July 5, 1955 E. INGELSTAM 2,712,265

REFRACTOMETER

Filed Oct. 16, 1951 2 Sheets-Sheet 1

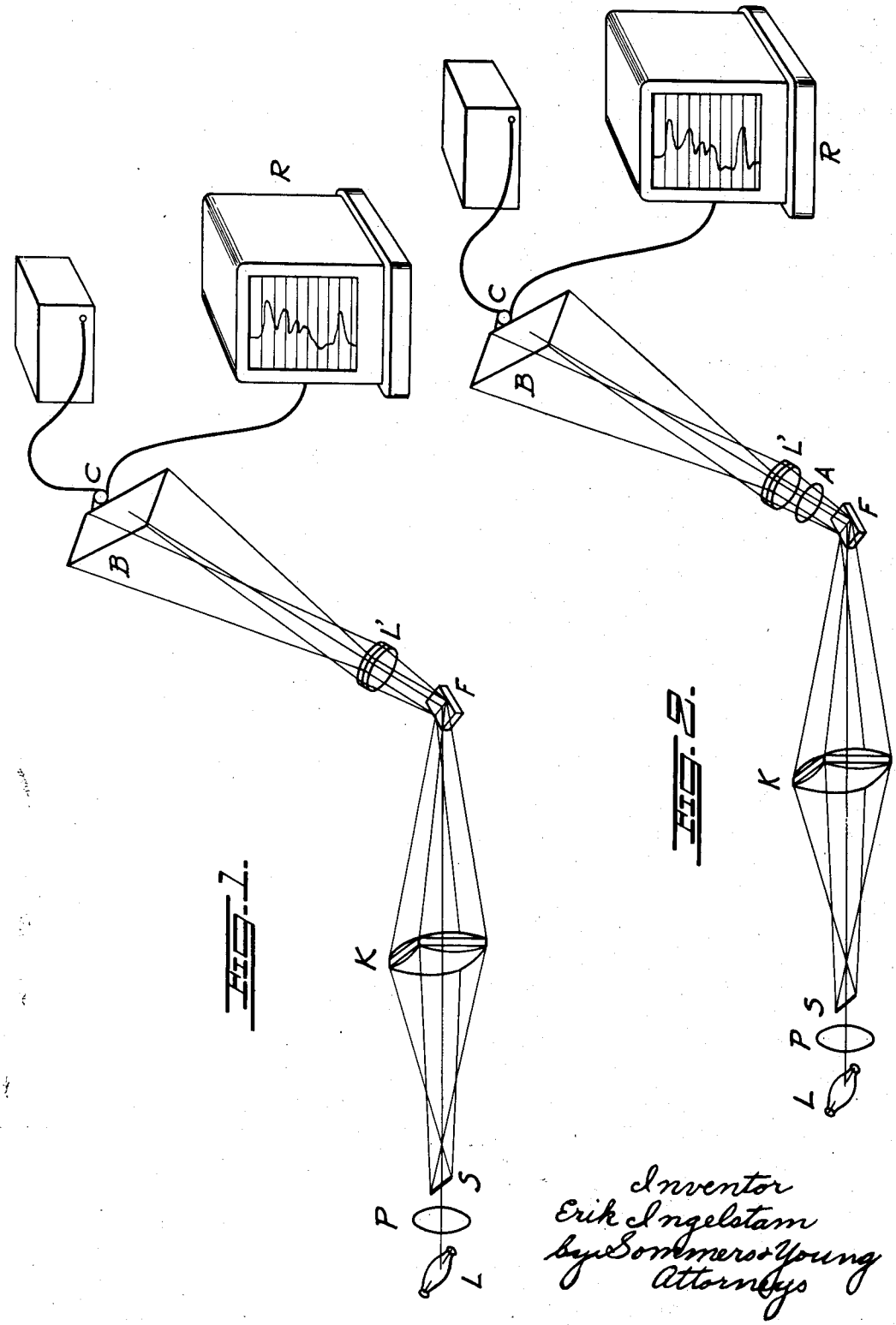


Fig. 1.

