Dimensioning

Rough estimation of the necessary pumping time for a vacuum vessel

Task formulation

A closed tank with various assembly parts has to be evacuated with a combination of turbomolecular pump and backing pump from normal pressure (p_0 = 1013 mbar) to a certain vacuum level (ultimate pressure p_{End}).
The evacuation procedure can be assumed in two steps:
1. the rough evacuation step from normal pressure to a rough vacuum level
2. the final evacuation step from the rought vacuum level to the end vacuum level.
How long does the pump down procedure takes to reach the desired end pressure?

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I. Definitions, Constants und Data

A. Common data

def. $\mathrm{mbar} := 10^{-3}\mathrm{bar}$

initial pressure $P_0 := 1013\cdot\mathrm{mbar}$

desired ultimate pressure $P_{End} := 5 \times 10^{-4}\mathrm{mbar}$

universal gas constant $R_. := 8.31446\cdot\frac{\mathrm{kg}\cdot\mathrm{m}^2}{\mathrm{s}^2\cdot\mathrm{mol}\cdot\mathrm{K}}$

gas temperature $T_{gas} := 293\mathrm{K}$

average molar mass of the gas (here air) $M_{gas} := 0.0288\frac{\mathrm{kg}}{\mathrm{mol}}$

average gas particle speed $c_{gas} := \sqrt{\frac{8\cdot R_.\cdot T_{gas}}{\pi\cdot M_{gas}}}$ $c_{gas} = 464.1\,\frac{\mathrm{m}}{\mathrm{s}}$

B. Vacuum vessel

chamber volume $V_{vessel} := 1500\mathrm{L}$

inner surface $A_{vessel} := 7.540\mathrm{m}^2$

leak rate $q_L := 1 \times 10^{-5}\cdot\mathrm{mbar}\cdot\frac{\mathrm{L}}{\mathrm{s}}$

C. Assembly parts

surface of the assembly parts of metal $A_{components.metal} := 2.46\mathrm{m}^2$

surface of the plastics assembly parts $A_{components.plastic} := 10\mathrm{m}^2$

D. Material choice, Outgassing from surfaces

In a open vacuum vessel the inner vessel surface and the assembly part surfaces contain adsorbed resp. absorbed gas molecules (water too). Under vacuum these gas (and water) molecules enter into the evacuated volume. The desorption of the metal-, glass- and plastic surfaces leads in the vacuum system to a time dependent gas accrual. We can approximately assume, that the desorption rate for metal and glass after about 1 hour decreases linearly. For plastics the outgassing flow declines about inversely proportional to the square root of the time.

1. Outgassing from the vacuum tank inside walls

definition

Vessel =		
	1	stainless steel, surface polished and cleaned
	2	aluminium, surface cleaned
	3	copper, surface cleaned
	4	brass, surface cleaned
	5	glass, surface cleaned

choice : $\text{Vessel} := 1$

desorption rate after 1 hour /1/

$$q_{des.ves} := \begin{cases} 2 \times 10^{-4}\,\frac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Vessel} = 1 \\ 6 \times 10^{-4}\,\frac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Vessel} = 2 \\ 3.5 \times 10^{-3}\,\frac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Vessel} = 3 \\ 1.6 \times 10^{-2}\,\frac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Vessel} = 4 \\ 4.5 \times 10^{-5}\,\frac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Vessel} = 5 \\ 2.0 \times 10^{-4}\,\frac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{otherwise} \end{cases}$$

outgassing constant $K_{ves} := q_{des.ves}\cdot 3600\text{s}$ $K_{ves} = 0.7\cdot\frac{\text{mbar}\cdot\text{L}}{\text{m}^2}$

