FYSS320 – Vacuum techniques

Exam, 30.8.2013

Short, concise answers are preferred.
Vastaukset voi antaa myös Suomen kielellä.

Problem 1.
Let's assume a cubic-shaped vacuum chamber with a length of the inside wall equal to 20 cm. Assume two pressures:

a) 10 Pa.
b) 10^{-5} Pa.

In both cases, describe the amount of the rest gas, its composition and the state. Explain how the heat is transferred in the rest gas and list means to reach such a vacuum.

Problem 2.
a) Discuss shortly different sources of gas load in the vacuum system.
b) Explain shortly the principle of gas ballast.
c) Is it possible to measure the absolute partial pressure of the certain gas component by using the rest gas analyzer? Present a short justification for your answer.

Problem 3.
Two thermally isolated vacuum chambers have a common wall with an aperture diameter equal to d. Absolute temperatures of chambers are T_1 and T_2.

a) Show that diffusion coefficients D_1 and D_2 have the following dependence:
$D_1/D_2 = (T_1/T_2)^{3/2}$, when $d \gg \langle\lambda\rangle$ and $\langle\lambda\rangle$ is an average collision distance of molecules.

b) Show, that the pressure and density of the gas are different in different chambers and those can be expressed as
$\rho_1/\rho_2 = (T_2/T_1)^{1/2}$ and $P_1/P_2 = (T_1/T_2)^{1/2}$, when $d \ll \langle\lambda\rangle$

Problem 4.
A vacuum chamber should be pumped down from an atmospheric pressure to high vacuum. For this purpose it is connected to a pumping station containing a turbo molecular pump, a roughing pump and necessary valves, etc. Draw a layout of the typical connection to vacuum system and name all components. Describe means to prevent oil diffusion, if any, to the vacuum system.

Appendices:

Table 2.5.

Critical constants T_c, P_c, Van der Waals' constants A, b, molecular diameters ξ, and mean free paths λ, computed from eqs. (2.26), (2.29), (2.56).

Gas	Formula	T_c	P_c	A	b	ξ	λ*
		°C	atm	$\left[\frac{cm^3}{mole}\right]^2$·atm	cm^3/mole	cm	cm
Helium	He	−267.9	2.26	3.412×10^4	23.70	2.61×10^{-8}	9.26×10^{-3}
Neon	Ne	−228.5	25.9	2.107×10^5	17.09	2.38×10^{-8}	1.03×10^{-2}
Argon	A	−122.0	48.0	1.345×10^6	32.19	2.94×10^{-8}	7.34×10^{-3}
Krypton	Kr	−63.0	54.2	2.318×10^6	39.78	3.16×10^{-8}	6.38×10^{-3}
Xenon	Xe	16.6	58.2	4.194×10^6	51.05	3.43×10^{-8}	5.40×10^{-3}
Hydrogen	H_2	−239.9	12.8	2.450×10^5	26.61	2.76×10^{-3}	8.33×10^{-3}
Nitrogen	N_2	−147.1	33.5	1.390×10^6	39.13	3.14×10^{-8}	6.44×10^{-3}
Air	—	—	—	1.33×10^6	36.6	—	—
Oxygen	O_2	−118.8	49.7	1.360×10^6	31.83	2.93×10^{-8}	7.40×10^{-3}
Mercury	Hg	>1500	>200	8×10^6	17.0	2.38×10^{-8}	1.12×10^{-2}
Ammonia	NH_3	132.4	111.5	4.17×10^6	37.07	3.09×10^{-8}	6.68×10^{-3}
Carbon monoxide	CO	−139.0	35.0	1.485×10^6	39.9	3.16×10^{-8}	6.36×10^{-3}
Carbon dioxide	CO_2	31.1	73.0	3.59×10^6	42.67	3.22×10^{-8}	6.13×10^{-3}
Acetylene	C_2H_2	36.0	62.0	4.39×10^6	51.40	3.44×10^{-8}	5.38×10^{-3}

*Mean free path for $P=1$ Torr, $T=273$°K.

