Chapter 10: Turbomolecular Pumps

In the previous chapter we covered the operation of diffusion pumps that pump gases by the mechanism of momentum transfer. Molecular pumps, of which turbo pumps are a subset, are also momentum transfer pumps. In turbo pumps gases are caused to move in a preferred direction due to the interaction with high speed surfaces. Gaede recognized the possibility of pumping gases by this technique as early as 1912, and he constructed a simple molecular pump that demonstrated his theory. This early molecular pump was similar in construction to a modern rotary vane mechanical pump, with the exception that the rotor of Gaede's molecular pump had no moving vanes and was concentric with the stator (see figure 10.1).

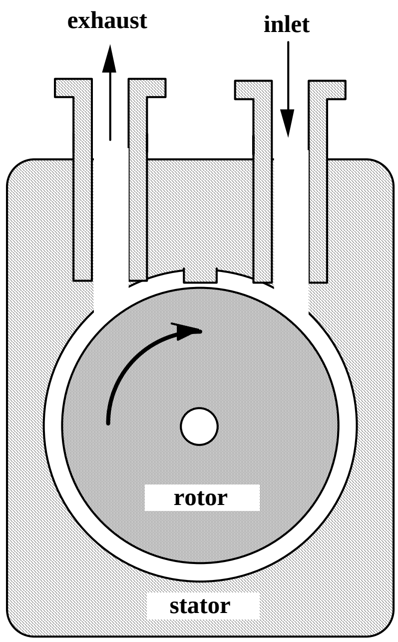

Figure 10.1 Gaede's molecular drag pump of 1912.

In the operation of Gaede's design, gas molecules entering the molecular drag pump's inlet strike the surface of the moving rotor, and remain on this moving surface for a period called the "Residence time" (see equation 4.8). Molecules leave the surface of the rotor, obeying the "Cosine Law" distribution presented in figure 4.1. The molecule then strikes the inner surface of the stator, remains there for the "Residence time", desorbs and may again strike the surface of the rotor to again be moved in the preferred direction.

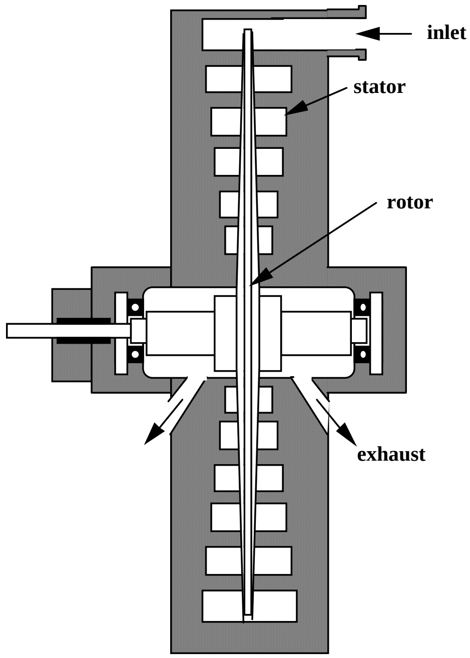

Figure 10.2 Cross-section of a molecular drag pump using a spiral channel machined into the stator and a flared disc as a rotor.

Molecular drag pumps designed in the early 1900's had low pumping speeds, due in part to the practical limits encountered in machining techniques and bearing designs which limited rotational velocity of the rotor.

Theory of Operation, Modern Molecular Drag Pumps

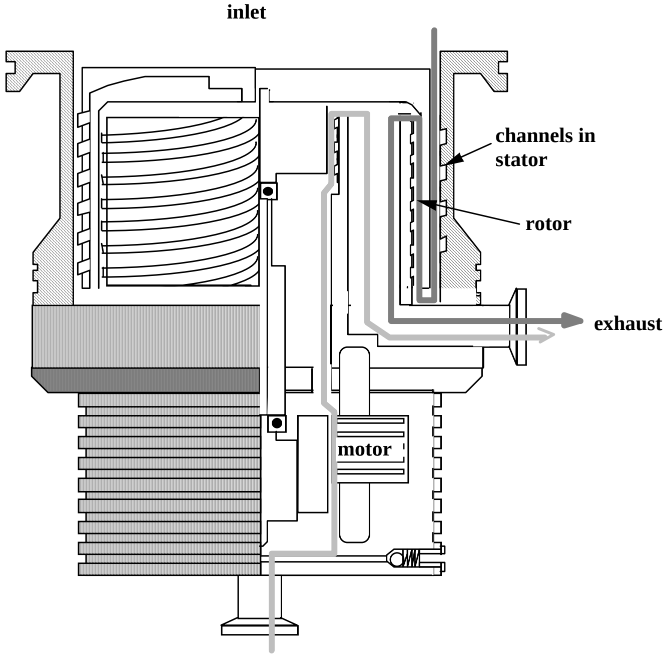

Figure 10.3 A modern design for a molecular drag pump.