2. Outgassing from assembly parts with metal surfaces

definition

Metal =		
	1	stainless steel, surface polished and cleaned
	2	aluminium, surface cleaned
	3	copper, surface cleaned
	4	brass, surface cleaned

choice : $\text{Metal} := 1$

desorption rate after 1 hour /1/

$$q_{des.met} := \left| \begin{array}{ll} 2 \times 10^{-4} \dfrac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Metal} = 1 \\ 6 \times 10^{-4} \dfrac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Metal} = 2 \\ 3.5 \times 10^{-3} \dfrac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Metal} = 3 \\ 1.6 \times 10^{-2} \dfrac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{if Metal} = 4 \\ 1.0 \times 10^{-3} \dfrac{\text{mbar}\cdot\text{L}}{\text{s}\cdot\text{m}^2} & \text{otherwise} \end{array} \right.$$

outgassing constant

$$K_{met} := q_{des.met} \cdot 3600\text{s}$$

$$K_{met} = 0.7 \cdot \frac{\text{mbar}\cdot\text{L}}{\text{m}^2}$$

3. Outgassing from assembly parts with plastic surfaces

definition

Plastics =		
	1	Viton
	2	Perbunan
	3	Plastic according /2/, p. 685

choice : $\text{Plastics} := 2$

degassing constant /2/

$$K_{pla} := \begin{cases} 0.4\dfrac{\text{mbar}\cdot\text{L}}{\sqrt{\text{s}}\cdot\text{m}^2} & \text{if Plastics} = 1 \\ 4\dfrac{\text{mbar}\cdot\text{L}}{\sqrt{\text{s}}\cdot\text{m}^2} & \text{if Plastics} = 2 \\ 1.1\dfrac{\text{mbar}\cdot\text{L}}{\sqrt{\text{s}}\cdot\text{m}^2} & \text{if Plastics} = 3 \\ 4\dfrac{\text{mbar}\cdot\text{L}}{\sqrt{\text{s}}\cdot\text{m}^2} & \text{otherwise} \end{cases}$$

$$K_{pla} = 4\cdot\frac{\text{mbar}\cdot\text{L}}{\sqrt{\text{s}}\cdot\text{m}^2}$$

E. Vacuum pumps and connecting tubes

1. Backing pump

Name: Alcatel ACP 28

absorption capacity $S_V := 15\frac{m^3}{h}$ $S_V = 4.167\cdot\frac{L}{s}$

theoretical ultimate pressure $P_{theo.V.end} := 3 \times 10^{-2}\,mbar$

Connecting vacuum tube

nominal tube diameter DN40

tube length $l_{V.tube} := 150cm$

2. Turbomolecular pump

Name: Pfeiffer CompactTurbo TMH 521 YP

nominal absorption capacity (e.g. for N_2) $S_{T.rated} := 500\frac{L}{s}$

theoretical ultimate pressure $P_{theo.T.end} := 10^{-8}\,mbar$

start-up pressure $P_1 := 0.1\cdot mbar$

Connecting vacuum tube

nominal tube diameter DN160

inside tube diameter $d_{T.tube} := 150mm$

tube length $l_{T.tube} := 200mm$

II. Calculations

A. Effective absorption capacities

1. Effective absorption capacity of the backing pump

The backing pump works in the area of laminar gas flow. The conductivity for laminar flow at 20°C can be determined from following graphic.

