avoids any overload of the high-vacuum pump, the gas load from the chamber must be below the point Q_{max} shown in Figure 2. For a simple graphical representation, we can draw a constant mass flow line as shown in Figure 3. The point of intersection of this line with the net pumping speed curve of the roughing pump is the recommended cross-over pressure. If this condition is observed, then the time after opening the high-vacuum valve and obtaining and achieving a pressure in the high-vacuum range should be only a few seconds. If it is longer than a few seconds, then the high-vacuum pump is overloaded.

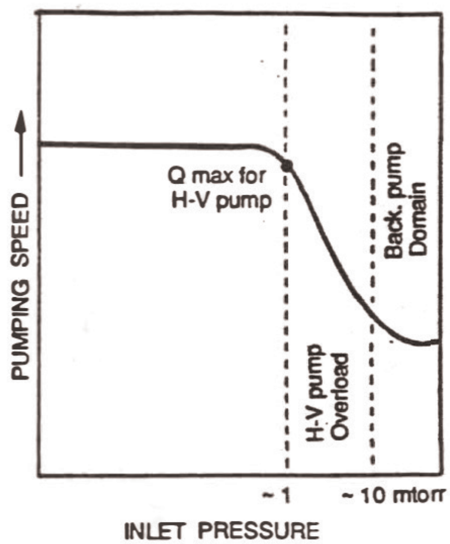

Figure 2. Showing a typical overload domain of a high-vacuum pump.

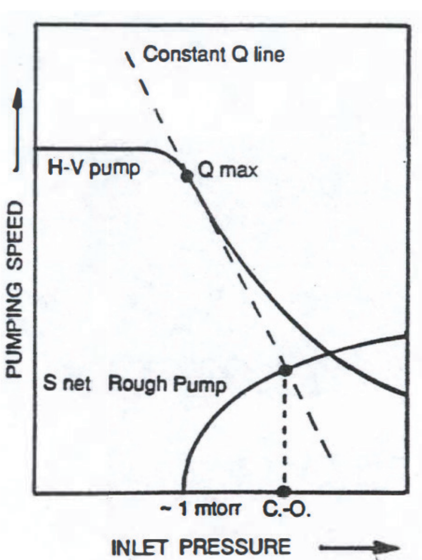

Figure 3. Showing the cross-over point (c.o.) for a fully functioning high-vacuum pump.

In Figure 4, the larger the roughing pump for a given high-vacuum pump, the lower the cross-over pressure must be. This may appear counterintuitive, but it will explain why sometimes no advantage is gained for the overall pumpdown time when a larger roughing pump is installed in an existing system.

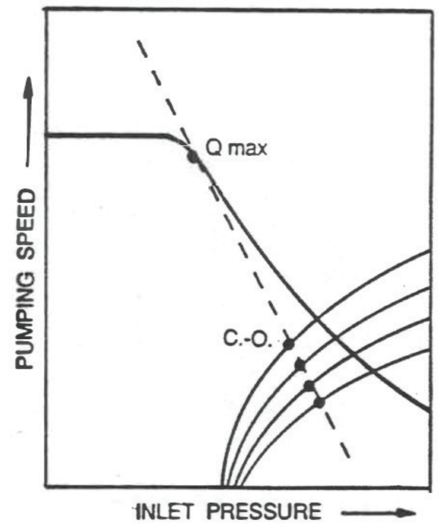

Figure 4 . The larger the roughing pump, for a given high-vacuum pump, the lower the cross-over pressure must be.

To further illustrate this point, Figure 5 shows what happens when the gas load is slightly higher or slightly lower than the maximum permissible throughput for the particular high-vacuum pump. Two gas load values are shown, which result in widely different system pressures. It is easier to see the separation between the effects of pumping by

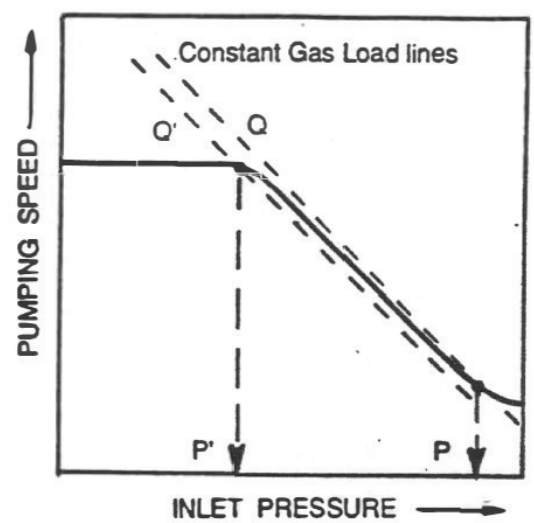

Figure 5 . Illustrating the effect of gas loads, slightly higher (Q) and slightly lower (Q') than the Q_{max}. P and p' are pressures resulting in the system.

the high-vacuum pump and the rough vacuum pump if we plot the same information based on the gas load as the independent variable, as shown in Figure 6, which corresponds to Figure 3. The effect of switching to the high-vacuum pump at the appropriate throughput value is shown in Figure 7, which corresponds to Figure 5.

