

## A Simple Method for the Measurement of Turbidity

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If, during transmission measurements of turbid suspensions with a photoelectric colorimeter, the distance between the sample holder and the photocell is increased, the amount of light received by the photocell decreases. This is due to the fact that the amount of scattered light which strikes the photocell, diminishes with the solid angle within which it is seen from the suspension. Dognon<sup>1, 2</sup> discussed the error caused hereby in colorimetric measurements and possible ways of improving the determinations. Later the same author<sup>3-5</sup> showed that the relative change in apparent absorption of light, when the photocell is moved from the sample holder to a position infinitely distant from it, should be independent of the concentration of the particles. He also discussed at length the possibility of using experimentally obtained values to get information about the size and shape of the particles.

This paper will describe how transmission measurements with different distances between photocell and suspension can give the relation between turbidity and concentration. Any of the commercially available photoelectric colorimeters which has a large compartment for the sample holders can be used without alterations. The influence of the color of the liquid is eliminated and it is not necessary to utilize a standard at each measurement. Correspondence with generally accepted standards for turbidity, such as the silica scale, can be established once and for all as long as the same instrument is used. The method has been in use in our laboratory for routine turbidimetric measurements on viscose for some time and has been found reliable and rapid.

### THEORY

A beam of parallel light enters a suspension in a plane parallel sample holder at right angles. The light is received by a photocell on the other side.

The following notations will be used:

- $I_0$  = intensity of light entering the suspension  
 $I_t$  = intensity of transmitted (undeviated) light  
 $I_s$  = total intensity of scattered light  
 $\alpha I_s$  = fraction of scattered light, striking the photocell  
 $I_a$  = intensity of absorbed light  
 $x$  = distance between suspension and photocell  
 $d$  = length of light path through suspension  
 $T_x$  = intensity of light received by the photocell when the distance from the suspension is  $x$

According to the definitions given above, we have

$$I_0 = I_t + I_s + I_a \quad (1)$$

$$\text{and } T_x = I_t + \alpha I_s \quad (2)$$

where  $\alpha$  is a function of  $x$  and the experimental arrangements, as well as of the form and size of the scattering particles. Reflections at the glass walls of the sample holder are neglected.

It is assumed that Lambert's law is valid, *i.e.*

$$I_t = I_0 e^{-\kappa d} \quad (3)$$

( $\kappa$  = extinction coefficient)

Different cases will be considered.

*First case:* Dilute suspension with a measurable amount of directly transmitted light; no light absorption.

If measurements are made at two different distances  $x_1$  and  $x_2$  ( $x_2 > x_1$ ), we get the formula:

$$\frac{T_{x_2}}{T_{x_1}} = \frac{\alpha_2(1 - e^{-\kappa d}) + e^{-\kappa d}}{\alpha_1(1 - e^{-\kappa d}) + e^{-\kappa d}} \quad (4)$$

As only dilute suspensions are considered, we may substitute  $e^{-\kappa d} = 1 - \kappa d$ . This gives

$$\frac{T_{x_2}}{T_{x_1}} = \frac{1 - \kappa d (1 - \alpha_2)}{1 - \kappa d (1 - \alpha_1)} \quad (5)$$

and as a special case:

$$y = \frac{T_\infty}{T_{x_1}} = \frac{1 - \kappa d}{1 - \kappa d (1 - \alpha_1)} \quad (6)$$

If Beer's law is valid,  $\kappa$  can be substituted by  $kc$  ( $k = \text{constant}$ ,  $c = \text{concentration}$ ). The equations thus obtained are referred to as (5a) and (6a).