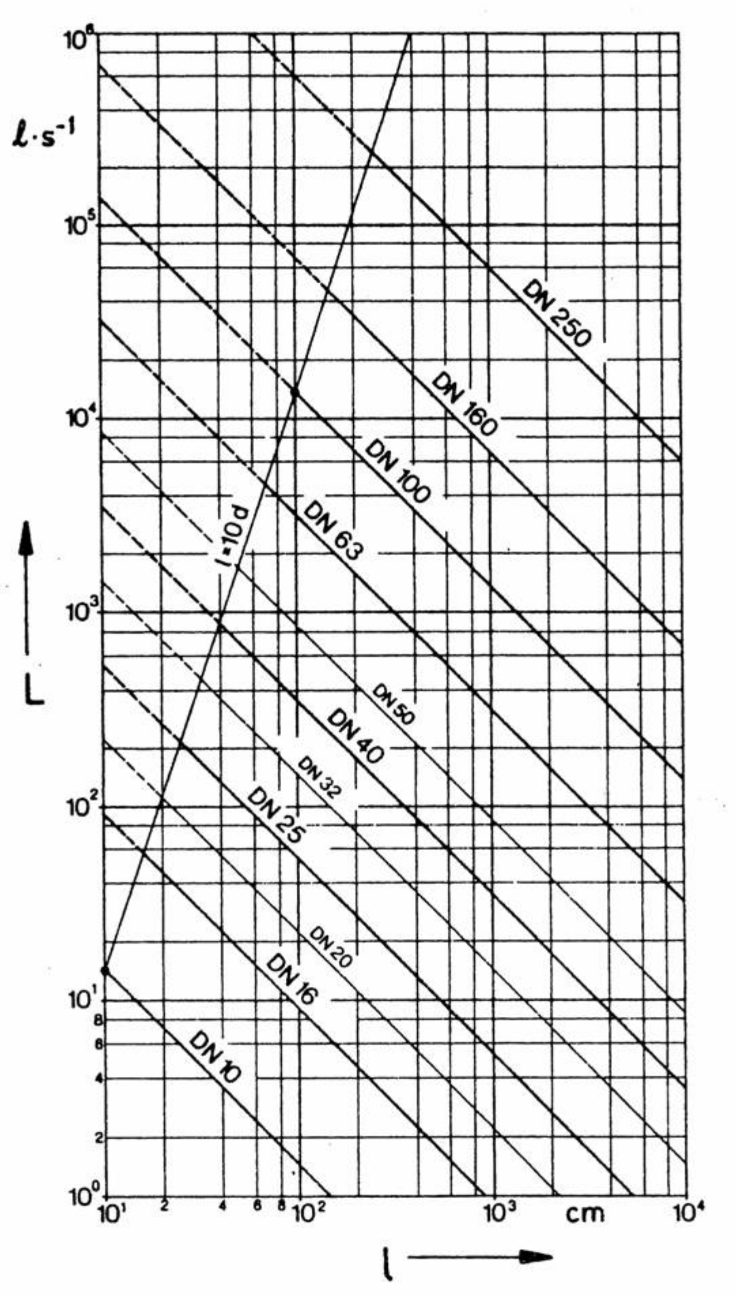

Fig. 1:
conductivity L of tubes with DN nominal diameter d and circular cross section for **laminar flow** in dependence on pipe length l.
Conditions:

Air, 20°C, $\eta = 1{,}82 * 10^{-5}$ kg m^{-1} s^{-1}
average pressure = 1 mbar, l >10 d

conductivity for laminar flow for the tube with above-mentioned (I,E.1) proportions

$$L_{V.tube} := 200 \frac{L}{s}$$

The effective absorption capacity of the backing pump results from:

$$S_{V.eff} := \frac{1}{\frac{1}{S_V} + \frac{1}{L_{V.tube}}}$$

$$S_{V.eff} = 4.1 \cdot \frac{L}{s}$$

2. Effective absorption capacity of the turbomolecular pump

The turbomolecular pump works at first in the area of the so called Knudsen flow and reaches below about 0.01 mbar the area of the molecular flow. The connecting tube between the vacuum vessel and the turbomolecular pump should be as short as possible. The molecular flow conductivity of a short connection tube can be estimated roughly by combining a aperture mask conductivity with a long tube conductivity.

