First name .... Date ....

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Exercise 364

Determination of the dependence of the refractive index on the concentration of a solution using an Abbe refractometer

Solution	Concentration, c [g/cm^3]	Coefficient refractive index, n_i	Average co. of refraction, n	Limit angle [in degrees]
distilled water	0			
1	0,050			
2	0,100			
3	0,150			
4	0,200			
5	0,250			
6	0,300			
7	c_x =			

Exercise 364. Determination of the dependence of the refractive index on the concentration of a solution using an Abbe refractometer

Light reflection and refraction

When describing the interaction of light with macroscopic objects, in many cases it is possible to use an approximation that ignores the corpuscular-wave nature of light. We then use the concept of a light ray, by which we mean a very narrow beam of light, the axis of which determines the direction of propagation of light energy. The course of light rays in a transparent medium can be determined by relying on the basic assumption of geometrical optics, that light in a homogeneous and isotropic medium propagates along straight lines, and that intersecting light beams do not interact. This assumption ignores the possibility of deflection or interference of light.

The behavior of light rays at the boundary of two media is described by the laws of reflection and refraction. These laws, initially formulated as experimental laws, can also be justified theoretically using the wave or corpuscular theory of light. When a beam of light hits another medium on its way, at the boundary surface part of the radiation is reflected, scattered or absorbed, and the rest passes on undergoing refraction. The transition of light from medium 1 to 2 is shown in Fig.1.

The laws of reflection and refraction are as follows:

1. The incident, reflected and refracted rays and the normal to the boundary surface lie in one plane.
2. The angle of incidence is equal to the angle of reflection : α_1':

$$\alpha_1 = \alpha_1'.$$

3. The ratio of the sine of the angle of incidence α_1 to the sine of the angle of refraction α_2 is a constant quantity $\frac{\sin\alpha_1}{\sin\alpha_2} = n_{2,1}$, (1)

where $n_{2,1}$ is the refractive index of medium 2, into which the ray enters, relative to medium 1, from which it exits.

It can be shown that the refractive index depends on the speed of light in both centers:

$$n_{2,1} = v_1/v_2 , \qquad (2)$$

- v_1 — velocity of light in the medium **1**, v_2 — velocity of light in the medium **2**.
- The refractive index of a medium relative to a vacuum is called the absolute refractive index *n*,

$$n = c/v , \qquad (3)$$

c — speed of light in a vacuum, *v* — in a given medium. The absolute refractive index of a medium differs very little from that of air due to the fact that the speed of light in air v_p is approximately equal to the speed of light in a vacuum *c*. In practice, we use the refractive index of a given medium relative to air. It depends on the color of the light, and therefore on its wavelength. Transforming formula (2), we get

$$n_{2,1} = \frac{v_1}{v_2} = \frac{c/v_2}{c/v_1} = \frac{n_2}{n_1} , \qquad (4)$$

From where it follows that the relative refractive index of two adjacent media is equal to the ratio of the absolute refractive indices of these media. A simple way to determine the refractive index of a medium is based on the use of the phenomenon of *total internal reflection*.

Total internal reflection

It occurs when a light ray runs from an optically denser medium 2 to a sparser medium 1 (i.e., from a medium in which the speed of light is lower to a medium in which the speed of light is higher) at an angle greater than the so-called limiting angle, Figure 2. Light passing from medium 2 to medium 1 undergoes refraction from the normal, that is, the angle of refraction is greater than the angle of incidence. In this case, therefore, there must be such a limiting angle of incidence α_g, at which the angle of refraction equals $\pi/2$ and then the refracted ray runs parallel to the boundary of the two media. At the angle of incidence $\alpha > \alpha_g$, the refracted ray is not observed at all. This phenomenon is called total internal reflection, since the total energy of the incident ray is contained in the reflected ray. From the law of refraction, it follows that in the case of the passage of light from medium 2 to 1, we can write

$$\frac{\sin\alpha_2}{\sin\alpha_1} = n_{1,2} = \frac{n_1}{n_2} = \frac{1}{n_{2,1}} \qquad (5)$$

Value of the limit angle $\alpha_2 = \alpha_g$ is determined by the condition that the angle of refraction of the α_1 in the medium **1** was equal to 90° and from (5) and we get:

$$n_{2,1} = 1/\sin\alpha_g \ . \qquad (6)$$

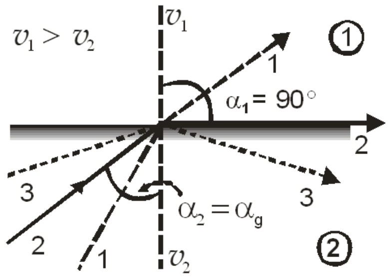


Fig. 2 Total internal reflection of light

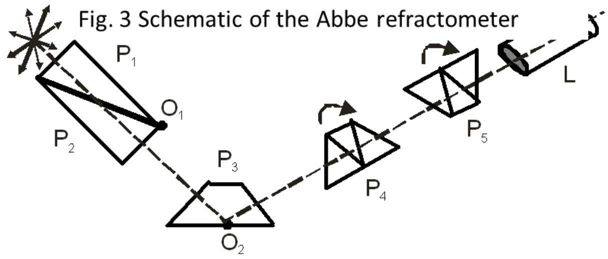
By measuring the limiting angle of incidence in an optically denser medium 2, we can determine its refractive index from equation (6) $n_{2,1}$ relative to the medium 1 optically rarer. In addition, if we know the absolute refractive index of one medium, from relation (4) we can determine the absolute refractive index of the other medium.