Fig. 2.

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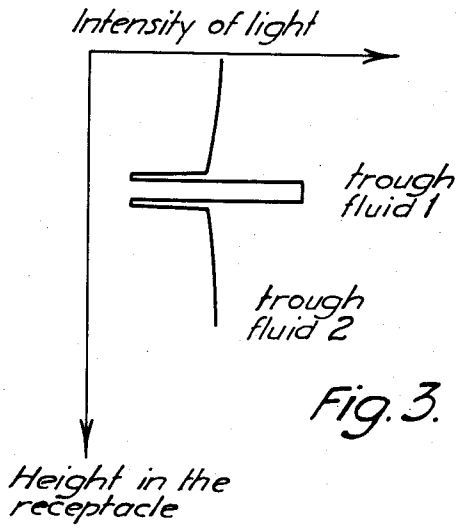


Fig. 3.

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5 Claims. (Cl. 88—14)

This invention relates to refractometers for liquid and gaseous fluids and has for its principal object to provide an improved refractometer capable of measuring refractive indexes with an accuracy hitherto unknown in the art.

The main feature of the invention consists broadly in utilizing the well-known principle of phase contrast in designing such refractometers.

The invention will hereinbelow be described in greater details with reference to the annexed drawing in which Fig. 1 is a perspective view diagrammatically illustrating one form of this invention and Fig. 2 is a similar view showing an alternative embodiment.

Fig. 3 is a diagram showing an illustrative form of an intensity curve, as obtained in accordance with the present invention.

On the drawing L represents a lamp emitting monochromatic light through a slit S onto a receptacle K containing the fluid the refraction of which is to be determined. Preferably two opposite walls of receptacle K consists of two plano-convex lenses the inner plane faces of which form the opposite parallel inner walls of receptacle K. Although a receptacle thus constructed is to be preferred in practising this invention it is, however, also possible within the scope thereof to use a receptacle and a separate lens system. F is a phase shifting element, for instance, according to Françon-Nomarski, Comptes rendus des Académie de Sciences, Paris, 230, pages 1392, 1950 or Ingelstam, Arkiv för fysik 3, No. 2, 1951, consisting of a plate-shaped, obliquely oriented glass body having its top side carefully flat polished. The top side comprises, in addition, a split-shaped zone corresponding to the image of slit S and the diffraction image of the entire receptacle K, this zone consisting of a very thin metal coating, for example, of aluminum as described below in accordance with the previously known construction according to Ingelstam. The shift in phase between the central fringe light, which is the image of the slit, and the light diffracted from details of the receptacle is caused by their different paths when reflected at the two parallel surface levels of the top side. The Brewsterian angle is a suitable angle of reflection as evidently the intensity reflected against glass can be varied and reduced nearly to zero by polarizing plates.

The slit-shaped zone can also be carried out according to Françon-Nomarski so that the entire top surface of the glass body is coated with the metal of the desired thickness except said slit-formed zone. After being reflected by the different parts of said phase shifting element F the light is collected by a lens system L' forming a phase contrast image of the receptacle K in the plane B. Another type of a suitable phase shifter is that mainly consisting of a transparent plate standing perpendicularly on the optical axis and used by the inventor of the principle, Prof. Zernike: F. Zernike, Physica 9, pages 686 and 947 (1942). Furthermore, an extensive discussion of preparing transparent phase shifting plates is given in Bennett, Jupnik, Osterberg, Richards, Phase Microscopy (Wiley & Sons, New York, 1951) pages 87–93. A physical receiver extends or is displaced along said image plane and may consist of a photographic plate or of a photo-multiplicator cell C as shown on the drawing, said cell being movable at right angles to the slits and associated with a recorder R.