Many of the current molecular drag vacuum pumps are similar in design to that presented in figure 10.3. The rotor is often fabricated out of a high strength aluminum alloy and is shaped like an inverted cup. Both inside and outside surfaces of the rotor are machined to create spiral grooves which work with the surfaces of the stator to provide the pumping action. Using both the internal and external surfaces of the rotor creates an elongated pumping path.

The size, shape and tolerances of the grooves change from the inlet side to the exhaust side of the pump to allow for multiple compression stages. Flush gas is intentionally admitted to the pump to provide cooling and as an aid to exhausting the compressed gas. High quality molecular drag pumps can attain compression ratios for nitrogen of approximately 10^9:1. Since the pumping action is dependent upon the residence time of a gas on the stator and rotor, and the average velocity of gases, it should be obvious that the pumping efficiency for molecular drag pumps decreases with the molecular weight of the gas being pumped.

Sample Problem:

10.1 For the atmospheric gases listed in table 4.1 arrange the gases in order according to the pumping speed you would expect for a molecular drag pump.

Molecular drag pumps in general cannot compress gases to atmospheric pressure, and must, therefore have a backing pump attached to the exhaust of the drag pump to accomplish this final stage of compression. The critical foreline pressure range for many molecular drag pumps is 10 to 40 Torr, which allows these pumps to be backed by diaphragm or dry pumps, greatly reducing the possibility of oil backstreaming into the vacuum vessel. Crossover pressures for molecular drag pumps is often as high as 1 Torr, and systems pumped by this means may achieve base pressures as low as 10^{-6} Torr.

Modern Turbomolecular Pumps

Some insight into the operational characteristics of turbomolecular pumps may be gained by comparing and contrasting them to diffusion pumps. Both turbomolecular and diffusion pumps are high vacuum pumps which cannot compress gases to atmospheric pressure, and therefore both require backing pumps (typically rotary vane mechanical pumps). Both turbo pumps and diffusion pumps provide pumping action by momentum transfer, that is, they induce molecules to flow in a preferred direction through the use of high speed surfaces or particles. The pumping efficiency of both types of pumps is a function of the gas specie being pumped, and in general, the pumping efficiency decreases with decreasing molecular weight of the gas. Unlike diffusion pumps, turbomolecular vacuum pumps do not require traps and baffles, as the possibility for backstreaming into the vacuum vessel is very limited in a turbo pump. Advances in fabrication techniques, high strength/low weight alloys and bearing design have allowed the development of high performance turbo-molecular vacuum pumps. Two designs for turbomolecular pumps have been produced commercially: the horizontal twin rotor design (Sargent-Welch) and the axial flow design (Balzers, Leybold, Inc., and others). The operating principles are the same for both designs, so we will use the more currently popular axial flow design to illustrate the operation of turbo pumps. In practice, the horizontal twin rotor design has a much more massive rotor assembly which is more difficult to dynamically balance than the lighter weight rotor of an axial flow turbo pump. The result is that the rotational velocity (Rpm's) that a horizontal turbo pump may attain is much lower than for a comparably sized axial flow turbo, and therefore pumping speed for the horizontal pump is less than for an axial design pump.

In the axial flow design, the compressor is comprised of matched sets of rotors and stators, which are typically fabricated from aircraft quality aluminum alloys. Typical rotational velocities for the rotor of turbo pumps of this design are from 20,000 to 60,000 RPM.