Kaasu	D (10^{-5} m^2/s)	K (10^{-2} J/m·s·K)	η (10^{-5} kg/m·s)	ξ (10^{-10} m)
H_2	12,8	16,8	0,847	2,74
He		14,3	1,87	2,19
CH_4	2,06	3,04	1,03	4,18
Ne	4,52	4,60	3,12	2,54
CO		2,30	1,66	3,78
N_2	1,78	2,37	1,67	3,77
O_2	1,81	2,42	1,91	3,64
Ilma		2,41	1,71	3,76
Ar	1,57	1,63	2,09	3,68
CO_2	0,97	1,46	1,38	4,64
Cl_2		0,77	1,24	5,52

Unit	**Pa**
bar	10^5
Torr = mmHg	133.3
atm	1.013×10^5
psi	6.89×10^3

$$\langle E_{tr} \rangle = \tfrac{3}{2} \cdot k \cdot T$$

$$U_{tr} = \frac{3}{2} NkT = \frac{3}{2} nRT$$

$$\langle v \rangle = \left(\frac{8kT}{\pi m} \right)^{1/2}$$

$$v_{prob} = \left(\frac{2kT}{m} \right)^{1/2}$$

$$\Phi = \rho_N \cdot \left(\frac{kT}{2\pi m} \right)^{1/2}$$

$$\Phi = \frac{1}{4} \cdot \rho_N \cdot \langle v \rangle$$

$$\Phi = \frac{P}{(2\pi mkT)^{1/2}}$$

$$\tau_m = \frac{1}{\xi^2 \Phi}$$

$$\langle \lambda \rangle = \frac{1}{\pi \sqrt{2} \cdot \rho_N \cdot \zeta^2}$$

$$\tau = \frac{\langle \lambda \rangle}{\langle v \rangle}$$

$$f = \frac{1}{\tau} = \frac{\langle v \rangle}{\langle \lambda \rangle}$$

$$D = \frac{1}{3} \cdot \langle v \rangle \cdot \langle \lambda \rangle$$

$$K = \frac{1}{2} \cdot \rho_N \cdot k \cdot \langle v \rangle \cdot \langle \lambda \rangle$$

$$\eta = \frac{1}{3} \cdot \rho_N \cdot \langle m \rangle \cdot \langle v \rangle \cdot \langle \lambda \rangle$$

$$C = \frac{\pi}{8} \cdot d^2 \cdot \langle w \rangle \cdot \frac{P_1 + P_2}{P_1 - P_2}$$

Conductance in compressible flow

$$C = \frac{\pi \cdot d^4}{256 \cdot \eta \cdot L} \cdot (P_1 + P_2)$$

Conductance in laminar flow

$$C = \frac{1}{6} \cdot \left(\frac{2 \cdot \pi \cdot k \cdot T}{m} \right)^{1/2} \cdot \frac{d^3}{L}$$

Conductance in molecular flow

$$C = \frac{\pi \cdot d^4}{128 \cdot \eta \cdot L} \cdot \langle P \rangle + \frac{1}{6} \cdot \left(\frac{2 \cdot \pi \cdot k \cdot T}{m} \right)^{1/2} \cdot \frac{d^3}{L} \cdot \frac{\left[1 + (m/k \cdot T)^{1/2} \cdot d \cdot \langle P \rangle / \eta \right]}{\left[1 + 1.24 \cdot (m/k \cdot T)^{1/2} \cdot d \cdot \langle P \rangle / \eta \right]}$$

1. PHYSICAL CONSTANTS

Table 1.1. Reviewed 2005 by P.J. Mohr and B.N. Taylor (NIST). Based mainly on the "CODATA Recommended Values of the Fundamental Physical Constants: 2002" by P.J. Mohr and B.N. Taylor, Rev. Mod. Phys. 77, 1 (2005). The last group of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the corresponding fractional uncertainties in parts per 10^9 (ppb) are given in the last column. This set of constants (aside from the last group) is recommended for international use by CODATA (the Committee on Data for Science and Technology). The full 2002 CODATA set of constants may be found at `http://physics.nist.gov/constants`