The fluid the refraction of which is to be examined (fluid **1**) relative to another fluid (fluid **2**) is caused to occupy a position intermediate bottom and top layers of fluid **2** and approximately at the middle of the height of receptacle K. A small quantity of fluid **1** may be used having a height of say 1 millimeter. It is, however, also possible to use a different mutual arrangement of fluids **1** and **2** in receptacle K. The boundary regions between fluids **1** and **2** must not take up more than a minor part of the whole receptacle and for this reason receptacle K may be constructed in conformity with principles well known in the arts of electrophorese or diffusion measurements. Alternatively the fluids may be separated from each other by means of thin plates controlled from outside. A thin plate of this kind is described, for instance in F. Kohlrauch, Praktische Physik, Fig. 121, pages 236 and 237. The original descriptions are given in the papers referred to on page 236; Fürth, Physikalische Zeitschrift 26, p. 719 (1925), and Ullman, Zeitschrift für Physik 41, p. 301 (1927). The thin plate (or, in relation to the present invention, rather two thin plates) can be moved from outside either by hand or by means of an electromagnetic device. At the beginning of the examination of a diffusion process between two liquids which were separated from one another by these plates, these are withdrawn, thus leaving the two liquids in contact with one another, a sharp boundary being formed between them.

On the phase contrast image at B fluid **1** is sharply outlined against fluid **2** as shown in Fig. 3, due to different intensity of light which then may be measured in different ways.

By means of a refractometer thus constructed it is possible to measure the difference between refractive indexes and possibly also the gradient of such refractive indexes, more accurately than by means of any method hitherto known including the interferometric methods. Besides it is possible to vary the sensitivity regions for the purpose of measuring greater differences.

If polarized light is used the phase shifting element F preferably consists of the glass plate shown in the above mentioned references with the slit-shaped metal coating or with the metal coating except for a slit-shaped free glass zone, the light being reflected under the Brewster's angle i_B. In this case the system comprises a polarizing plate P as shown in Fig. 1. The utilization of this method in this invention consists of the phase shift by means of this plate, the zones dividing all of the diffraction figures, as it should be for applying the phase contrast method. This is effected by the path difference of the light reflected from the different levels of the central slit-shaped zone and the peripheral zones. In either of the cases where the central zone is aluminum and the peripheral zones glass as shown in the reference to Ingelstam or where the contrary is, as shown in the reference to Françon-Nomarski, the height e of the aluminum gives rise to a difference in optical path between the reflected parts of the absolute value $|\Delta|=2e \cos i_B$ with a slight and calculable correction to e on account of the metallic reflection. By means of regulating e it is possible to have the optical path difference $|\Delta|=\eta/4$, or, counted in angular phase shift ($\psi=2\pi\Delta/\tau$), $|\psi|=\pi/2$ moreover wanted. We find that the thickness of the layer should for this case, be $e=\tau/8 \cos i_B$, slightly corrected for the mentioned phase shift difference on account of the metallic reflection. Any other wanted value for $|\Delta|$ and $|\psi|$ may also be found from e and the angle; and the thickness e is measured with the accuracy

wanted (say 15A.) by means of cultiple-*eas* interferences. The phase shift $|\psi|$ or $|\Delta|$ makes that the image of receptacle K formed by means of lens L' appears in phase contrast, i. e. that the phase differences in the light undulations caused by the different optical paths of the rays through the fluids 1 and 2, appear in said image as light intensity differences. On account of said construction of the phase shifting plate, the intensity amount values very quantitatively correspond to the optical path differences in the two fluids according to the theory of phase contrast, and knowing the geometrical thickness of the receptacle it is possible to calculate the unknown refractive index of fluid 1. The intensity differences, or ratios, give the part of the path difference which is a fraction of one wave length with great accuracy.