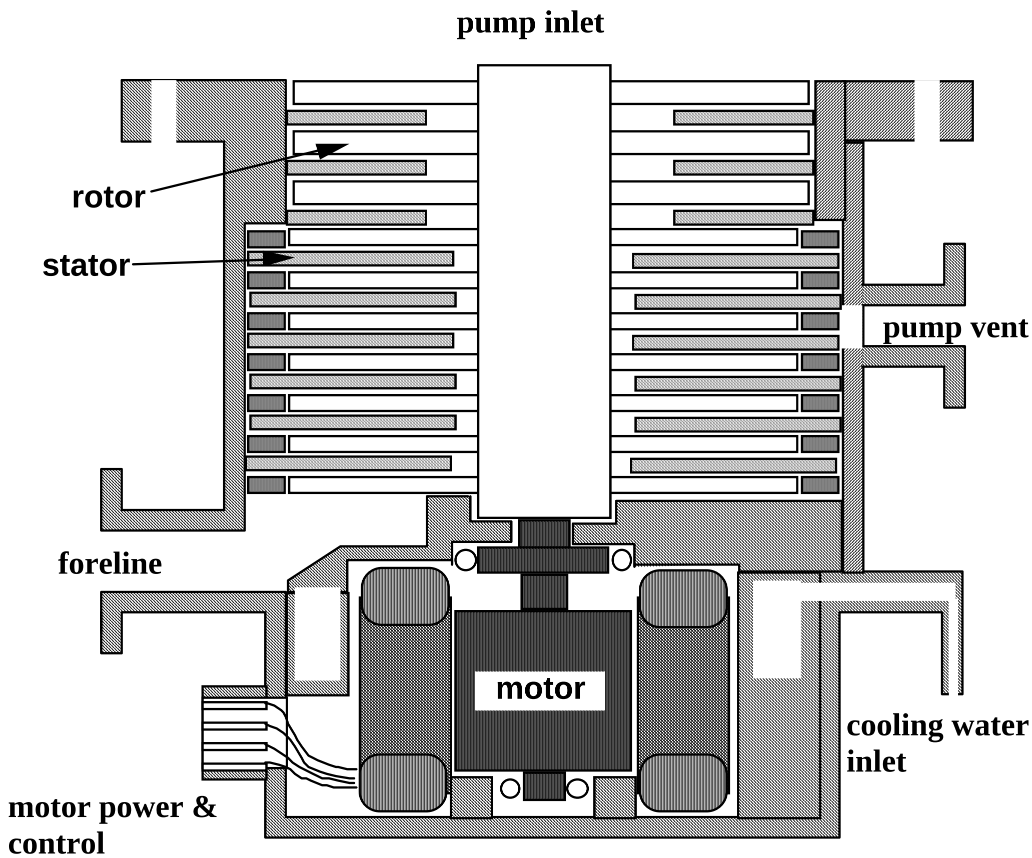

Figure 10.4 Cross-section of an axial flow turbomolecular vacuum pump.

Sample Problems:

10.2 Calculate the speed of the tip of a 5 cm radius rotor operating at 60,000 RPM and compare that value to the average velocity of nitrogen and hydrogen at room temperature. What conclusions can you draw from this data?

Look again at figure 10.4. Note that the size and aspect ratio (length divided by width) of the rotor blades at the inlet are different that for the rotor blades at the exhaust. Most modern axial flow turbo pumps have rotors and stators which are designed in stages to optimize pumping performance for the pressures at locations throughout the pump. The inlet stage typically is designed with the goal of achieving high volumetric speed with minimal compression. Stages at the exhaust line are designed with the opposite goal in mind: maximizing compression of the gas at the expense of volumetric speed. It should be noted that the function of the stators and rotors is slightly different. The high speed rotors provide a surface on which gas molecules "reside" for some short time, then desorb, leaving in a preferred direction. The stators serve to improve the effectiveness of the rotors by providing a baffle effect, directing the gas flow to the next rotor. For this reason, the stator is often omitted from the final stage of the turbo pump, as it would serve no purpose, and would impede the flow of gas to the backing pump. Since the low molecular weight gases are the most difficult to pump using a turbo, the ultimate pressure one may attain using a turbomolecular pump is often due to the inefficiency of the pumping of these gases.

