Methodological Notes

NEW EXPERIMENTS IN MOLECULAR PHYSICS

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WE have set up in our laboratory two new scientific experiments, which we regard as worthy of discussion, since they are more modern than those recommended in the program for higher technical schools.

The first is called "Determination of the Coefficient of Diffusion and the Mean Free Path of Water-vapor Molecules in Air." A diagram of the apparatus is shown in Fig. 1. A drop of water is suspended from a thin wire in the glass bell of a vacuum pump. The vapor released is absorbed in concentrated sulfuric acid placed in cuvette 2. The cuvette and the drop are covered with the bell and a measuring microscope is used to determine the diameter of the drop in successive time intervals. The measured values of R^2 are plotted as functions of τ, and the coefficient of diffusion is determined from the slope of the averaged line drawn through these points:

$$D=\frac{\varrho}{2c_0}\,\frac{-\Delta(R^2)}{\Delta\tau}\,. \qquad (1)$$

Here ρ —density of the liquid, c_0 —equilibrium concentration of water vapor in air, expressed in the same units (g/cm^3). The value of c_0 is taken from the tables of saturated vapor pressure concentration at the temperature of the experiment. In a school laboratory there is no need to take into account the cooling of the evaporating drop and to suspend it from a special thermocouple.

The commercial mercury vacuum gauge supplied with the equipment is replaced by a technical pointer vacuum gauge reading from 0 to 760 mm. After the evaporation of the first drop, the bell is removed, a second drop suspended, the bell replaced, and the air rapidly evacuated to a pressure on the order of $\frac{1}{2}$ atm. The decrease of the radius with time is again measured under these conditions and D calculated from (1). It is sufficient to make the measurements at three pressures, $p_0 \approx 1$, $\frac{1}{2}$, and $\frac{1}{4}$ atm, within the accuracy limits of the pointer vacuum gauge. There is no need to try for lower pressures, since the high evaporation speed makes the visual measurements difficult. In addition, the drop starts to boil when p_0 becomes equal to the saturated vapor pressure at the ambient temperature.

Measurements at three pressures provide a check on the inverse proportionality of the diffusion coefficient to the pressure, which follows from kinetic gas theory, i.e., a check on the constancy of the product

$$Dp_0=\text{const.}$$

In addition, by measuring D and knowing the average molecule velocity $c = (3RT/\mu)^{1/2}$ we can determine from the theoretical relation $D = lc/3$ the mean free path of the vapor molecules in air at different pressures.

The experiment lasts approximately one hour. In view of the difficulty of grinding down the bell every time a new drop is placed in it, we prefer to coat the lower part of the bell with plasticine to avoid leakage.

The second experiment is called "Study of the Pressure Dependence of the Viscosity of a Gas (Air) and Determination of the Mean Free Path of Molecules." The main part of the apparatus is shown in Fig. 2. A series of parallel brass discs approximately 50 mm in diameter are arranged horizontally on a brass post, equally spaced about 2.5 mm apart. A rod passes through central holes of the discs and supports a set of parallel discs, each about 0.2 mm thick. This impeller is suspended on an elastic filament and is adjusted by means of a screw so that the moving plates are exactly halfway between the stationary ones. On the lower end of the rod are fastened

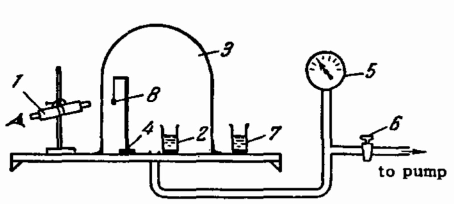

FIG. 1. Setup for measuring the coefficient of diffusion of water vapor in air. 1 – Reading microscope; 2 – cuvette with concentrated H_2SO_4; 3 – glass bell; 4 – support with suspension for drop; 5 – pointer vacuum gauge; 6 – petcock; 7 – water beaker and glass rod; 8 – suspended drop.

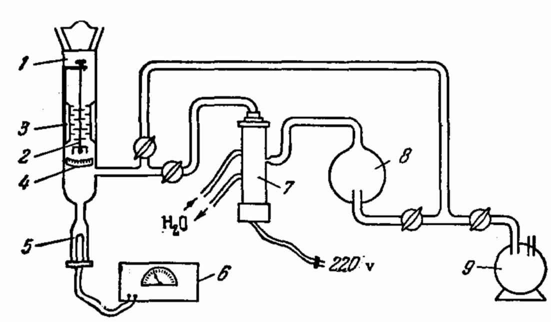

FIG. 2. Setup for measuring the pressure dependence of the viscosity of air. 1 – Glass cylinder; 2 – impeller with moving plates; 3 – stationary plates; 4 – scale; 5 – measuring bulb, type LT-2; 6 – thermocouple vacuum meter, VT-2; 7 – oil-vapor pump, MM-40; 8 – forevacuum bulb; 9 – forevacuum pump.

a weight and a steel pointer to indicate the angle of rotation of the impeller.