Because of the identity  $T_\infty = I_s$ , (1) can also be written

$$\frac{I_s}{I_0} = 1 - y \frac{T_{x_1}}{I_0} \quad (7)$$

As long as (6) or (6a) is valid, we also have

$$I_s/I_0 = \kappa d = kcd = \frac{1 - y}{1 - y(1 - \alpha_1)} \quad (8)$$

By definition also

$$\alpha_1 = \frac{1 - y}{I_0/T_{x_1} - y} \quad (9)$$

By derivation of (6a) an expression is obtained which, when the concentration approaches zero, becomes simply

$$\lim_{c=0} dy/dc = -kda_1 \quad (10)$$

[the corresponding expression derived from (5a) is:  $-kd(\alpha_1 - \alpha_2)$ ]

With the aid of the equations derived, the method can now be discussed in detail. It can be seen from (10) that the sensitivity of the method increases with the difference  $(\alpha_1 - \alpha_2)$ . The difference in distance  $(x_2 - x_1)$  should consequently be as great as possible. It is not possible, however to diminish the distance  $x_1$  between photocell and suspension below a certain value. The photocell can, on the other hand, without difficulty be placed so far from the suspension that the values for  $x_2 = \infty$  (*i. e.*  $\alpha_2 = 0$ ) can be found by extrapolation. The discussion will, for the sake of simplicity, be limited to the case where the photocell is moved from a position as near the suspension as possible, to a position infinitely distant from it.

The value of  $y = T_\infty/T_{x_1}$  is obtained through extrapolation from the experiments, as is described below. The relationship between  $y$  and  $c$ , as seen from (6a), is not linear. It is advantageous to measure  $T_{x_1}/I_0$  at the same time. For that purpose the sample holder is first filled with the liquid medium and then with the suspension. The amount of light lost through reflections in the glass walls of the sample holder is thus compensated for.

Regardless of the validity of the Lambert-Beer law, the two experimentally obtained quantities allow determination of  $\alpha_1$  and  $I_s/I_0$ , *i.e.* the percentage of scattered light. The latter quantity is independent of the experimental arrangements. For very dilute suspensions,  $\alpha_1$  can also be calculated from (10) after a separate determination of  $kd$ . If different suspensions are studied with the same apparatus and the values of  $\alpha_1$  compared, some conclusions as to form and size of scattering particles might be drawn. The possibilities in this respect have been discussed by Dognon in his papers cited above.

*Second case:* Dilute suspension in a light-absorbing medium.

It is assumed that the absorption follows the laws of Lambert and Beer; the intensity of the directly transmitted light is thus:

$$I_t = I_0 e^{-(\kappa + k'c')d} \quad (11)$$

( $k'$  = extinction coefficient and  $c'$  = concentration of light absorbing substance). Formula (4), however, assumes the same form as before, which means that the light absorption is without influence on the turbidity measurement. The result is easily understandable if we think of the sample holder as divided into two compartments; one filled with the light absorbing matter, the other with the scattering substance.

Formulas (5), (6), and (10) remain unchanged. Instead of (7) we get

$$\frac{I_s + I_a}{I_0} = 1 - y \frac{T_{x_1}}{I_0} \quad (12)$$

$I_a/I_0$  is determined separately from a sample of the colored solution without scattering particles. It is then a simple matter to calculate  $I_s/(I_0 - I_a)$ . Likewise

$$\alpha_1 = \frac{1 - y}{I_0/T_{x_1} \left(1 - \frac{I_a}{I_0}\right) - y} \quad (13)$$

*Third case:* Concentrated suspension. The directly transmitted intensity  $I_t$  practically = 0.

In this case the suspension itself acts as source of light for the photocell. Changes in concentration of the scattering particles mean only a change in the intensity of the light source. The ratio  $y$  is therefore independent of the concentration. It is necessary either to dilute the suspension or to use sample holders with a shorter light path.

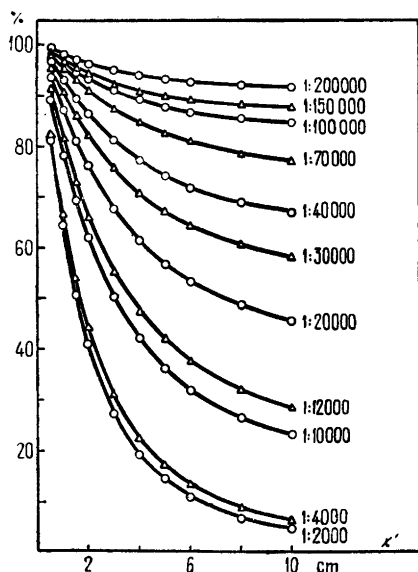


Fig. 1. Measurements on latex. Decrease in illumination of photocell when sample holder is moved away from it.