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	$299\,792\,458$ m s^{-1}	exact*
Planck constant	h	$6.626\,0693(11)\times10^{-34}$ J s	170
Planck constant, reduced	$\hbar \equiv h/2\pi$	$1.054\,571\,68(18)\times10^{-34}$ J s	170
		$= 6.582\,119\,15(56)\times10^{-22}$ MeV s	85
electron charge magnitude	e	$1.602\,176\,53(14)\times10^{-19}$ C $= 4.803\,204\,41(41)\times10^{-10}$ esu	85, 85
conversion constant	$\hbar c$	$197.326\,968(17)$ MeV fm	85
conversion constant	$(\hbar c)^2$	$0.389\,379\,323(67)$ GeV^2 mbarn	170
electron mass	m_e	$0.510\,998\,918(44)$ MeV$/c^2 = 9.109\,3826(16)\times10^{-31}$ kg	86, 170
proton mass	m_p	$938.272\,029(80)$ MeV$/c^2 = 1.672\,621\,71(29)\times10^{-27}$ kg	86, 170
		$= 1.007\,276\,466\,88(13)$ u $= 1836.152\,672\,61(85)\ m_e$	0.13, 0.46
deuteron mass	m_d	$1875.612\,82(16)$ MeV$/c^2$	86
unified atomic mass unit (u)	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	$931.494\,043(80)$ MeV$/c^2 = 1.660\,538\,86(28)\times10^{-27}$ kg	86, 170
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	$8.854\,187\,817\ldots\times10^{-12}$ F m^{-1}	exact
permeability of free space	μ_0	$4\pi\times10^{-7}$ N A^{-2} $= 12.566\,370\,614\ldots\times10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	$7.297\,352\,568(24)\times10^{-3} = 1/137.035\,999\,11(46)^\dagger$	3.3, 3.3
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,325(28)\times10^{-15}$ m	10
(e^- Compton wavelength)/2π	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$	$3.861\,592\,678(26)\times10^{-13}$ m	6.7
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	$0.529\,177\,2108(18)\times10^{-10}$ m	3.3
wavelength of 1 eV/c particle	$hc/(1\text{ eV})$	$1.239\,841\,91(11)\times10^{-6}$ m	85
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	$13.605\,6923(12)$ eV	85
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	$0.665\,245\,873(13)$ barn	20
Bohr magneton	$\mu_B = e\hbar/2m_e$	$5.788\,381\,804(39)\times10^{-11}$ MeV T^{-1}	6.7
nuclear magneton	$\mu_N = e\hbar/2m_p$	$3.152\,451\,259(21)\times10^{-14}$ MeV T^{-1}	6.7
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	$1.758\,820\,12(15)\times10^{11}$ rad s^{-1} T^{-1}	86
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	$9.578\,833\,76(82)\times10^{7}$ rad s^{-1} T^{-1}	86
gravitational constant‡	G_N	$6.6742(10)\times10^{-11}$ m^3 kg^{-1} s^{-2}	1.5×10^5
		$= 6.7087(10)\times10^{-39}\ \hbar c\ (\text{GeV}/c^2)^{-2}$	1.5×10^5
standard gravitational accel.	g_n	$9.806\,65$ m s^{-2}	exact
Avogadro constant	N_A	$6.022\,1415(10)\times10^{23}$ mol^{-1}	170
Boltzmann constant	k	$1.380\,6505(24)\times10^{-23}$ J K^{-1}	1800
		$= 8.617\,343(15)\times10^{-5}$ eV K^{-1}	1800
molar volume, ideal gas at STP	$N_A k(273.15\text{ K})/(101\,325\text{ Pa})$	$22.413\,996(39)\times10^{-3}$ m^3 mol^{-1}	1700
Wien displacement law constant	$b = \lambda_{\max} T$	$2.897\,7685(51)\times10^{-3}$ m K	1700
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	$5.670\,400(40)\times10^{-8}$ W m^{-2} K^{-4}	7000
Fermi coupling constant**	$G_F/(\hbar c)^3$	$1.166\,37(1)\times10^{-5}$ GeV^{-2}	9000
weak-mixing angle	$\sin^2\hat\theta(M_Z)\ (\overline{\text{MS}})$	$0.23122(15)^{\dagger\dagger}$	6.5×10^5
$W^\pm$ boson mass	m_W	$80.403(29)$ GeV$/c^2$	3.6×10^5
Z^0 boson mass	m_Z	$91.1876(21)$ GeV$/c^2$	2.3×10^4
strong coupling constant	$\alpha_s(m_Z)$	$0.1176(20)$	1.7×10^7