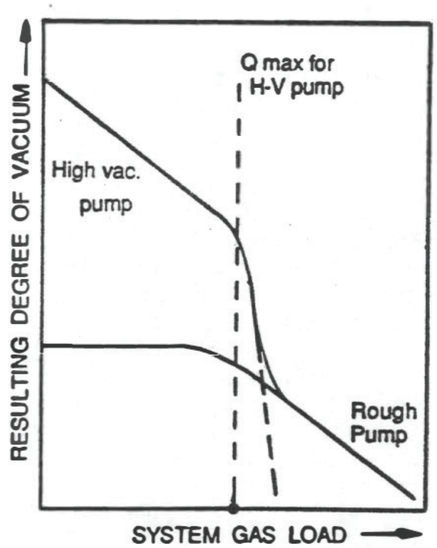

Figure 6. Resultant degree of vacuum versus gas load; same as Figure 3, replotted in terms of throughput.

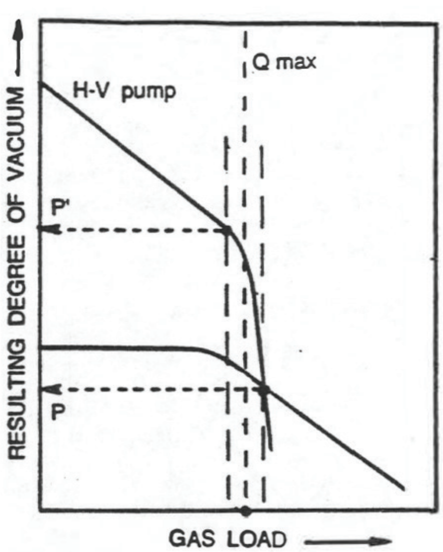

Figure 7. Same information as in Figure 5 replotted in terms of throughput

Diffusion pumps

Diffusion pumps are normally multistage devices. If properly designed, they should begin to overload, in regard to maximum permissible gas flow rate (throughput), at the first (upstream) stage, then gradually at the next stage, etc. There is no clear recommended standard for designating the maximum permissible gas load at the inlet to the diffusion pump, which, given a certain pumping speed, can be translated into a maximum permissible inlet pressure before the first jet becomes overloaded. One obvious result of overloading is the increase of the backstreaming rate of the pumping fluid. Typically, the recent historic tendency is to relate the maximum throughput for the pump to inlet pressures near 10 mtorr. This may be justifiable from the point of view of the ability of the pump to maintain the maximum pressure difference (i.e., retain its forepressure tolerance). However, the increased amount of backstreaming must be acceptable for the particular application. It is possible, then, to have a partial overload situation where the vapor jets in one or two top stages are not reaching the pump walls and can even flow backwards while the lower stages are functioning properly. To prevent this possibility, the gas load into the diffusion pump should not exceed the Q_{max} point shown in Figure 3. To illustrate the possibility of the partial overload in the region of inlet pressures of 0.5 to 10 mtorr, the pumping speeds of all stages are shown in Figure 8. It should be evident from Figures 5, 6, and 8 that when the maximum throughput of the diffusion pump is quoted at the pressure of 30 or 40 mtorr, its value has nothing to do with the performance of the diffusion pump itself but simply reflects the size of the roughing or backing pump.

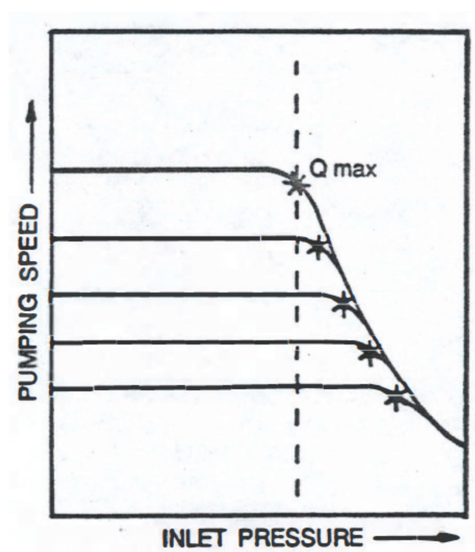

Figure 8. Illustrating the break-down pressures for each stage of a diffusion pump.