The stand with the impeller is introduced through a ground joint inside an evacuated cylindrical bulb and secured there. The bulb is connected to a system comprising a rotary forevacuum pump and a type MM-40 metallic oil-vapor high-vacuum pump. The vacuum in the bulb is measured with the LT-2 tube of the VT-2 thermocouple vacuum meter, which has two measurement ranges, 1—0.1 mm and 10^{-1}—10^{-3} mm Hg.

The impeller is turned about 45° by an external magnet and is allowed to execute torsional oscillations with a period τ_0 on the order of 4—5 sec. Air friction causes the oscillations to attenuate gradually, and the experimenter either measures the damping time or counts the number z of oscillations before the amplitude is reduced by ⅓, which is proportional to the damping time. This number remains practically constant from atmospheric pressure down to a vacuum on the order of 1 mm Hg, and amounts to 15—20 complete oscillations.

The qualitative analysis is based on calculating the motion of a plate of thickness δ and density ρ between two stationary planes. The friction on each side is proportional to the air viscosity η and to the velocity gradient, which is equal to the speed of the plate u divided by the gap width h between the moving and stationary plates. The equation of motion of the plate is

$$\frac{du}{dt} = -\frac{2\eta}{\varrho\delta h}u. \tag{2}$$

The quantity

$$\tau = \frac{\varrho\delta h}{2\eta} \tag{3}$$

is the time during which the plate covers approximately ⅔ of its total path before stopping. By analogy we can generalize this relationship, without detailed calculation, to include the rotational oscillations of the impeller

$$z\tau_0 \approx \frac{\varrho\delta h}{2\eta}. \tag{4}$$

Consequently, the air viscosity η is inversely proportional to the number of oscillations z executed before the amplitude has decreased by about ⅓:

$$\eta \sim \frac{1}{z}. \tag{5}$$

The air is evacuated from the bulb to different pressures p; z is measured, and 1/z plotted as a function of p. According to the molecular-kinetic theory, the viscosity of the gas is independent of the pressure and $1/z = \text{const} = 1/z_0$ at pressures for which the mean free path l is small compared with the gap width h. In the pressure interval 0.1—0.01 mm Hg, l becomes comparable with h and 1/c starts decreasing. When $l \ll h$ we have

$$\eta \sim \frac{1}{z} \sim p. \tag{6}$$

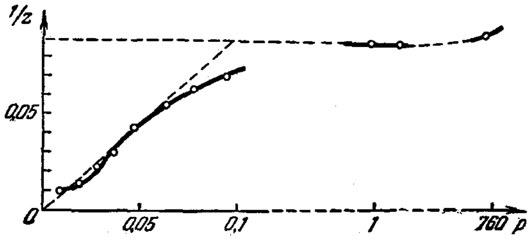

FIG. 3. Approximate plot of experimental data.

Figure 3 shows the experimental curve $1/z = f(p)$. Continuation of the tangent to the curve until it crosses the horizontal line $1/z_0$ yields the value of the pressure p_b at which $l = h$. This yields the mean free path at atmospheric pressure p_0:

$$l_0 = h\frac{p_b}{p_0}. \tag{7}$$

If the peripheral speed u of the moving disc is high, account must be taken of possible turbulence of the air flow in the gap. Since the Reynolds number which determines the turbulence,

$$\mathrm{Re} = \frac{uh\varrho_g}{\eta} \tag{8}$$

is directly proportional to the gas density ρ_g, the damping of the oscillations may become stronger at pressures close to atmospheric. It is therefore best to choose for z_0 the value of z measured at pressures on the order of 1 mm Hg. On the other hand, at very low pressures z may no longer be inversely proportional to p [see Eq. (6)]. When the friction against the air becomes very small, the damping is determined primarily by irreversible losses of mechanical energy within the suspension filament.

These two circumstances bring about the deviations between the experimental points and the limiting analytical relationships, shown in Fig. 3.

The measurements last somewhat more than one hour. The results of the measurements demonstrate the validity of the molecular-kinetic theory equations relating the internal friction of a gas and the pressure, and make it possible to estimate the mean free path.

The use of modern methods for producing and measuring vacuum (metallic oil-vapor pump, thermocouple vacuum meter) dispense with the use of mercury vapor in the laboratory.

Translated by J. G. Adashko