From the 9th & 10th lecture, April 11th & 14th: VACUUM

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Kaspar Schott, “Technica Curiosa” (1664), Otto von Guericke: Experiment in Regensburg and Magdeburg
Vacuum technology is needed in many different fields:

- All experiments with accelerators and particles
- Atomic physics with traps and spectrometers
- VUV spectroscopy
- Electron microscopy
- Plasma physics
- Low temperature experiments (insulation)
- Material research
- Space simulation
- Industrial processes as thin film production, glass coating
- Chemical industry
- Food processing
Very useful and comprehensive compendium and collection of formulas (CD)

Fundamentals of Vacuum Technology

00.200.02
Kat.-Nr: 199 90
### Vacuum Regimes

(16 powers of ten!)

<table>
<thead>
<tr>
<th>Regime</th>
<th>Pressure Range</th>
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</thead>
<tbody>
<tr>
<td>Rough Vacuum (RV)</td>
<td>$1000 \ldots 1\text{ mbar}$</td>
</tr>
<tr>
<td>Medium Vacuum (MV)</td>
<td>$1 \ldots 10^{-3}\text{ mbar}$</td>
</tr>
<tr>
<td>High Vacuum (HV)</td>
<td>$10^{-3} \ldots 10^{-7}\text{ mbar}$</td>
</tr>
<tr>
<td>Ultrahigh Vacuum (UHV)</td>
<td>$10^{-6} \ldots 10^{-14}\text{ mbar}$</td>
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</table>

These regimes can be delineated from gas kinetics and the nature of gas flow.

SI-unit: $1 \text{ pascal (Pa)} \equiv 1 \text{ N}\cdot\text{m}^{-2} \equiv 1 \text{ J}\cdot\text{m}^{-3} \equiv 1 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2} \equiv 10^{-5}\text{ bar}$

usual: $1 \text{ mbar} \equiv 1 \text{ hPa}$
Outline

• Gas laws, models and theory
• Some Formula’s
• Vacuum Generation
• Vacuum connections, feedthrough’s
• Vacuum Measurement, Control and Regulation
• Mass spectroscopy
• Leak Detection
• Some Vacuum Applications
Gas equation for ideal gas:

\[ p \cdot V = \nu \cdot R \cdot T = N \cdot k \cdot T \]

\[ p \cdot V_m = R \cdot T \]

\( V_m = \text{Mol volume} = 22.4 \text{ l at } 0 \degree \text{C and 1013 mbar} \)

\( N_A = 6.022 \cdot 10^{23} \text{ mol}^{-1} \)

high pressures or near boiling point at use Van-der-Waals equation

Particle density:

at 1 bar (1013 mbar): \( n \approx 3 \cdot 10^{19} \text{ cm}^{-3} (0 \degree \text{C}) \)

at 10^{-14} \text{ mbar}: \( n \approx 350 \text{ cm}^{-3} \)
Types of gas flow

- Viscous flow
  - laminar \( \text{Re}^* < 2200 \)
  - turbulent \( \text{Re} > 2200 \)

\( \lambda^* < \frac{d}{100} \)

* Reynold’s number

\( p \cdot d > 6 \cdot 10^{-1} \text{ mbar cm} \)

*mean free path length \( \lambda \)

- Knudsen flow

\( \frac{d}{100} < \lambda < \frac{d}{2} \)

\( 6 \cdot 10^{-1} > p \cdot d > 1.3 \cdot 10^{-2} \text{ mbar cm} \)

- Molecular

\( \lambda > \frac{d}{2} \)

\( p \cdot d < 1.3 \cdot 10^{-2} \text{ mbar cm} \)
The "Zoo" of Vacuum Pumps

Vacuum pump
(Operating principle)

Positive displacement vacuum pump
- Reciprocating positive displacement vacuum pump
  - Diaphragm vacuum pump
  - Piston vacuum pump
- Rotary vacuum pump
  - Liquid sealed vacuum pump
  - Liquid ring vacuum pump
  - Multiple vane vacuum pump
    - Rotary vane vacuum pump
      - Rotary piston vacuum pump
      - Rotary plunger vacuum pump
      - Dry compressing vacuum pump
        - Roots vacuum pump
        - Claw vacuum pump
        - Screw pump

