Absorption of radiation by a gas

A cylindrical vessel, with its axis vertical, contains a molecular gas at thermodynamic equilibrium. The upper base of the cylinder can be displaced freely and is made out of a glass plate; let's assume that there is no gas leakage and that the friction between glass plate and cylinder walls is just sufficient to damp oscillations but doesn't involve any significant loss of energy with respect to the other energies involved. Initially the gas temperature is equal to that of the surrounding environment. The gas can be considered as perfect within a good approximation. Let's assume that the cylinder walls (including the bases) have a very low thermal conductivity and capacity, and therefore the heat transfer between gas and environment is very slow, and can be neglected in the solution of this problem.

Through the glass plate we send into the cylinder the light emitted by a constant power laser; this radiation is easily transmitted by air and glass but is completely absorbed by the gas inside the vessel. By absorbing this radiation the molecules reach excited states, where they quickly emit infrared radiation returning in steps to the molecular ground state; this infrared radiation, however, is further absorbed by other molecules and is reflected by the vessel walls, including the glass plate. The energy absorbed from the laser is therefore transferred in a very short time into thermal movement (molecular chaos) and thereafter stays in the gas for a sufficiently long time.

We observe that the glass plate moves upwards; after a certain irradiation time we switch the laser off and we measure this displacement.

1. Using the data below and - if necessary - those on the sheet with physical constants, compute the temperature and the pressure of the gas after the irradiation. *[2 points]*

2. Compute the mechanical work carried out by the gas as a consequence of the radiation absorption. *[1 point]*

3. Compute the radiant energy absorbed during the irradiation. *[2 points]*

4. Compute the power emitted by the laser that is absorbed by the gas, and the corresponding number of photons (and thus of elementary absorption processes) per unit time. *[1.5 points]*

5. Compute the efficiency of the conversion process of optical energy into a change of mechanical potential energy of the glass plate. *[1 point]*

Thereafter the cylinder axis is slowly rotated by 90°, bringing it into a horizontal direction. The heat exchanges between gas and vessel can still be neglected.

6. State whether the pressure and/or the temperature of the gas change as a consequence of such a rotation, and - if that is the case – what is its/their new value. *[2.5 points]*

Data

Room pressure: $p_0 = 101.3\,\mathrm{kPa}$
Room temperature: $T_0 = 20.0°\mathrm{C}$
Inner diameter of the cylinder: $2r = 100\,\mathrm{mm}$
Mass of the glass plate: $m = 800\,\mathrm{g}$
Quantity of gas within the vessel: $n = 0.100\,\mathrm{mol}$
Molar specific heat at constant volume of the gas: $c_\mathrm{V} = 20.8\,\mathrm{J/(mol \cdot K)}$
Emission wavelength of the laser: $\lambda = 514\,\mathrm{nm}$
Irradiation time: $\Delta t = 10.0\,\mathrm{s}$
Displacement of the movable plate after irradiation: $\Delta s = 30.0\,\mathrm{mm}$

Physical constants and general data

In addition to the numerical data given within the text of the individual problems, the

knowledge of some general data and physical constants may be useful, and you may find them among the following ones. These are nearly the most accurate data currently available, and they have thus a large number of digits; you are expected, however, to write your results with a number of digits that must be appropriate for each problem.

Speed of light in vacuum: $c = 299792458\,\mathrm{m \cdot s^{-1}}$
Magnetic permeability of vacuum: $\mu_0 = 4\pi \cdot 10^{-7}\,\mathrm{H \cdot m^{-1}}$
Dielectric constant of vacuum: $\varepsilon_0 = 8.8541878\,\mathrm{pF \cdot m^{-1}}$
Gravitational constant: $G = 6.67259 \cdot 10^{-11}\,\mathrm{m^3/(kg \cdot s^2)}$
Gas constant: $R = 8.314510\,\mathrm{J/(mol \cdot K)}$
Boltzmann's constant: $k = 1.380658 \cdot 10^{-23}\,\mathrm{J \cdot K^{-1}}$
Stefan's constant: $\sigma = 56.703\,\mathrm{nW/(m^2 \cdot K^4)}$
Proton charge: $e = 1.60217733 \cdot 10^{-19}\,\mathrm{C}$
Electron mass: $m_\mathrm{e} = 9.1093897 \cdot 10^{-31}\,\mathrm{kg}$
Planck's constant: $h = 6.6260755 \cdot 10^{-34}\,\mathrm{J \cdot s}$
Base of centigrade scale: $T_\mathrm{K} = 273.15\,\mathrm{K}$
Sun mass: $M_\mathrm{S} = 1.991 \cdot 10^{30}\,\mathrm{kg}$
Earth mass: $M_\mathrm{E} = 5.979 \cdot 10^{24}\,\mathrm{kg}$
Mean radius of Earth: $r_\mathrm{E} = 6.373\,\mathrm{Mm}$
Major semiaxis of Earth orbit: $R_\mathrm{E} = 1.4957 \cdot 10^{11}\,\mathrm{m}$
Sidereal day: $d_\mathrm{S} = 86.16406\,\mathrm{ks}$
Year: $y = 31.558150\,\mathrm{Ms}$
Standard value of the gravitational field at the Earth surface: $g = 9.80665\,\mathrm{m \cdot s^{-2}}$
Standard value of the atmospheric pressure at sea level: $p_0 = 101325\,\mathrm{Pa}$
Refractive index of air for visibile light, at standard pressure and 15 °C: $n_\mathrm{air} = 1.000277$
Solar constant: $S = 1355\,\mathrm{W \cdot m^{-2}}$
Jupiter mass: $M = 1.901 \cdot 10^{27}\,\mathrm{kg}$
Equatorial Jupiter radius: $R_\mathrm{B} = 69.8\,\mathrm{Mm}$
Average radius of Jupiter's orbit: $R = 7.783 \cdot 10^{11}\,\mathrm{m}$
Jovian day: $d_\mathrm{J} = 35.6\,\mathrm{ks}$
Jovian year: $y_\mathrm{J} = 374.32\,\mathrm{Ms}$
π: 3.14159265