Operational Aspects of Turbomolecular Pumps

The maximum crossover pressure for turbomolecular pumps is approximately 1 Torr, this is a factor of ten times higher pressure than the maximum suggested crossover pressure for most oil vapor diffusion pumps (100 mTorr). At pressures above 1 Torr the turbo pump blades will be slowed by collisions with gas molecules such that the motor will overload and the rotational velocity of the rotor will decrease to a speed that is ineffective for pumping gas. Unlike diffusion pumps, turbo pumps do have moving parts that can cause vibration which may adversely affect some precision instruments including scanning electron microscopes and surface science probes. A 60 or 120 Hz vibration typically is caused by a mechanical backing pump, while high frequency vibration is due to imbalances in the turbo pump rotor. Most vacuum applications are insensitive to this minute amount of vibration, but if vibration must be held to a minimum, and the pumping characteristics of a turbo pump are desired, a magnetically levitated rotor design may provide the solution. In this type of turbo pump conventional (but oil free) bearings are only used on start-up and shut-down of the turbo. During normal operation the rotor is suspended above the bearings by well matched sets of strong magnets, virtually eliminating all mechanical vibration. Magnetically levitated turbo pumps are designed to operate for long periods of time with very few interruptions. Each time a magnetically levitated turbo pump is started or stopped, the oil-free mechanical bearings suffer wear and eventually will require replacement. Beyond reduction of vibration, the magnetically levitated rotor design turbos offer the option of mounting in any orientation, as there is no oil sump as in most conventional turbo pumps. Standard sequence of operation of turbomolecular pumped vacuum systems (see figure 10.5) is as follows:

Start-up:

1. Close all valves in the vacuum system.
2. Start the mechanical pump.
3. Open the foreline valve and rough pump the turbomolecular pump to a pressure of less than 1 Torr.
4. Start turbo pump; wait for rotor to attain normal operational velocity (20 minutes for most small to medium size pumps).
5. Close the foreline valve.
6. Open the vessel roughing valve; evacuate the vacuum vessel to a pressure of less than 500 mTorr*.
7. Close the vessel roughing valve; open the foreline valve.
8. Open the head gate valve; turn on the ion gauge.

Venting the vessel without stopping the turbo pump:

1. Turn off the ion gauge.
2. Close the head gate valve.
3. Open the vessel vent valve.
4. Open the vessel as soon as it reaches an internal pressure equal to atmospheric.
5. Close the vacuum vessel and the vessel vent valve.
6. Close the foreline valve.
7. Open the vessel roughing valve; evacuate the vacuum vessel to a pressure of less than 500 mTorr*.
8. Close the vessel roughing valve; open the foreline valve.
9. Open the head gate valve; turn on the ion gauge.

Shut-down:

1. Turn off the ion gauge.
2. Close the head gate valve.
3. Turn off power to the turbo pump, wait for rotation to stop.
4. Close the foreline valve and turn off the mechanical pump.
5. Vent the roughing line.
6. Open the air admittance valve on the turbo pump to gradually bring the pump to atmospheric pressure.
7. Open the vacuum vessel vent valve.

*Check manufacturer's suggested crossover pressure for the particular pump you are using.

Sample Problem:

10.3 Why are turbomolecular pump compressors designed in several "stages"? What are the characteristics of the inlet and exhaust stages?

