Vacuum Science, Apparatus, and Experiments

AP 4018y Applied Physics Laboratory
Dept. of Applied Physics and Applied Mathematics
Columbia University
New York, NY 10027 USA

<mailto:mauel@columbia.edu>

January 14, 2010

Overview. Using a mechanical pump and an oil diffusion pump (or a turbomolecular pump), the operation and pumping characteristics of those devices are studied. The experiment also makes use of several types of pressure measuring instrumentation commonly used in a research laboratory. The effectiveness of vacuum pumps are quantified by "pumping speed", S, which is defined to be the ratio of the throughput to the pressure, $S \equiv Q/P$. One of two vacuum test stations will be used by each student group. One station is used to measure surface outgassing and the other is used to measure pipe conductance. This experiment is required before attempting any of the Plasma Physics experiments.

1 Guide to Procedures

Before coming to lab, read over the introductory materials and articles. Understand: (1) the difference between laminar gas flow and molecular flow, (2) the definition of pumping speed, S, and (3) how to calculate pumping throughput, Q, from measurements of pressure as a function of time.

1.1 Week 1

- Familiarize yourself with the equipment and proper operating procedures with the lab supervisor. Measure the dimensions of your vacuum chamber so that you can calculate the chamber volume, V, and the lengths and diameters of all of the pipes connecting the chamber to the pumps.

- Use the mechanical roughing pump, and rough down the vacuum chamber while recording the pressure as a function of time, $P(t)$. You need to measure the pressure at intervals of approximately one every 10 sec.

  After correcting for gauge calibration factors, you can model your measurements with a "constant speed" approximation:

$$V\frac{dP}{dt} \approx -SP(t)$$

  How should you plot your data to best exhibit the pump-down of the chamber and the validity of the model equation?

- Fill the chamber with 2 or 3 Torr of air, argon, and helium and repeat your procedure. Use your data to estimate the variation of roughing pump speed as a function of atomic species.

- After the system is at rough vacuum, turn on the diffusion pump or the turbomolecular pump and observe the pump-down to high-vacuum. For the diffusion pump, what was the temperature of the oil when high-speed pumping started?

1.2 Week 2

Your objective is to measure the pumping speed of your high-vacuum pump (either the diffusion pump or the turbomolecular pump.) In order to do this, you will adjust a fine leak valve. The system pressure is modeled with the equation:

$$V\frac{dP}{dt} \approx Q_{leak} - \begin{cases} SP & \text{when gate} - \text{valve open} \\ 0 & \text{when gate} - \text{valve closed} \end{cases}$$

When the gate to the high-vacuum pump is closed, then the pressure increases linearly in proportion to the leak rate. When the gate-valve is open, then the pressure quickly settles to a constant throughput equilibrium between the leak and the pump.

A step-by-step procedure:

- With the gate-valve open, adjust the leak valve to find the "equilibrium" pressure, which is when the pump throughput balances the leak. Measure and record the pressure, P_{eq}.

- Close the gate valve to the high-vacuum pump, and measure the pressure as a function of time, $P(t)$. (Careful: the pressure will rise quickly when you have a large leak. So that you'll need to record the pressure at 5-10 sec intervals.) Determine the leak rate from the equation above, $Q_{leak} = d(PV)/dt$.

- Estimate the high-vacuum pumping speed as $S \approx Q_{leak}/P_{eq}$.

- Repeat for air, argon, and helium gas at different values of P_{eq}. Is the high-vacuum pumping speed independent of pressure?

A word of caution: The manufacturer specifies the pumping speed of the pump for air (or nitrogen). But this published speed does not include the effect of the pipes that connect the vacuum chamber to the pump. The conductances of these pipes can be estimated using the formula in the handouts. Your experiments actually measured the "effective" pumping speed *including* the effects of pipe conductance. As explained in the handouts, the pumping speed at the inlet of the pump, S, is related to the pumping speed at the connection to the vacuum chamber, S_{eff}, through the equation

$$S = \frac{S_{eff}}{1 - S_{eff}/C}$$

where C is the total conductance between the pump and the chamber. You will need to estimate C for both the high-vacuum and roughing pumps. Remember, the conductance of the high-vacuum pump is determined by molecular flow; whereas, the conductance of the pipes connecting the roughing pump is determined by laminar flow.

1.3 Week 3

We have two vacuum experiment stations, and your Week 3 experiments will depend whether or not you are using the turbomolecular pump station or the diffusion pump station.

Using the *turbomolecular pump station*, you will be given several pipes of different lengths and diameters. These are inserted between two vacuum chambers. The fine leak valve is connected to the small chamber, and you measure the pressure at both the main chamber, P_m, and the small chamber, P_s. The conductance of the pipe connecting the two chambers is related to the pressure difference, $C_{pipe} = Q_{leak}/(P_s - P_m)$. Once you've measured the pressure difference, closed the gate valve to the pump and record $P_s(t)$ and $P_m(t)$. The rate of change of pressure along with the measured volume of the two chambers can be used to calculate the leak rate, Q_{leak}.

Using the *diffusion pump station*, you will measure the outgassing rate of vacuum chamber wall as a function of temperature and time. Outgassing is complex atomic physics. Atoms are bound to the surface of solids and escape thermally, and gas atoms can diffuse through the solid. For the experiments that you perform this week, most of the atoms are either bound to the surface or near the surface of the inner chamber wall. (Most of the gas is probably water molecules.) The outgassing is proportional to the number of atoms (or molecules) *bound to the surface* and exponentially dependent on the temperature. Later in the pump-down, when the number of surface-bound molecules decreases, the outgassing rate will depend upon *diffusion* of gas through the solid walls. For these experiments, you need to measure pressure as a function of both time and temperature. Indeed, since the outgassing rate depends upon the condition and history of the walls, it is best to compare the outgassing from an unheated wall to a heated wall that

have been prepared identically. You can bring the chamber up to air, and pump-down the system to measure $P(t, T = 300\,\mathrm{deg}\,K)$. Then, bring the chamber back to air again (keeping the conditions as similar as possible), and then heat the chamber during the second pump-down. Measure both $P(t, T)$ and $T(t)$ as a function of time. For surface-bound gas, the outgassing rate should scale as $\sim \exp(-\Delta/kT)$, where Δ is the molecular binding energy to the inner chamber wall.

2 Summary

Key experimental methods:

- Vacuum system and vacuum pump operation
- Vacuum diagnostics and measurements
- Preparing data

Key analysis methods:

- Comparing data to model equations
- Curve fitting
- Graphing data

Key Physics Concepts:

- Gas flow
- Viscosity and atomic physics
- Conductance
- Surface binding

References

[1] Handouts, including book chapters, and pages from various equipment manuals.

[2] J.M.F. dos Santos, "Simple vacuum experiments for undergraduate student laboratories," *Vacuum*, **80**, 258 (2005).