Dependent on the polarization direction of the light falling onto plate F, the part reflected by the glass is weakened according to the Fresnel formulae, the part reflected against metal, on the other side, only very little, what causes a desired change of the light intensity scale. This quality of the plate F, founded on its property of having different reflection properties (metal and glass, see the above mentioned references) at its both zones is obviously very convenient. The angular position of the polarizer P determines the ratio of light undulation amplitudes of the light reflected from the central slit-shaped zone and the amplitudes of the light reflected from the peripheral zones. This makes it possible to vary the scale of intensity in the phase contrast image, according to the references, and thus the sensitivity of the intensity measurement means.

If, as mentioned hereinbefore, the fluid 1 to be examined, is caused to occupy in the form of a single thin layer a position in the reference fluid 2 intermediate the bottom and top of the receptacle K, the intensity curve recorded at R of Figs. 1 and 2 would consist of a substantially straight line corresponding to fluid 2 interrupted by a flat topped portion corresponding to the fluid 1, said flat topped portion being sharply outlined according to the phase contrast theory. The curve shown on R at the figures gives the more general arrangement of several and partly mixed layers of fluid 1 at about the middle of the height of receptacle K, the fluid 2 also in this case occupying the major part of the field. The flat intensity levels belonging to this fluid extend to the upside and downside continuations of the recording paper corresponding to the entire height of the receptacle K from bottom to top. In either case, one measures the heights of the intensity curves corresponding to fluid 1 and the average intensity curve for medium 2, from which heights the refractive indices are obtained by the simple functions known to a man skilled in the art.

If the fluid 1 is enclosed between thin walls at about halfway height of the receptacle, as hereinbefore assumed, the appearance of the intensity curve of the image plane B is substantially as shown in Fig. 3. The curve shown in the modification previously indicated the two fluids being arranged in another way, the intensity function belonging to the image B has another shape, and also these intensity values are evaluable in refractive indices and their gradients in a quantitative way.

A polarizing plate A as shown in Fig. 2 or another equivalent device for reducing the intensity of light may according to one form of this invention be used for measuring the intensities of light of fluids 1 and 2 at the phase contrast image B direct by means of the eye. When using the polarizing plate A in combination with the polarizing plate P as shown in Fig. 2 it is possible by rotating the plate A to reduce either of said light amounts, the polarization states of which being changed at the reflection, so as to make the intensity of the final image of fluid 1 equal to that of fluid 2 or to a predetermined proportion thereof.

Alternative 1

When the polarizers P and A are adjusted so that the intensities of the two parts of light in the final image are equalized or adjusted to a predetermined ratio of intensity the mutual angular adjustment of the two polarizers P and A are read on the ordinary scales of said polarizers. Said readings are then the measuring data for determination of the refractive index. (In practice these reading scales are conveniently calibrated in advance against known refraction indexes of pure media.)

Alternative 2

This reduction of light amounts is most easily treated in diagrams where the components of light undulations in respect of the incidence plane of the reflection and the orientations (angular positions) of the polarizing plates P and A are outlined, all in conformity with known theories of polarization and reflection and as obvious from the references. This angular position of the two polarizers given by their ordinary scales thus gives the measuring data for determination of the refractive index. (In practice these reading scales are conveniently calibrated in advance against known refraction indices of pure media.) Then the physical receiver comprises such light intensity reducing device which for measuring purposes adjusts the two intensities at the phase contrast image so that they appear equal to the eye.

Special applications of the present phase contrast refractometer are, for instance, study of diffusion and other phenomena appearing in boundary layers but before all measurements of relative refractive indexes with utterly high precision, particularly for determining the concentration of mixtures of H_2O and D_2O. A great advantage is then the relative small quantity necessary for fluid 1.

