TURBIDITY MEASUREMENT

Introduction

This article defines turbidity, how it is measured, and the effects that suspended particle size, shape, distribution, and stray light have on turbidity measurement. Information is also provided on calibration standards and the different optical configurations that are available.

Definitions and Measuring Principle

Turbidity is defined as an "expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through a sample."[1] Simply stated, turbidity is the measure of relative sample clarity. It is not color. Figure 1 shows the interaction of a light beam and undissolved, finely distributed particles known as suspended solids. When the light beam passes through the sample fluid, the suspended solids scatter the light in all directions (360° spherically).

Reduction in the intensity of the light beam is caused primarily by the suspended solids scattering the light. However, color absorption by dissolved substances can also reduce the light's intensity and should be taken into consideration by manually or automatically subtracting its effect. This can be accomplished optically if a turbidimeter is used (refer to the "Modulated Four-Beam Method" later in this article for details) or electronically if a separate absorption photometer is used in combination with a turbidimeter and their outputs are subtracted.

Small quantities of suspended solids are usually monitored by measuring the scattered light effect rather than the absorption effect because, with scattered light, the photocell detects small changes in light intensity with respect to a dark background. The disadvantage occurs at higher suspended solids levels, where multiple scattering limits the amount of side-scattered light received by the photocell. The condition results in lower-than-actual turbidity readings. At suspended solids concentrations above 2000 ppm, alternate measurement methods such as absorption must be used in place of turbidity measurement.

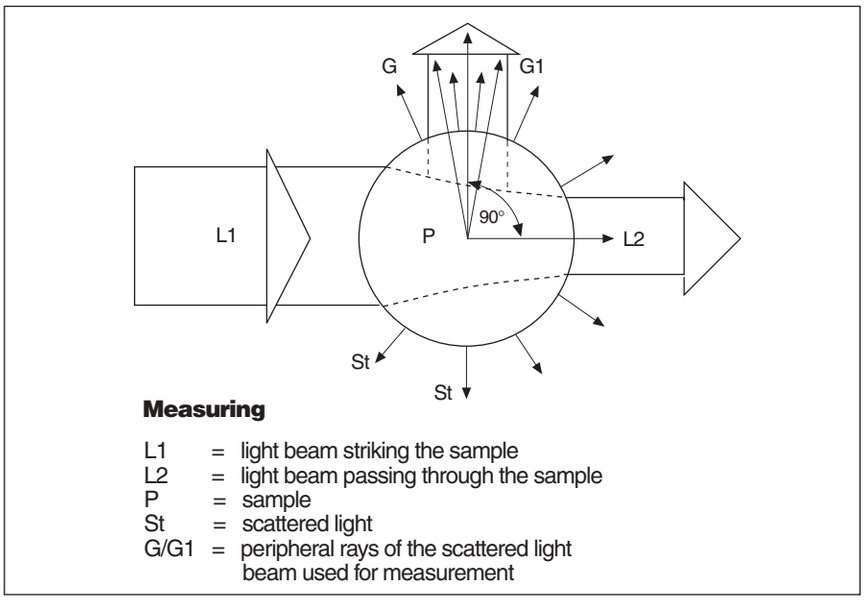

Figure 1
90° Scattered Light Principle

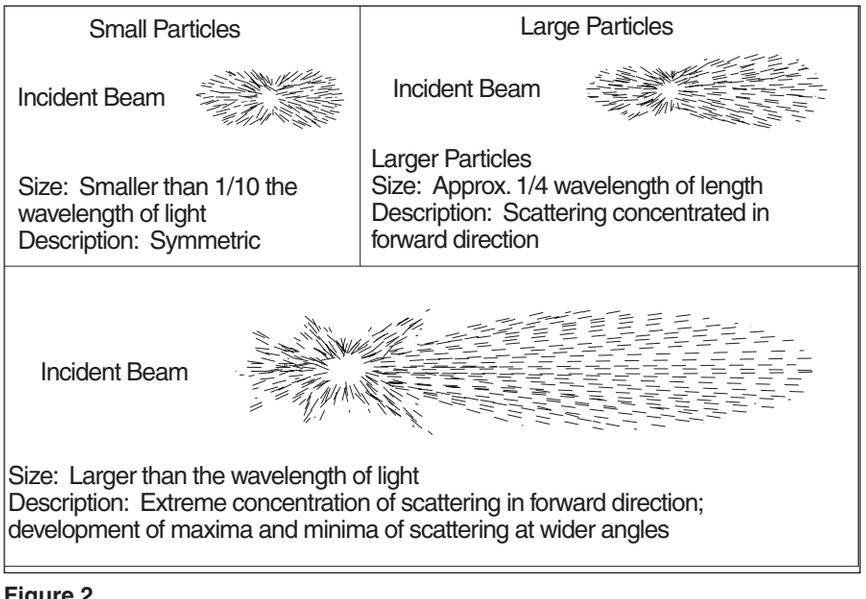

Figure 2
Angular Patterns of Scattered Intensity for Three Basic Particle Sizes[2]

Turbidity measurements provide a reading of the amount of scattered light and cannot be directly related to a gravimetric equivalent unless a working curve for the specific sample is created. The intensity of scattered light is affected by many variables including wavelength, particle size, color, and shape.