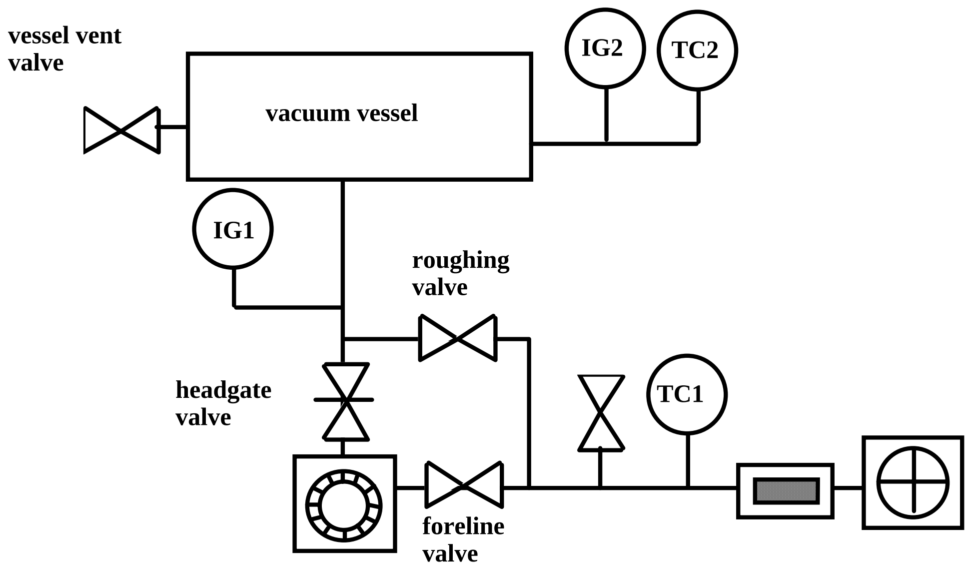

Figure 10.5 .Typical turbomolecular vacuum pumped vacuum system configuration

Maintenance of Turbomolecular Pumps

Normally, turbomolecular pumps operate for years and require little maintenance. Those pumps which have an oil sump and circulation system should have the oil changed approximately every six months or when the oil turns from clear to brown. Turbo pumps that use thick grease should have the lubricant replaced every six months. Bearing life in turbo pumps is approximately two to three years. Replacement of bearings is usually performed by trained technicians at the manufacturer's facility due to the precision balancing required for the high speed rotor.

If a turbomolecular pump inlet becomes contaminated, due to backstreaming of lubrication oil, occasionally a user may be able to clean the pump inlet and the first few stages by inverting the pump (oil having previously drained from the sump) in a container of solvent. Care must be taken to prevent immersion of any electrical components of the pump. It is wise to check with the pump manufacturer prior to cleaning a turbo pump by this method.

Applications for Turbomolecular Pumps

Three areas of vacuum technology that take advantage of the pumping characteristics of turbomolecular pumps are semiconductor equipment manufacturing, thin film deposition industry and the leak detector manufacturing industry.
Vacuum processes such as sputter deposition, which rely upon the flow of a process gas, usually at pressures of 3 to 50 milliTorr are often conducted using throttled turbomolecular pumps. Argon, a common process gas is pumped effectively by turbo pumps; variable orifice valves are used to control the pressure or throughput of gas in the vacuum vessel.

Modern vacuum leak detectors also often use turbo pumps as the high vacuum pump. Portable units typically have turbo pumps with greased bearings or magnetically levitated rotors so as to eliminate the possibility of oil contamination from the sump were the unit to be oriented horizontally during shipment. Another desirable characteristic of turbo pumps for leak detector application is the relatively high pumping speed for atmospheric gases (oxygen, nitrogen, carbon dioxide) compared with that for the light gas, helium. In most instances helium is used for leak detection due to its small molecular size, rarity in the atmosphere, and low toxicity. Some of the newer "counter-flow" leak detectors rely upon the low pumping efficiency of turbo pumps for light gases, such as helium, to permit backwards flow of helium through the operating turbo pump. This design allows for a much more compact and portable leak detector unit (more on this in Unit 13, Leak detection).

Sample Problems:

10.4 What are advantages of a turbomolecular pump over a diffusion pump?
10.5 Turbomolecular pump suffer severe mechanical damage when solid objects fall into the inlet during operation of the pump. Can you suggest two ways to prevent this occurrence?
10.6 What limits the base pressure one may attain using a turbomolecular pump?
10.7 Accessories available for turbomolecular pumps include the following:

Flange Heaters: To aid in the removal of residual gases and any contamination that may be present at the inlet area of the pump. Care must be taken not to exceed the manufacturer's suggested maximum temperature, as severe bearing wear may result.

Venting Devices: Upon interruption of electrical power these valves admit air into the inlet area of the pump to achieve pressure equilibrium within the turbo pump. This action serves to reduce the possibility of mechanical damage to the rotors and to minimize backstreaming of oil from the foreline.

Vibration Isolation Bellows: Reduce the transmission of high frequency vibration from the turbo pump to the vacuum vessel.

Water Flow Interlock: Prevents the operation of the turbo pump without proper flow of cooling water.

Compound Molecular Pumps

Compound molecular pumps are typically of the axial flow design and are essentially a combination of a turbomolecular and a molecular drag pump built into one unit. The advantage of a compound pump is that the molecular drag pump at the exhaust stage is able to compress the gas to a higher pressure than a conventional turbo pump. Most compound pumps are made to be backed by a diaphragm pump, thereby eliminating the possibility of backstreaming oil from an oil sealed rotary vane pump. Some of the newer compound pump can exhaust to atmospheric pressure; these pumps are often small (less than 150 liters per second pumping speed).