Kinetic vacuum pump
- Drag vacuum pump
  - Gaseous ring vacuum pump
  - Turbine vacuum pump
    - Axial flow vacuum pump
    - Radial flow vacuum pump
      - Molecular drag vacuum pump

- Fluid entrainment vacuum pump
  - Ejector vacuum pump
    - Liquid jet vacuum pump
    - Gas jet vacuum pump
    - Vapor jet vacuum pump

- Ion transfer vacuum pump
  - Adsorption pump
    - Getter pump
    - Bulk getter pump
    - Sublimation pump
    - Getter ion pump
    - Evaporation ion pump
    - Sputter-ion pump
    - Cryopump
    - Condenser
Rotary Vane Pump

I High vacuum stage
II Second forevacuum stage
Diaphragm Pump

Opening and closing of the valves, path and pumping mechanism during four subsequent phases of a turn of the connecting rod (a-d)
Diaphragm Pumps
Vacuubrand
Lederle Hermetic Pump (Screw Pump)
SIHIdry - Pump

3-fold Cooling:
1. Housing
2. Internal Axis Cooling
3. Direct Gas Cooling

Easy Service
Claw Pump
Roots Pump (Pfeiffer)
Two Stage Roots Pump (Pfeiffer)
1 Inlet port
2 Degassing port
3 Support
4 Pump body
5 Thermal conducting vanes
6 Adsorption material (e.g. Zeolith)
Diffusion Pump

Diagram of a Diffusion Pump:

1. Heater
2. Boiler
3. Pump body
4. Cooling coil
5. High vacuum flange
6. Gas molecules
7. Vapor jet
8. Backing vacuum connection

A, B, C, D: Nozzles
Turbomolecular Pump with double Holweck stage and magnetic suspension of the rotor
Mini Turbomolecular Pumps with Holweck Stages (Alcatel-Adixen)

ATH 31
The ATH 31 includes one turbo stage and one Holweck stage. With excellent compression ratios and a backing pressure tolerance of up to 25 mbar, it can be backed by a membrane pump. It features one intermediate pumping port.

ATH 31+
The ATH 31+, with one turbo stage and three Holweck stages, offers outstanding compression ratios. It is the ideal version for pumping light gases. Its exceptional performance can be achieved with a membrane pump as a fore pump. It also features two intermediate ports.

ATH 31 C
The ATH 31 C includes one turbo stage, and two Holweck stages. A purge offers protection against corrosive gases. It can be backed by a membrane pump. It features one intermediate pumping port.
Sputter Ion Pump
(diode type)

← Direction of motion of the ionized gas molecules
• → Direction of motion of the sputtered titanium

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Spiral tracks of the electrons
PZ Penning cells
Ion Getter Pump (triode type)
(better for noble gases)

- Titanium atoms
- Gas molecules
- Ions
- Electrons

A: Anode cylinder (same as in the diode pump)
B: Magnetic field
F: Target plate (pump housing) as the third electrode
K: Cathode grid
Phase 1:
The displacer is at the left dead center, $V_2$ where the cold is produced has its minimum size. Valve N remains closed, H is opened. Gas at the pressure $p_H$ flows through the regenerator into $V_2$. There the gas warms up by the pressure increase in $V_1$.

Phase 2:
Valve H remains open, valve N closed: the displacer moves to the right and ejects the gas from $V_1$ through the regenerator to $V_2$ where it cools down at the cold regenerator; $V_2$ has its maximum volume.

Phase 3:
Valve H is closed and the valve N to the low pressure reservoir is opened. The gas expands from $p_H$ to $p_N$ and thereby cools down. This removes heat from the vicinity and it is transported with the expanding gas to the compressor.

Phase 4:
With valve N open the displacer moves to the left; the gas from $V_{2,\text{max}}$ flows through the regenerator, cooling it down and then flows into the volume $V_1$ and into the low pressure reservoir. This completes the cycle.
Why is steady pumping required?

