30th International Physics Olympiad

Padua, Italy

Theoretical competition

Thursday, July 22nd, 1999

Please read this first:

1. The time available is 5 hours for 3 problems.
2. Use only the pen provided.
3. Use only the **front side** of the provided sheets.
4. In addition to the problem texts, that contain the specific data for each problem, a sheet is provided containing a number of general physical constants that may be useful for the problem solutions.
5. Each problem should be answered on separate sheets.
6. In addition to "blank" sheets where you may write freely, for each problem there is an *Answer sheet* where you **must** summarize the results you have obtained. Numerical results must be written with as many digits as appropriate to the given data; don't forget the units.
7. Please write on the "blank" sheets whatever you deem important for the solution of the problem, that you wish to be evaluated during the marking process. However, you should use mainly equations, numbers, symbols, figures, and use *as little text as possible*.
8. **It's absolutely imperative** that you write on top of *each* sheet that you'll use: your name ("**NAME**"), your country ("**TEAM**"), your student code (as shown on the identification tag, "**CODE**"), and additionally on the "blank" sheets: the problem number ("**Problem**"), the progressive number of each sheet (from 1 to *N*, "**Page n.**") and the total number (*N*) of "blank" sheets that you use and wish to be evaluated for that problem ("**Page total**"). It is also useful to write the section you are answering at the beginning of each such section. If you use some sheets for notes that you don't wish to be evaluated by the marking team, just put a large cross through the whole sheet, and don't number it.
9. When you've finished, turn in all sheets in proper order (for each problem: answer sheet first, then used sheets in order; unused sheets and problem text at the bottom) and put them all inside the envelope where you found them; then leave everything on your desk. You are not allowed to take **any** sheets out of the room.

This set of problems consists of 13 pages (including this one, the answer sheets and the page with the physical constants)

These problems have been prepared by the Scientific Committee of the 30th IPhO, including professors at the Universities of Bologna, Naples, Turin and Trieste.

Problem 1

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 kPa
Room temperature: T_0 = 20.0°C
Inner diameter of the cylinder: 2*r* = 100 mm
Mass of the glass plate: *m* = 800 g
Quantity of gas within the vessel: *n* = 0.100 mol
Molar specific heat at constant volume of the gas: c_V = 20.8 J/(mol·K)
Emission wavelength of the laser: λ = 514 nm
Irradiation time: Δt = 10.0 s
Displacement of the movable plate after irradiation: Δ*s* = 30.0 mm

NAME________________________

TEAM________________________

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Answer sheet

In this problem you are requested to give your results both as analytical expressions and with numerical data and units: write expressions first and then data (e.g. $A=bc=1.23\ \mathrm{m}^2$).

1. Gas temperature after the irradiation ………………………………………………………...

Gas pressure after the irradiation ……………………………………………………………….

2. Mechanical work carried out ……………………………………………………………...

3. Overall optical energy absorbed by the gas …………………………………………………

4. Optical laser power absorbed by the gas ……………………………………………………

Absorption rate of photons (number of absorbed photons per unit time) …………………...

5. Efficiency in the conversion of optical energy into change of mechanical potential energy of the glass plate ……………………………………………………………….

6. Owing to the cylinder rotation, is there a pressure change? YES ☐ NO ☐

If yes, what is its new value? ………………………………………………………

Owing to the cylinder rotation, is there a temperature change? YES ☐ NO ☐

If yes, what is its new value? ………………………………………………………

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: $c = 299792458\ \text{m}\cdot\text{s}^{-1}$
Magnetic permeability of vacuum: $\mu_0 = 4\pi\cdot10^{-7}\ \text{H}\cdot\text{m}^{-1}$
Dielectric constant of vacuum: $\varepsilon_0 = 8.8541878\ \text{pF}\cdot\text{m}^{-1}$
Gravitational constant: $G = 6.67259\cdot10^{-11}\ \text{m}^3/(\text{kg}\cdot\text{s}^2)$
Gas constant: $R = 8.314510$ J/(mol·K)
Boltzmann's constant: $k = 1.380658\cdot10^{-23}\ \text{J}\cdot\text{K}^{-1}$
Stefan's constant: $\sigma = 56.703\ \text{nW}/(\text{m}^2\cdot\text{K}^4)$
Proton charge: $e = 1.60217733\cdot10^{-19}$ C
Electron mass: $m_e = 9.1093897\cdot10^{-31}$ kg
Planck's constant: $h = 6.6260755\cdot10^{-34}$ J·s
Base of centigrade scale: $T_K = 273.15$ K
Sun mass: $M_S = 1.991\cdot10^{30}$ kg
Earth mass: $M_E = 5.979\cdot10^{24}$ kg
Mean radius of Earth: $r_E = 6.373$ Mm
Major semiaxis of Earth orbit: $R_E = 1.4957\cdot10^{11}$ m
Sidereal day: $d_S = 86.16406$ ks
Year: $y = 31.558150$ Ms
Standard value of the gravitational field at the Earth surface: $g = 9.80665\ \text{m}\cdot\text{s}^{-2}$
Standard value of the atmospheric pressure at sea level: $p_0 = 101325$ Pa
Refractive index of air for visibile light, at standard pressure and 15 °C: $n_{air} = 1.000277$
Solar constant: $S = 1355\ \text{W}\cdot\text{m}^{-2}$
Jupiter mass: $M = 1.901\cdot10^{27}$ kg
Equatorial Jupiter radius: $R_B = 69.8$ Mm
Average radius of Jupiter's orbit: $R = 7.783\cdot10^{11}$ m
Jovian day: $d_J = 35.6$ ks
Jovian year: $y_J = 374.32$ Ms
π: 3.14159265