For Further Reading:

High Vacuum Technology, Hablanian, Marsbed, M., Marcel Dekker, INC., New York, New York. 1990, pp. 231-258.

A User's Guide to Vacuum Technology, O'Hanlon, John F. John Wiley & Sons New York, New York. 1980, pp. 181-191.

Modern Vacuum Practice, Harris, Nigel, McGraw-Hill, New York, New York, 1989, pp.146-159.

Laboratory Exercise 10.1: Inspection of a turbomolecular high vacuum pump.

Goals of this experiment: to operate a turbo pumped vacuum system, to observe the pump down rate for a vessel, to observe the base pressure of the system and to calculate the total gas load in the vessel.

Equipment required: An axial flow turbomolecular pump.

Procedure: Locate the manufacturer's literature for the model pump you will be working with. What is the rated speed for air? What is the ultimate pressure the pump can attain? What is the crossover pressure? What is the critical foreline pressure? What type bearings does the pump have? How is the pump cooled? What are the utilities requirements (water and electrical)? What is the recommended routine maintenance procedure?
Inspect the pump. Is there an air admittance valve on the unit? How is this valve actuated? Will this valve safely vent the pump during a power failure? If the pump has an oil sump, inspect the oil through the viewport. Note the appearance, clarity and level of the oil.

Create a written report of your findings for submission to the Laboratory Instructor.

Laboratory Exercise 10.2: Operation of a vacuum system with a turbomolecular pump.

Equipment required: small vacuum vessel or bell jar vacuum system to which a suitably sized turbomolecular pump can be attached, a vent valve for the vessel, two ionization gauges two thermocouple gauges and controllers, a gate valve to match the turbo pump inlet, roughing lines, a mechanical pump, a roughing valve, a foreline valve and a roughing line vent valve.

Procedure: Prior to any experimental work, make certain that the roughing pump selected will deliver adequate pumping speed to the foreline of the turbo pump.

Assemble the equipment as shown in figure 10.5. Make certain the cooling water flow is adequate if the pump is a water cooled model. After the Laboratory Instructor has checked the vacuum system, follow the system start-up procedures provided in this unit. Measure the vacuum vessel pressure as a function of time during pump down. Graph the data clearly showing which portion of the curve is due to evacuation by the mechanical pump, the point of crossover, and the pumping action due to the turbo pump. Following completion of the measurements safely shut down the turbo pumped vacuum system as outlined in this unit.

Submit a written report for this experiment to the Laboratory Instructor.

Discussion:
Assuming the rated speed of the turbo pump, and the measured base pressure, calculate the total gas load in the vacuum system.

What, in your opinion, are the sources of this gas load? How would you reduce these gas sources?

Laboratory Exercise 10.3: Measurement of pumping speed for a turbo pump.

Goals of this experiment: to measure the pumping speed of a turbo pump using the constant pressure method.

Equipment required: The turbo pumped system assembled for experiment 10.1, a needle valve /atmosphere valve assembly, a 1 ml graduated pipette, tygon tubing to fit the pipette, a 500 ml plastic beaker, food coloring or ink, and two thermocouple gauges with controllers.

Procedure: Using the vacuum system assembled for experiment 10.1, attach a needle valve/atmosphere valve assembly to the vacuum vessel as was done for the speed measurement at constant pressure for diffusion pumps. Bring the system into high vacuum operation using the set of procedures used in this unit. Open the needle valve slightly; wait for the pressure in the vessel to stabilize. Close the atmosphere valve by placing a thumb over the hole, and record the time required to pull 1 ml of water up into the graduated pipette. Record this time along with the pressure during the measurement. Open the needle valve another small increment and repeat the measurement of time required to draw 1 ml of water into the graduated pipette at the new pressure. Make at least ten measurements in this manner. Using equations 8.1 and 8.2 calculate the speed at each pressure, then plot the data as speed versus pressure.

Following completion of the measurements safely shut down the turbo pumped vacuum system as outlined in this unit.

Submit a written report for this experiment to the Laboratory Instructor.

Discussion:
Was the pumping speed data you collected over a range of pressures comparable to the data published by the turbo pump manufacturer?

