Introduction to vacuum technology
Solutions to the exercises

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Exercise 1

a) The total number of adsorbed atoms is $N_{\rm atoms} = (2\times 10^{19}\,{\rm m}^{-2})\times A_{\rm sph}$, where $A_{\rm sph} = 4\pi\, r_{\rm sph}^2$ is the total internal area of the wall.

The total volume of the chamber, whose walls we assume to be at room temperature ($T = 293\,{\rm K}$) is $V_{\rm sph} = \frac{4}{3}\pi\, r_{\rm sph}^3$ so, using the ideal gas law, we have

$$\begin{aligned} p &= \frac{N_{\rm atoms}\, k_B T}{V_{\rm sph}} = \frac{(2\times 10^{19}\,{\rm m}^{-2})\times(4\pi\, r_{\rm sph}^2)\times k_B T}{\frac{4}{3}\pi\, r_{\rm sph}^3} \\ &= \frac{(2\times 10^{19}\,{\rm m}^{-2})\times 3\times(k_B\cdot 293\,{\rm K})}{r_{\rm sph}} \\ &= 2.4\,{\rm Pa} \quad (= 2.4\times 10^{-2}\,{\rm mbar})\ . \end{aligned}$$

Any experiment at similar low operating pressure could be strongly contaminated if the monolayer desorbs.

b) The equivalent pressure of 20 monolayers is $20\cdot 2.4\,{\rm Pa} = 48\,{\rm Pa} \approx 50\,{\rm Pa}$. Therefore, after pumpdown from atmosphere, there may be as many water molecules adsorbed on the wall as there are in 0.5 mbar of a process gas!

That is bad news for clean processing.

For example, in the semiconductor industry, important parts of silicon wafer processing are done in machines called "dry etchers" which need to operate in very clean conditions to be capable of patterning features all the way down to $\sim 10\,{\rm nm}$ scales. Consequently, after opening the machine, one needs to make sure that the walls are clean of contaminants (and, actually, re-coated with silicon film; which leads to a paradox: A "cleaned" dry-etcher is not really *clean*) to avoid having to scrap the first silicon wafers that pass by.

Exercise 2

The key observation to derive the expressions for S_{eff} is that the throughput must be constant along the pumping line.

This means that $Q = p_1 \, S_{\text{eff}} = p_{\text{p}} \, S_{\text{p}}$ and, therefore, $p_{\text{p}}/p_1 = S_{\text{eff}}/S_{\text{p}}$. However, we also have $Q = C\,(p_1 - p_{\text{p}})$, so $Q = p_1 \, S_{\text{eff}} = C\,(p_1 - p_{\text{p}})$ and, upon dividing throughout by p_1,

$$
\begin{aligned}
S_{\text{eff}} &= C\left(1 - \frac{p_{\text{p}}}{p_1}\right) = C\left(1 - \frac{S_{\text{eff}}}{S_{\text{p}}}\right) \\
\frac{S_{\text{eff}}}{C} &+ \frac{S_{\text{eff}}}{S_{\text{p}}} = 1 \\
\frac{1}{S_{\text{eff}}} &= \frac{1}{S_{\text{p}}} + \frac{1}{C}
\end{aligned}
$$

Alternatively, one can use the second line to solve for S_{eff} and obtain the form shown on slide 35.

Exercise 3

The vacuum system under consideration is shown in Fig. 1 for reference.

a) The total conductance C is the series combination of C_{ap}, the conductance of the aperture, and C_{cy}, the conductance of the cylindrical tube.

   From Fig. 1, the diameter of the aperture and the tube is 14 cm and the length of the tube is 15 cm.

   From slide 27, $C_{\text{ap}} \approx 11.6 \times \pi \left(\frac{14}{2}\right)^2 \frac{l}{\text{s}} = 1786 \, \frac{l}{\text{s}}$ and $C_{\text{cy}} \approx 12.1 \times \left(\frac{14^3}{15}\right) \frac{l}{\text{s}} = 2214 \, \frac{l}{\text{s}}$.

   Then, from slide 30, $\frac{1}{C} = \frac{1}{C_{\text{ap}}} + \frac{1}{C_{\text{cy}}}$, so $C \approx 990 \, \frac{l}{\text{s}}$.

b) Using the value of C obtained above and the turbopump pumping speed in Fig. 1 ($S_{\text{p}} = 300 \, \frac{l}{\text{s}}$), the value of the effective pumping speed S_{eff} can be computed as

$$
S_{\text{eff}} = \frac{S_{\text{p}}}{1 + S_{\text{p}}/C} = 230 \, \frac{l}{\text{s}} \, .
$$

c) According to Fig. 1, the ultimate pressure of the pump is 3×10^{-7} mbar. The base pressure stated is only a factor 1.33 larger, so this is indeed an acceptable number.