Turbomolecular pumps

The overload situation for turbomolecular pumps is usually not as acute as in diffusion pumps. The many stages of the turbine pump are attached to the same rotor, so they accelerate and decelerate together. A sudden short pressure burst in the low-vacuum region will not significantly decelerate the rotor because of its rotational inertia and the stored energy associated with it. A continuous overload condition will result in slower pumping speed and slower rotational speed as may be indicated by the electrical controller of the pump. The occurrence of overload is more gradual, and there is no sudden reversal of the pumping fluid as may be the case with a diffusion pump. In other words, the overload part of the performance curve corresponding to Figure 7 is usually less vertical, as shown in Figure 9 (however, its angle will depend on the size of the backing pump). In addition, the liquid in oil-lubricated turbopumps is located at the discharge side of the pump and it will not suddenly appear at the inlet when the inlet pressure exceeds the Q_{max} point. Therefore, turbopumps can also be started at a somewhat higher cross-over throughput (after the initial evacuation), provided the ratio of the chamber volume and the pumping speed of the turbopump is not too high.

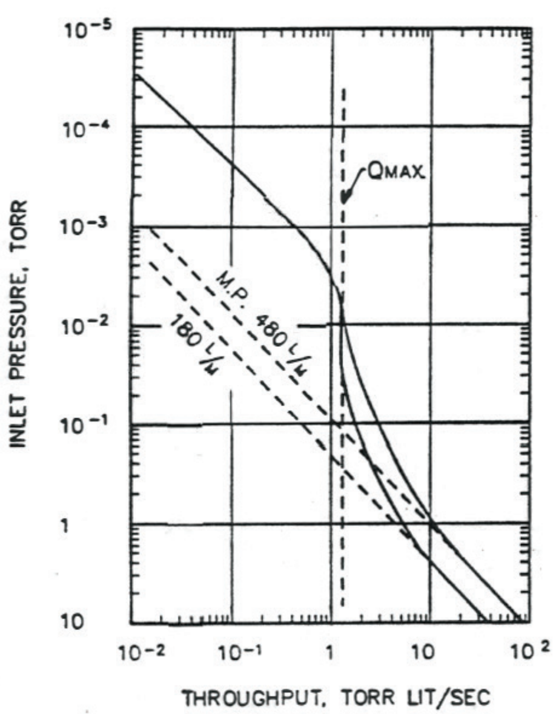

Figure 9. Indicating an overload throughput for a typical turbopump (~340 L/s pumping speed).

Cryopumps and ion-gettering pumps

The overload situations in pumps that do not exhaust the pumped gases are somewhat different than in compressor-type devices such as turbopumps or diffusion pumps. In addition to a maximum permissible inlet pressure, they have a limit of maximum total gas accumulation. Figure 10 reflects the typical periods between regeneration of cryopumps or the cathode replacement of ion-gettering pumps, depending on the amount of ingested gases. The cryopump response to a momentary overload will depend on its cryogeneration capacity as well as heat capacity of cryo-arrays. If the amount of the gas causing the overload condition is high enough, the temperature of the pumping surfaces may rise, resulting in the release of previously pumped gases. Typically, compared to diffusion pumps, cryopumps can absorb higher momentary pressure bursts without ill effects, but the value of the tolerable continuous maximum throughput is lower (for a reasonable period between regenerations). This situation can be reflected in terms of the cost per unit of maximum throughput, as shown in Figure 11. A very similar graph can be constructed for the power consumption per unit of maximum throughput The overload associated with the total amount of pumped gases usually can be established by monitoring the pumping performance for hydrogen. The values shown in Figures 10 and 11 are typical for medium sized pumps (approximately 20 cm diameter). The term "dual cryopump" refers to a system with two cryopumps with isolating valves in which one is regenerated while the other is pumping the system.[1]

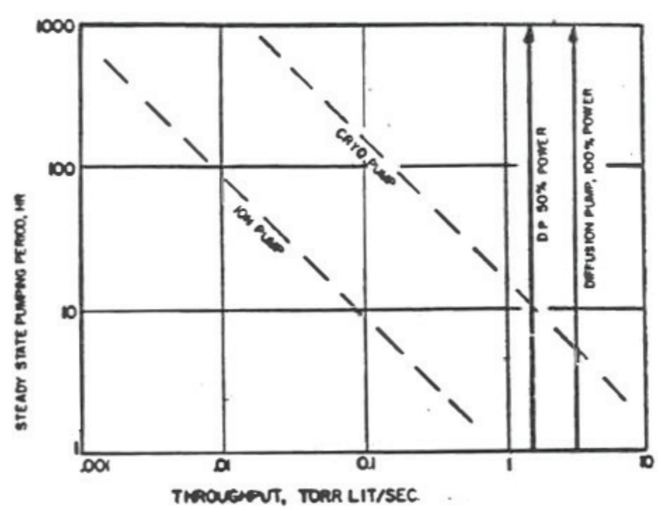

Figure 10. In capture pumps, the pumping period between regenerations depends on the gas load.