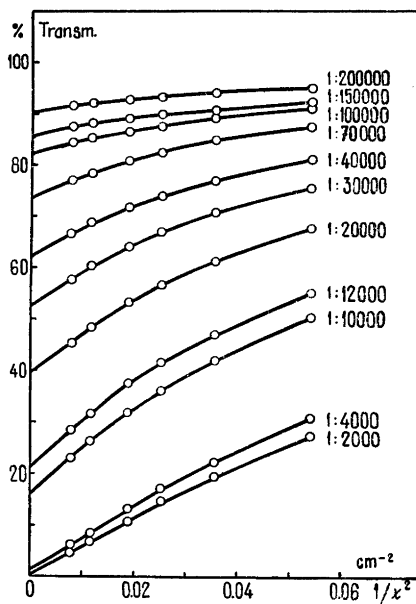


Fig. 2. Measurements on latex. Extrapolation of transmission measurements.

### EXPERIMENTS

The measurements described were all made with a Lumetron Photoelectric Colorimeter, Model 402 E (from Photovolt Corp., New York, USA). No changes were made on the instrument. A special feature of this colorimeter is the large compartment for the sample holders, which makes it possible to move a 2 cm sample holder to a maximum distance of 13 cm from the photocell. The light beam is somewhat divergent because of the extension of the light source.

The sample holder was first put in position 'zero', that is as near the photocell as possible, and the instrument balanced to read 100 %. The illumination was then determined at different distances from the photocell. Fig. 1 shows a set of curves obtained with dilute rubber latex solutions. It is obvious that due to the extension of the 'light source' in the sample holder, the illumination of the photocell from the suspension does not vary linearly with  $1/x^2$ . Nevertheless, plotting the transmission values against  $1/x^2$  greatly facilitates the extrapolation necessary to find values of  $y$  (Fig. 2).

From the extrapolated values, the concentration dependence of a number of quantities have been calculated and are shown in Fig. 3. It is difficult to

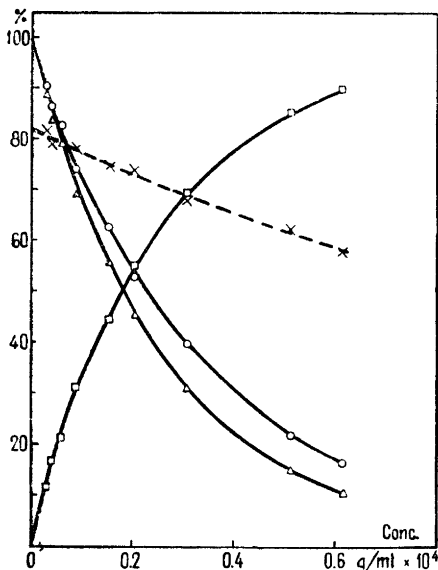


Fig. 3. Measurements on latex. Concentration dependence of different quantities calculated from measurements in Figs. 1-2.

- $T_{\infty}/T_{x_1}$
- $I_s/I_0$
- △  $T_{\infty}/I_0$
- ×  $\alpha_1$

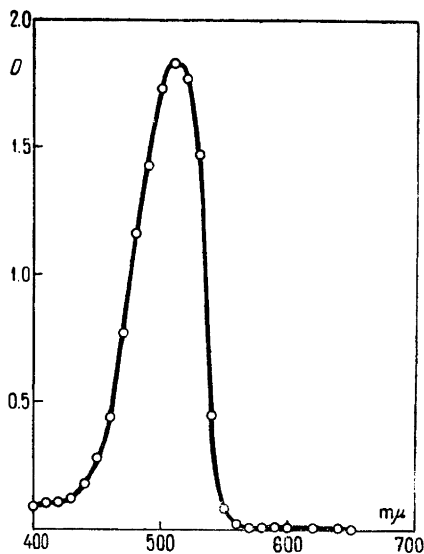


Fig. 4. Absorption curve of eosin.

calculate the value which  $\alpha_1$  should have if the scattering were symmetrical, but it would necessarily always be less than 50 %. The obtained values of around 80 % therefore mean, that there is a pronounced forward scattering, which decreases slightly with increasing concentration. Calculation of  $\alpha_1$  at infinite dilution according to (10) gives 80 %, in good agreement with the extrapolated value in the diagram.  $I_s/I_0$  varies linearly with concentration only for rather dilute suspensions.