conductivity of a aperture mask (molecular flow)

$$L_{aperture} := \frac{\pi}{16} \cdot d_{T.tube}^{\ 2} \cdot c_{gas}$$

conductivity of a long tube (molecular flow)

$$L_{longtube} := \frac{\pi}{12} \cdot \frac{d_{T.tube}^{\ 3}}{l_{T.tube}} \cdot c_{gas}$$

conductivity of a short connecting tube (molecular flow)

$$L_{T.tube} := \frac{1}{\dfrac{1}{L_{aperture}} + \dfrac{1}{L_{longtube}}}$$

$$L_{T.tube} = 1025 \cdot \frac{L}{s}$$

The effective absorption capacity of the turbomolecular pump results from:

$$S_{T.eff} := \frac{1}{\dfrac{1}{S_{T.rated}} + \dfrac{1}{L_{T.tube}}}$$

$$S_{T.eff} = 336 \cdot \frac{L}{s}$$

B. Rough evacuation

possible ultimate pressure with
backing pump
(see also I.E.2: start-up pressure P_1)

$$P_{V.end} := P_{theo.V.end} + \frac{q_L}{S_{V.eff}}$$

$$P_{V.end} = 0.03 \cdot mbar$$

1. Pumping out of the free gas by means of the backing pump

pump out time

$$t_1 := \frac{V_{vessel}}{S_{V.eff}} \cdot \ln\left(\frac{P_0}{P_1 - P_{V.end}}\right)$$

$$t_1 = 59 \cdot min$$

2. Degassing from vessel surfaces at rough vacuum

exhaust time

$$t_{2.ves} := \frac{A_{vessel} \cdot K_{ves}}{S_{V.eff} \cdot \left(P_1 - P_{V.end}\right)}$$

$$t_{2.ves} = 19 \cdot s$$

3. Degassing from surfaces of metal assembly parts at rough vacuum

exhaust time

$$t_{2.met} := \frac{A_{components.metal} \cdot K_{met}}{S_{V.eff} \cdot \left(P_1 - P_{V.end}\right)}$$

$$t_{2.met} = 6 \cdot s$$

4. Degassing from surfaces of plastic assembly parts at rough vacuum

exhaust time

$$t_{2.pla} := \frac{{A_{components.plastic}}^2 \cdot {K_{pla}}^2}{{S_{V.eff}}^2 \cdot \left(P_1 - P_{V.end}\right)^2}$$

$$t_{2.pla} = 327 \cdot min$$

C. Final evacuation

possible ultimate pressure with turbomolecular pump
(see also I.A: desired ultimate pressure P_{End})

$$P_{T.end} := P_{theo.T.end} + \frac{q_L}{S_{T.eff}}$$

$P_{T.end} = 4 \times 10^{-8} \cdot mbar$

1. Pumping out of the free gas after power up the turbomolecular pump

pump out time

$$t_3 := \frac{V_{vessel}}{S_{T.eff}} \cdot \ln\left(\frac{P_1}{P_{End} - P_{T.end}}\right)$$

$t_3 = 24\,s$

2. Degassing from vessel surfaces with the turbomolecular pump

exhaust time

$$t_{4.ves} := \frac{A_{vessel} \cdot K_{ves}}{S_{T.eff} \cdot \left(P_{End} - P_{T.end}\right)}$$

$t_{4.ves} = 1 \cdot min$

3. Degassing from surfaces of metal assembly parts with the turbomolecular pump

exhaust time

$$t_{4.met} := \frac{A_{components.metal} \cdot K_{met}}{S_{T.eff} \cdot \left(P_{End} - P_{T.end}\right)}$$

$t_{4.met} = 0 \cdot min$

4. Degassing from surfaces of plastic assembly parts with the turbomolecular pump

exhaust time

$$t_{4.pla} := \frac{A_{components.plastic}^{\;2} \cdot K_{pla}^{\;2}}{S_{T.eff}^{\;2} \cdot \left(P_{End} - P_{T.end}\right)^2}$$

$t_{4.pla} = 944 \cdot min$

III. Result

The total exhaust time is about : $t_{ges} := t_1 + t_{2.ves} + t_{2.met} + t_{2.pla} + t_3 + t_{4.ves} + t_{4.met} + t_{4.pla}$

$t_{ges} = 1331 \cdot min$

IV. Appendix

Literature

/1/ Pfeiffer, Vacuum Datensammlung
/2/ Wutz, Handbuch Vakuumtechnik, Theorie und Praxis, Vieweg Verlag, Wiesbaden, 2004