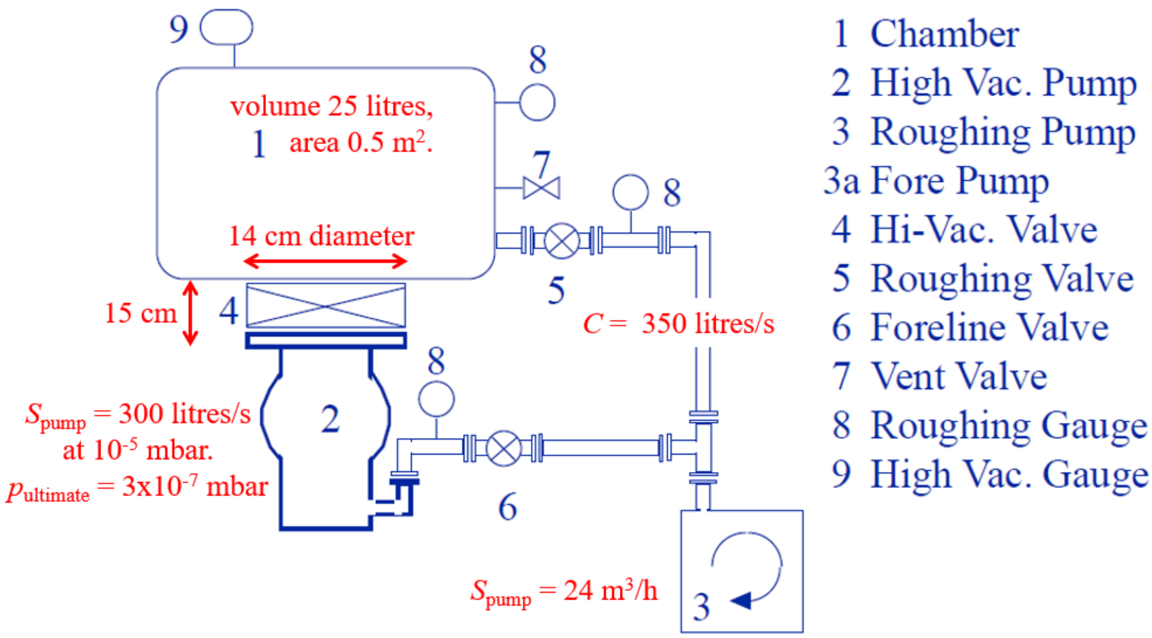

Figure 1: Vacuum system studied in Exercise 3.

d) The outgassing rate is $Q_{\text{og}} = p_{\text{base}}\, S_{\text{eff}} = (3 \times 10^{-7}\,\text{mbar}) \times (230\,\frac{l}{\text{s}}) = 9.2 \times 10^{-5}\,\frac{\text{mbar}\,l}{\text{s}}$. From this number, we can compute the specific outgassing rate upon dividing by the surface area of the inner wall of the chamber (see Fig. 1)

$$\frac{Q_{\text{og}}}{A_{\text{ch}}} = \left(9.2 \times 10^{-5}\,\frac{\text{mbar}\,l}{\text{s}}\right) / \left(5 \times 10^{3}\,\text{cm}^2\right) = 1.8\,\frac{\text{mbar}\,l}{\text{s}\,\text{cm}^2}\ .$$

This corresponds to the expected value for an unbaked clean metal chamber. This means that, most likely, the chamber has *no* leaks.

e) The roughing pumping speed is $S_{\text{ro}} = 24 \times 1000\,l/3600\,\text{s} = 6.6\,\frac{l}{\text{s}}$. This value is much lower than the conductance of the roughing line, $350\,\frac{l}{\text{s}}$. Therefore, the effective roughing pump speed is $\approx 6.6\,\frac{l}{\text{s}}$.

f) 10 Pa is equivalent to 0.1 mbar. This is the pressure that the roughing pump must maintain (at most) in the roughing line for the turbopump to work properly.

Since the throughput must be constant along the pumping line, we have then $Q = p_{\text{ch}}\, S_{\text{eff}} = p_{\text{ro}}\, S_{\text{ro}} \leqslant (0.1\,\text{mbar}) \times S_{\text{ro}}$ and, therefore,

$$p_{\text{ch}} \leqslant \frac{0.1 \times 6.6}{230}\,\text{mbar} = 0.0028\,\text{mbar}\ .$$

In experiments in TORPEX, for example, we typically use $p_{\rm ch} \leqslant 10^{-4}$ mbar. The value above would then be borderline and one would want to make the system more robust.

Since the conductance of the roughing line allows it, one way to do that is to purchase a roughing pump with a larger throughput.

g) From the preceding discussion, $Q_{\rm max} = (0.1\,{\rm mbar})\, S_{\rm ro} = (0.1\,{\rm mbar}) \times (6.6\,\frac{l}{\rm s}) = 0.66\,\frac{{\rm mbar}\,l}{\rm s}$.

This throughput is equivalent to $\approx 40\,$sccm. In many applications, one typically uses $\lesssim 10\,$sccm, so the setup in Fig. 1 is OK.

If larger flows are required, then one needs to replace the roughing pump with a more powerful one.