Experiments were made in which eosin was added to dilute solutions of latex in order to test the conclusion drawn above that the color of the liquid medium has no influence on the turbidity measurement. The absorption curve of eosin (Fig. 4) shows that this substance is well suited to experiments of this kind. It is possible, by changing the light filter, to vary the light absorption from zero to high values.

Measurements were made at two dilutions and with three filters: red, green, and blue (Table 1). Values of  $y$ ,  $T_{x_1}/I_0$ , and  $I_a/I_0$  were determined. The

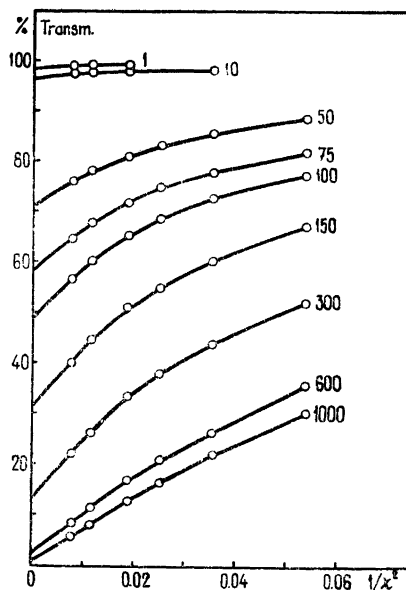


Fig. 5. Measurements on turbidity standard. Extrapolation of transmission measurements.

last column of the table shows that the percentage of scattered light is unaffected by the light absorption even at wave-lengths where the light absorption amounts to as much as 80 % of the incident light. This result proves, that the turbidity determinations are independent of the color of the suspension.

The relationship between the latex turbidities already described and the standard silica scale<sup>6</sup> was established by means of determinations on diluted samples of a turbidity standard no. 1 000 for water analysis (Fig. 5). The result is shown in Fig. 6. It can be seen that the turbidity of a sample to be investigated should preferably be greater than 20 p.p.m. For lower values the method is too insensitive.

If the sample holder were filled with water, the value of  $y$  differed from unity by only a few tenths of one percent, *i.e.* not more than the uncertainty of the instrument. Scattering and reflections in the glass walls therefore do not disturb the measurements.

For routine measurements the extrapolation is often unnecessary. It is sufficient to measure  $T_x$  at two positions as far apart as the instrument allows.

#### DETAILS OF THE MEASUREMENTS

The rubber latex ('T-Revertex') had a solids content of 61.6 % (after drying for 3 hours at 105° C). It was diluted with ammonia (approx. 5 %).

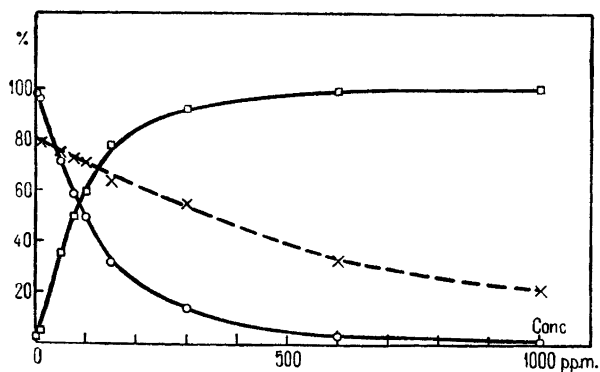


Fig. 6. Measurements on turbidity standard. Concentration dependence of different quantities.