- Leaks (different types)
- Out-gassing
- Vapor
- Pockets
- Diffusion
### Desorption rates from clean surfaces \([\text{mbar} \cdot \text{l/s} \cdot \text{cm}^2]\)

<table>
<thead>
<tr>
<th>Surface</th>
<th>1 h</th>
<th>10 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel, sanded, cleaned</td>
<td>2.7 (\times) 10(^{-7})</td>
<td>2.7 (\times) 10(^{-8})</td>
</tr>
<tr>
<td>Stainless steel, polished, cleaned</td>
<td>2.7 (\times) 10(^{-8})</td>
<td>2.7 (\times) 10(^{-10})</td>
</tr>
<tr>
<td>Stainless steel, pickled with acid 1h</td>
<td>1.4 (\times) 10(^{-9})</td>
<td>1.4 (\times) 10(^{-10})</td>
</tr>
<tr>
<td>Stainless steel, blasted with steel balls</td>
<td>3 (\times) 10(^{-10})</td>
<td>4 (\times) 10(^{-11})</td>
</tr>
<tr>
<td>Steel, Ni-plated, polished, cleaned</td>
<td>2 (\times) 10(^{-7})</td>
<td>5 (\times) 10(^{-9})</td>
</tr>
<tr>
<td>Steel, Cr-plated, polished, cleaned</td>
<td>1.3 (\times) 10(^{-8})</td>
<td>1.2 (\times) 10(^{-9})</td>
</tr>
<tr>
<td>Steel, rusty</td>
<td>6 (\times) 10(^{-7})</td>
<td>1 (\times) 10(^{-7})</td>
</tr>
<tr>
<td>Steel, bare, cleaned</td>
<td>5 (\times) 10(^{-7})</td>
<td>5 (\times) 10(^{-8})</td>
</tr>
<tr>
<td>Aluminum, cleaned</td>
<td>6 (\times) 10(^{-8})</td>
<td>1.1 (\times) 10(^{-8})</td>
</tr>
<tr>
<td>Brass, cleaned</td>
<td>1.6 (\times) 10(^{-6})</td>
<td>4 (\times) 10(^{-7})</td>
</tr>
<tr>
<td>Copper, cleaned</td>
<td>3.5 (\times) 10(^{-7})</td>
<td>5.5 (\times) 10(^{-8})</td>
</tr>
<tr>
<td>Porcelain, glazed</td>
<td>8.7 (\times) 10(^{-7})</td>
<td>2.8 (\times) 10(^{-7})</td>
</tr>
<tr>
<td>Glass, cleaned</td>
<td>4.5 (\times) 10(^{-9})</td>
<td>5.5 (\times) 10(^{-10})</td>
</tr>
<tr>
<td>Acrylglass</td>
<td>1.6 (\times) 10(^{-6})</td>
<td>4 (\times) 10(^{-7})</td>
</tr>
<tr>
<td>Perbunan</td>
<td>4 (\times) 10(^{-6})</td>
<td>1.3 (\times) 10(^{-6})</td>
</tr>
<tr>
<td>Viton</td>
<td>1.2 (\times) 10(^{-6})</td>
<td>2.2 (\times) 10(^{-7})</td>
</tr>
<tr>
<td>Viton, baked 4 h at 150 °C</td>
<td>3.3 (\times) 10(^{-10})</td>
<td>2.5 (\times) 10(^{-10})</td>
</tr>
<tr>
<td>Teflon, degassed</td>
<td>2.3 (\times) 10(^{-7})</td>
<td>1.5 (\times) 10(^{-7})</td>
</tr>
</tbody>
</table>
How to clean vacuum systems:

• degreasing by acetone or freon or tri to get rid of all oil, lubricant and grease rests
• or degreasing in a cooking pot with dishwasher detergent and boiling water for 2 hours
• alcohol doesn’t help much, but one can get rid of water
• the last two procedures super-pure water and drying with clean hot air
• heating or baking to overcome the outgassing
• use clean white cotton gloves for all procedures
Conductance and effective pumping speed

Only molecular flow considered here, different formula’s for different flow types

series of flow “resistors” (= \( \frac{1}{C} \); C = conductance):

\[
\frac{1}{C_{\text{tot}}} = \frac{1}{C_{\text{ap}}} + \frac{1}{C_{\text{tube1}}} + \frac{1}{C_{\text{tube2}}} + \frac{1}{C_{\text{tube3}}} + \frac{1}{C_{\text{Elbow}}} + \ldots
\]