What I claim is:

1. A refractometer for determining the refractive index of a medium in relation to a reference medium of known refractive index by comparing the intensities in a phase contrast image formed of light passed through said media, comprising in combination, means including a light source and an element having a linear slit for producing monochromatic light in the shape of said slit, an optical imaging element for producing an image of said linear slit, a transparent cell located in the beam of light from said slit so near the imaging element as to be out of focus for receiving the medium to be examined and a reference medium, the boundaries between which being substantially parallel to the light entrance slit, a phase contrast element having a slit-shaped central zone and an adjacent bordering zone, said slit-shaped zone being parallel to said light entrance slit for introducing a shift of the phase of light falling onto said slit-shaped zone with respect to the light falling onto the peripheral zones thereof, the slit shaped zone of this phase contrast element being placed approximately at the geometrical image of said light entrance slit produced by said optical imaging element, another optical imaging element placed in the beam of light beyond the phase contrast element for producing an image of the two media in a common plane and means for measuring the intensities of said image responsive to said two media with the view of comparing them.

2. A refractometer for determining the refractive index of a medium in relation to a reference medium of known refractive index by comparing the intensities in a phase contrast image formed of light passed through said media, comprising in combination, means including a light source and an element having a linear slit for producing monochromatic light in the shape of a said slit, an optical imaging element for producing an image of said linear slit, a transparent cell located in the beam of light from said slit so near the imaging element as to be out of focus for receiving the medium to be examined and a reference medium, the boundaries between which being substantially parallel to the light entrance slit, a phase contrast element having a slit-shaped central zone and bordering peripheral zones, said slit-shaped zone being parallel to said light entrance slit for introducing a shift of the phase

of light falling onto said slit-shaped zone which respect to the light falling onto the peripheral zones thereof, the slit shaped zone of this phase contrast element being placed approximately at the geometrical image of said light entrance slit produced by said optical imaging element, another optical imaging element placed in the beam of light beyond the phase contrast element for producing an image of the two media in a common plane and means for measuring the intensities of said image responsive to said two media with the view of comparing them.

3. In a refractometer as claimed in claim 2 the further feature that the phase contrast element consists of a mirror, the central slit-shaped zone of which being on another level than the bordering peripheral zones and having different reflecting properties than said bordering peripheral zones, and that polarizing means is provided in the beam of light between said light source and said phase contrast element for the purpose varying the sensitivity of the intensity measurement means.

4. A refractometer for determining the refractive index of a medium in relation to a reference medium of known refractive index by comparing the light intensities in a phase contrast image formed of rays passed through said medium, comprising in combination an optical system including a light source, an element having a linear slit illuminated by said source and imaging means for producing an image of said linear slit, said means including two juxtaposed lenses enclosing a cell therebetween, said cell adapted to receive the medium to be examined and a reference medium, the boundaries between which being substantially parallel to said linear slit, a phase contrast element having a slit-shaped central zone and bordering peripheral zones, said slit-shaped zone being parallel to said light entrance slit, for introducing a shift of the phase of light falling onto said slit-shaped zone with respect to the light falling onto the peripheral zones thereof, the slit-shaped zone of this phase contrast element being placed at the geometrical image of said light entrance slit produced by said optical imaging means, another optical imaging element placed in the beam of light beyond the phase contrast element for producing an image of said two media in a common plane and means for measuring the intensities of said image responsive to said two media with the view of comparing them.

5. A refractometer of the class described comprising in combination an optical system including a light source, an element having a linear light entrance slit, an optical imaging element for producing an image of said slit, a cell so near said imaging element as to be out of focus for receiving the medium to be examined and a reference medium the boundaries between which being substantially parallel to said light entrance slit, a phase contrast element having a slit-shaped central zone and bordering peripheral zones, said slit-shaped zone being parallel to said light entrance slit, for introducing a shift of the phase of light falling onto said slit-shaped zone with respect to the light falling onto the peripheral zones thereof, the slit-shaped zone of this phase contrast element being placed at the geometrical image of said light entrance slit produced by said optical imaging means, another optical imaging element placed in the beam of light beyond said phase contrast element for producing an image of the two media in a common plane and graduated control means in said path of light for reducing the light intensity of that part of the last-mentioned image having the highest intensity into equality with the other part of said image for quantitatively determining the relation between said light intensities.

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