○  $T_{\infty}/T_{x_1}$   
 □  $I_s/I_0$   
 ×  $\alpha_1$

The turbidity standard (from Hartman-Leddson Co, Philadelphia, USA) was prepared from specially treated fullers' earth and standardized with a Jackson candle turbidimeter according to the specifications of the American Public Health Association<sup>6</sup>. The undiluted suspension had a turbidity corresponding to 1000 p. p. m. Dilutions were made with distilled water.

In all experiments with suspensions the light path through the suspension was 2 cm long.

Figs. 1–3. Measurements were made with filter M 550, the transmission of which lies between 530 and 570  $\mu$ . The length  $x'$  in Fig. 1 is simply the distance the sample holder had been moved from the position closest to the photocell. By  $x$  in Fig. 2 is meant the distance from the middle of the suspension to the photocell. In this case  $x = x' + 1.3$

Table 1. Comparison between turbidity measurements on latex with and without eosin. The letter 'e' in the first column indicates measurements with eosin.

| Dilution of latex | Filter | $T_{\infty}/T_{x_1}$<br>% | $T_{x_1}/I_0$<br>% | $(I_s + I_a)/I_0$<br>% | $I_a/I_0$<br>% | $I_s/(I_0 - I_a)$<br>% |
|-------------------|--------|---------------------------|--------------------|------------------------|----------------|------------------------|
| 20 000            | M 620  | 47.7                      | 80.7               | 61.5                   | 0              | 61.5                   |
| e                 |        | 47.5                      | 80.9               | 61.6                   | 0.2            | 61.5                   |
|                   | M 550  | 40.2                      | 77.8               | 68.7                   | 0              | 68.7                   |
| e                 |        | 41.2                      | 42.3               | 82.6                   | 47.5           | 66.9                   |
|                   | M 465  | 31.5                      | 73.2               | 76.9                   | 0              | 76.9                   |
| e                 |        | 32.6                      | 14.3               | 95.3                   | 80.0           | 76.5                   |
| 100 000           | M 620  | 86.2                      | 95.7               | 17.5                   | 0              | 17.5                   |
| e                 |        | 86.0                      | 95.5               | 17.9                   | 0.2            | 17.7                   |
|                   | M 550  | 82.9                      | 95.5               | 20.8                   | 0              | 20.8                   |
| e                 |        | 82.5                      | 50.0               | 58.7                   | 47.5           | 21.3                   |
|                   | M 465  | 78.0                      | 93.8               | 26.8                   | 0              | 26.8                   |
| e                 |        | 75.6                      | 19.5               | 85.3                   | 80.0           | 26.5                   |



cm. In fact, as far as the extrapolation is concerned it is without importance from what point in the suspension the distance  $x$  is calculated, although the assumption made is the most natural.

The figures to the right of the curves indicate the dilution of the original latex. The concentration is expressed in g solids content per ml suspension.

*Fig. 4.* The absorption curve of eosin was measured with a Beckman Spectrophotometer, model DU, against distilled water. Concentration 0.005 % eosin in 5 %  $\text{NH}_3$ . Light path of sample holder 1.00 cm. Optical density  $D = -\log^{10} I_t/I_0$ .

*Figs. 5-6.* Same filter as in Figs. 1-3. The concentration is expressed in parts per million of silica. In order to avoid sedimentation of the particles, it was necessary to shake the suspension immediately before every measurement. Dilution with a more viscous liquid, *e. g.* glycol or glycerine, would probably have been better.

*Table 1.* Filters M 620 and M 465 transmit light in the intervals 610-640  $\text{m}\mu$  and 435-480  $\text{m}\mu$  resp. Concentration of eosin 0.005 %.

#### SUMMARY

A simple method for turbidity measurements with a commercially available photoelectric colorimeter is described. The change in apparent transmission with increasing distance between photocell and suspension is measured. The influence of color is eliminated, as is the necessity of utilizing a standard sample at each measurement. A theory has been worked out and tested by experiments with rubber latex and silica suspension. The method can be used for turbidities equal to and higher than 20 parts per million (calculated according to the silica standard scale).

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