Parallel setting of several conductances:

\[
C_{\text{tot}} = C_{\text{tube1}} + C_{\text{tube2}} + C_{\text{tube3}} + \ldots
\]

Conductance of a tube, molecular flow:

\[
C_{\text{tube}}^{\text{mol}} = 12 \cdot \frac{d^3}{l} \left[ \frac{1}{s} \right] \quad \text{d,l in cm}
\]

Reduction of pumping speed by the use of tubes, elbows, apertures:

\[
S_{\text{eff}} = \frac{1}{\frac{1}{C_{\text{tot}}} + \frac{1}{S_{\text{nom}}}} = \frac{C_{\text{tot}} \cdot S_{\text{nom}}}{C_{\text{tot}} + S_{\text{nom}}} \left[ \frac{1}{s} \right]
\]
ANGLE VALVES

1 plate seal  2 bellows  3 bonnet seal  ▽ valve seat side
GATE VALVES

DN 63 - 320

1. valve gate
2. counter plate
3. leaf springs
4. ball pairs
5. detents
6. gate seal
7. spring stop

\( \nabla \) valve seat side
The customary limits are indicated in the diagram.

- Ultrahigh vacuum: $<10^{-9}$ mbar, $<10^{-9}$ Pa
- High vacuum: $10^{-9}$ to $10^{-3}$ mbar, $10^{-9}$ to $10^{-3}$ Pa
- Medium vacuum: $10^{-3}$ to 1 mbar, $10^{-3}$ to $10^{0}$ Pa
- Rough vacuum: 1 to approx. $10^{3}$ mbar, $10^{0}$ to approx. $10^{3}$ Pa

- Capacitance diaphragm vacuum gauge
- Bourdon vacuum gauge
- Diaphragm vacuum gauge
- Piezoelectric vacuum gauge
- Liquid level vacuum gauge
- U-tube vacuum gauge
- Compression vacuum gauge
- (McLeod vacuum gauge)
- Decrement vacuum gauge
- Thermal conductivity vacuum gauge
- Pirani vacuum gauge
- Thermocouple vacuum gauge
- Bimetallic vacuum gauge
- Thermistor vacuum gauge
- Cold-cathode ionization vacuum gauge
- Penning ionization vacuum gauge
- Magnetoionization vacuum gauge
- Hot-cathode ionization vacuum gauge
- Triode ionization vacuum gauge for medium vacuum
- Triode ionization vacuum gauge for high vacuum
- Bayard-Alpert ionization vacuum gauge
- Bayard-Alpert ionization vacuum gauge with modulator
- Extractor vacuum gauge
- Partial pressure vacuum gauge

$p$ in mbar →
Mechanical Membrane Manometer

1. Base plate
2. Lever system
3. Connecting flange
4. Diaphragm
5. Reference pressure pref
6. Pinch-off end
7. Mirror sheet
8. Plexiglass sheet
9. Pointer
10. Glass baffle
11. Mounting plate
12. Housing
Pirani Vacuum-Meter

Heat loss

Pressure [mbar]

Pressure

I. Thermal dissipation due to the gas, pressure-dependent
II. Thermal dissipation due to radiation and conduction in the metallic ends
III. Thermal dissipation due to radiation and convection
Cold Cathode Ionization Gauge

1. Small flange DN 25 KF; DN 40 KF
2. Housing
3. Ring anode with ignition pin
4. Ceramic washer
5. Current leadthrough
6. Connecting bush
7. Anode pin
8. Cathode plate
Hot Cathode Ionization Vacuum Gauges

- G100F
- G075N
- G8120
- G8130
- G100K
Partial Pressure Measurement: Quadrupole Mass Spectrometer
Example Mass Spectrum

Evaluation problems: The peak at atomic number 16 may, for example, be due to oxygen fragments resulting from O₂, H₂O, CO₂, and CO; the peak at atomic number 28 from contributions by N₂ as well as by CO and CO₂ as a fragment of CO₂; the peak at atomic number 20 could result from singly ionized Ne and double-ionized Ar.
Differential Pumping Scheme of “Rhinoceros”
Proton Beam in Air Windowless

Nuclear Pumped Laser

He⁺ Beam in Neon

Nuclear Pumped Laser