$\pi = 3.141\,592\,653\,589\,793\,238$ $\qquad$ $e = 2.718\,281\,828\,459\,045\,235$ $\qquad$ $\gamma = 0.577\,215\,664\,901\,532\,861$

1 in $\equiv$ 0.0254 m	1 G $\equiv 10^{-4}$ T	1 eV $= 1.602\ 176\ 53(14)\times10^{-19}$ J	kT at 300 K $= [38.681\ 684(68)]^{-1}$ eV
1 Å $\equiv$ 0.1 nm	1 dyne $\equiv 10^{-5}$ N	1 eV$/c^2 = 1.782\ 661\ 81(15)\times10^{-36}$ kg	0 °C $\equiv$ 273.15 K
1 barn $\equiv 10^{-28}$ m^2	1 erg $\equiv 10^{-7}$ J	$2.997\ 924\ 58\times10^9$ esu = 1 C	1 atmosphere $\equiv$ 760 Torr $\equiv$ 101 325 Pa

* The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.

† At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is $\sim 1/128$.

‡ Absolute lab measurements of G_N have been made only on scales of about 1 cm to 1 m.

** See the discussion in Sec. 10, "Electroweak model and constraints on new physics."

†† The corresponding $\sin^2\theta$ for the effective angle is 0.23152(14).

4. PERIODIC TABLE OF THE ELEMENTS

Table 4.1. Revised 2005 by C.G. Wohl (LBNL) and D.E. Groom (LBNL). Adapted from the Commission on Atomic Weights and Isotopic Abundances, "Atomic Weights of the Elements 1999," Pure and Applied Chemistry 73, 667 (2001), and G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. A729, 337 (2003). The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundances in the Earth's surface. Atomic masses are relative to the mass of ^{12}C, defined to be exactly 12 unified atomic mass units (u) (approx. g/mole). Relative isotopic abundances often vary considerably, both in natural and commercial samples; this is reflected in the number of significant figures given. A number in parentheses is the atomic mass of the longest-lived known isotope of that element—no stable isotope exists. The exceptions are Th, Pa, and U, which do have characteristic terrestrial compositions. As of early 2006 element 112 has not been assigned a name, and there are no confirmed elements with $Z > 112$.

PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907216)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lantha- nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982430)	85 At Astatine (209.987148)	86 Rn Radon (222.017578)
87 Fr Francium (223.019736)	88 Ra Radium (226.025410)	89–103 Actinides	104 Rf Rutherford (261.10877)	105 Db Dubnium (262.1141)	106 Sg Seaborg. (263.1221)	107 Bh Bohrium (262.1246)	108 Hs Hassium (277.1498)	109 Mt Meitner. (268.1387)	110 Ds Darmstadt. (271.1461)	111 Rg Roentgen. (272.1536)	112 (277.1639)						

Series															
Lanthanide series	57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912749)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide series	89 Ac Actinium (227.027752)	90 Th Thorium 232.038055	91 Pa Protactin. 231.035884	92 U Uranium 238.02891	93 Np Neptunium (237.048173)	94 Pu Plutonium (244.064204)	95 Am Americ. (243.061381)	96 Cm Curium (247.070354)	97 Bk Berkelium (247.070307)	98 Cf Californ. (251.079587)	99 Es Einstein. (252.08298)	100 Fm Fermium (257.095105)	101 Md Mendelev. (258.098431)	102 No Nobelium (259.1010)	103 Lr Lawrenc. (262.1096)