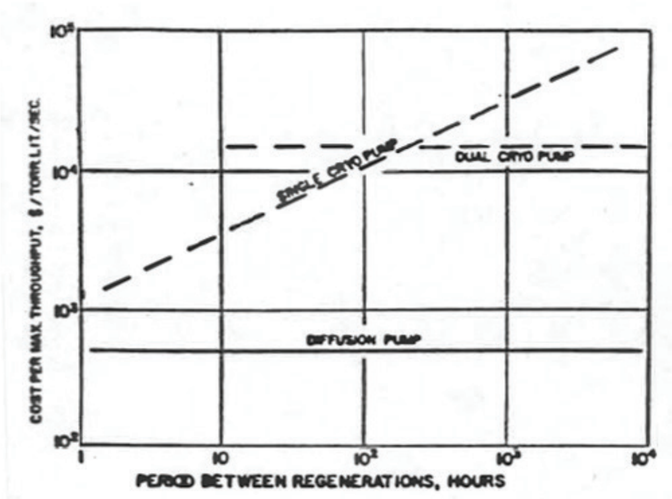

Figure 11. The desired period between regenerations will affect the cost of the capture pumps per unit of maximum throughput capability.

For ion pumps, the need for replacing the cathodes in the pump can be associated with the general degradation of performance, particularly the difficulty in starting the pump, or a sudden failure due to electrical shorts produced by mechanical fractures in the cathode structures.

Conclusion

To summarize the maximum mass flow (maximum throughput) capabilities of the various pumps, the location of the Q_{max} point can be shown in terms of maximum permissible inlet pressures, as indicated in Figure 12. The broader bands for ion-gettering and cryopumps are associated with the desired period between regenerations or cathode replacement. The time response of system pressure during cross-over is approximately equal to system volume divided by the speed of the high-vacuum pump. Generally, to reduce the amplitude of the transient pressure rise, the inlet valve to the high-vacuum pump should be opened slowly.[2]

When, to decrease the evacuation time of an existing vacuum system (which is designed to cross-over at the maximum troughput of the high-vacuum pump), a larger roughing pump is substituted, there may be no advantage. If the roughing pump has twice the speed, it must reach half the

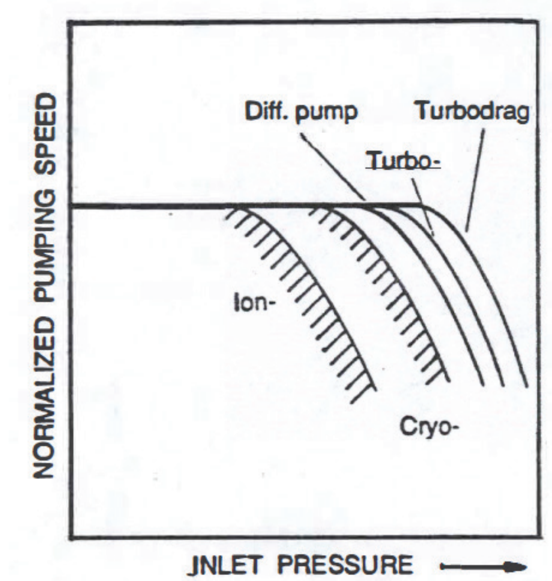

Figure 12. Comparison of typical performance near the overload region for various pumps. The shading for ion- and cryopumps reflects the length of regeneration periods.

pressure before a proper cross-over. Near molecular flow conditions, the outgassing rate of the vacuum system (i.e. the gas load arriving at the pump) depends mainly on time rather than the pressure. At a certain evacuation time, the gas load is nearly the same whether the system pressure is 50 mtorr or 100 mtorr. Therefore, in such cases, to shorten the evacuation time to a certain desired pressure, additional high-vacuum pumping speed is required, rather than a shorter roughing period.

The understanding of overload conditions of various high-vacuum pumps can help the system designer chose the appropriate pump for the particular application.

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DE44239.4539236111

Printed in the USA, February 16, 2021
5994-2036EN

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