Measurement of the limiting angle to determine the refractive index has been used in *refractometers*. They are primarily used to measure the refractive index of liquids.

Performance of the task

The purpose of this exercise is to measure the dependence of the refractive index on the concentration of solutions. Aqueous solutions of either sodium chloride or glycerin are used for the test. The refractive index of the liquid is determined using an Abbe refractometer.

Principle of operation of Abbe refractometer



A simplified schematic of the construction of an Abbe refractometer is shown in Figure 3. The essential part of an Abbe refractometer is two rectangular prisms - illuminated P1 and measuring P2, made of glass with a high refractive index (flint glass). Prism P1 can rotate around the O1 axis. Between these prisms we introduce a few drops of the liquid under test, the refractive index of which should be less than the refractive index of the glass of the prisms. The liquid forms a thin, flat-parallel layer between the counter-angled surfaces of the prisms. Diffuse white light is used to illuminate the P1 prism. It falls at different angles on the boundary surface between prism P1 and the liquid layer. Only rays that fall at an angle smaller than the boundary angle pass into the liquid. Rays that pass further run through prism P2, experiencing a slight parallel shift in the liquid layer. Prism P3, called the directing prism, changes the direction of the passing rays that reach the telescope L through the Amici prism system P4 and P5.

As a result of the phenomenon of internal reflection on the counter-rectangular surface of prism P1, part of the field of view in the telescope is illuminated and part remains dark. The line of demarcation between the illuminated and unilluminated part can be moved up and down by rotating the prism P3 around the axis O2 - for measurement it is positioned at the intersection of the spider threads of the telescope eyepiece L. Connected to the prism P3 is a scale, on which we read the value of the limiting angle or directly the refractive index of the liquid - this scale is observed in an additional telescope.

In the prisms of the refractometer as well as in the liquid under test, there is the phenomenon of dispersion, that is, the splitting of white light. As a result of this phenomenon, the line of demarcation of the field of view is not sharp, but colored and blurred. In the Abbe refractometer, the splitting is compensated for using two prism systems P4 and P5, made of several individual prisms made of different grades of glass. The breaking angles of the individual prisms are chosen so that the light of the yellow sodium line does not undergo any deviation, while deviations in opposite directions are experienced by the red and violet rays. By relative rotation of the compensator prisms, the coloration of the dividing line can be eliminated.

Measurement activities

1. Unscrew the cap shorting the measuring prisms P1 and P2 of the refractometer. We wash the surfaces of the prisms with distilled water and dry with blotting paper. We introduce a few drops of the test liquid on the matte surface of the lower prism. We close the prisms.
2. We turn on the light source (electric lamp) and use the refractometer mirror to direct the light beam onto both prisms so that it can simultaneously reach the observation telescope L above them.
3. We turn the knob located on the side of the refractometer (on the opposite side to the prisms) until we see the line separating the bright and dark fields.
4. By turning the compensator screw at the telescope L, we remove the coloration of the boundary line.

5. We adjust the eyepiece of the L telescope so that we see a sharp image of the crosshairs of the spider threads and a clear line of demarcation between the light and dark semicircles.
6. We adjust the position of the demarcation line at the intersection of spider threads.
7. We read the absolute refractive index n of the liquid under test on the scale, visible in the additional telescope. The reading should be taken to the nearest 0.0005. We repeat the measurement three times and calculate the average value of n.
8. We calculate the limit angle α_g from dependence: $\sin\alpha_g = 1/n$. This is the limiting angle for light rays passing from liquid to air.
9. Perform the measurement steps described above successively for distilled water and several glycerin solutions - of known concentration and for one solution of unknown concentration c_x. Clean the prism surfaces after each measurement.
10. We draw a graph of the dependence of the refractive index on the concentration of the solution. From the graph, we determine the unknown concentration of c_x solution, which refractive index we measured.

Calculation of the uncertainties

1. We assume that the concentrations of c solutions are given with accuracy Δc = 0,0025 g/cm^3.
2. measurement error Δn is equal to half of the smallest scale pitch of the refractometer (0,0005).
3. we mark the measurement errors around the measurement points on the graph (line, representing the relation $n = \mathrm{f}(c)$ should intersect the drawn rectangles of error).
4. Evaluate the accuracy of determining the concentration of an unknown solution — Δc_x. As Δc_x we take the maximum value of the distance, measured along the horizontal axis, between the measurement points and the graph line $n = \mathrm{f}(c)$.