Particle Effects

There is no absolute difference between dissolved and undissolved matter. The water treatment authority considers all particles of less than 0.45 microns in diameter as being dissolved. It is important to note that particles smaller than 0.45 microns will also scatter light. Scattering distribution patterns show that, when particles are equal to or larger than the wavelength of the incident light beam (1 micron), there

[1] *Standard Methods for the Examination of Water and Wastewater, APHA, AWWA and WPCF, 16th edition, 1985.*

[2] *Brumberger, et al., Light Scattering, Science and Technology, November, 1968, page 38.*

is a greater amount of forward scattered light. As the particle size becomes smaller, the pattern becomes somewhat peanut-shaped (see Figure 2). However, particles smaller than 0.05 microns in diameter (that is, colloids) scatter light equally in all directions.

Other factors which influence light scattering are:

1. Particle color — This determines the ability to absorb or reflect the incident light beam. For example, two different types of filter beds are typically used in water treatment: carbon and sand. Sand is light in color, which reflects the incident beam very well. Conversely, black carbon has a tendency to absorb the incident beam. Therefore, with all else being constant (particle size, shape, etc.), the fine particles from carbon filters have lower scattered light intensity.
2. Particle shape — This determines the ability of the suspended solids to provide a constant spatial distribution pattern. A smooth, spherical-shaped particle will provide predictable results, whereas an irregularly-shaped particle can produce widely varying responses depending on the side that the incident light beam strikes.
3. Differences between the refractive index of the particle and that of the sample fluid — This allows light scattering to occur. The intensity of the scattered light increases as the difference increases.

Optical Design Elements

The properties of suspended solids are not the only factors affecting the value of scattered light. Other important factors include:

- the angle of detection
- the light beam aperture
- the incident beam wavelength
- the color sensitivity of the photocell

The influence of the angle of measurement can be seen in Figure 2. As suspended particle size changes, the intensity of light which is scattered in all directions changes.

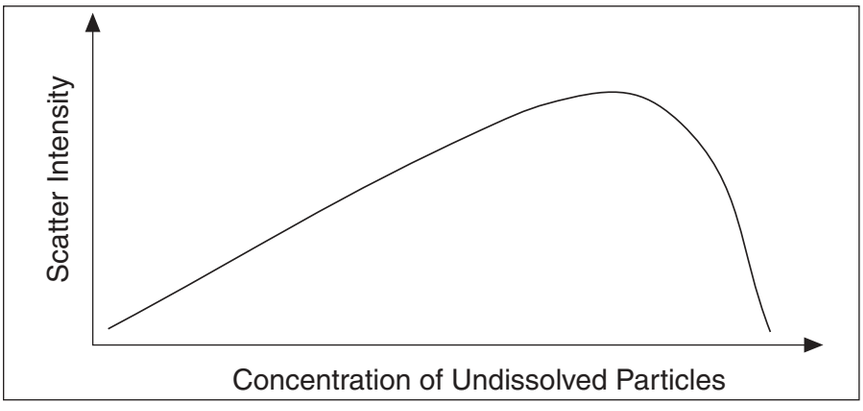

Figure 3
Intensity of Scattered Light As a Function of Concentration

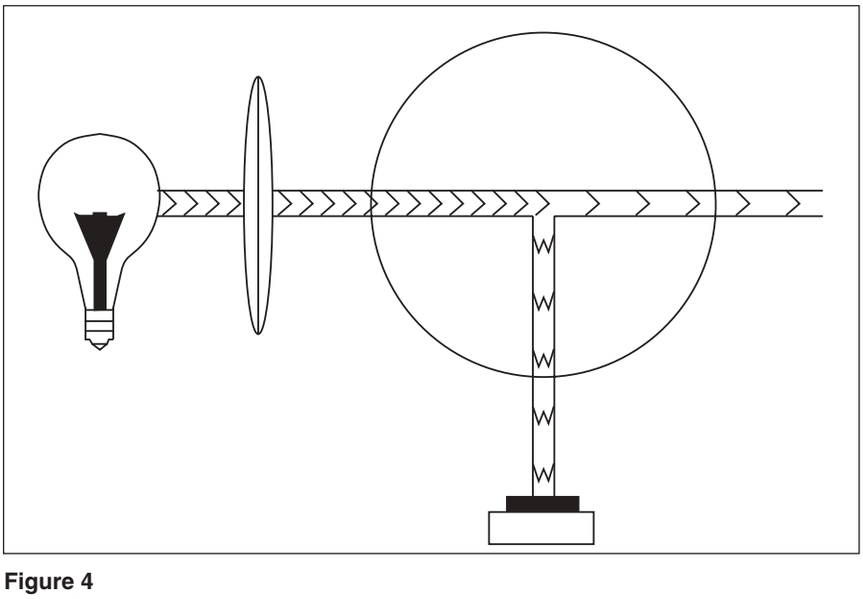

Figure 4
Basic Turbidimeter Design

An instrument which measures at 90° will receive different information than an instrument which measures in a forward direction.

Additionally, as the wavelength of detection changes, the scatter pattern will again be altered. The type of light source, photocell, and filter that are used in a turbidimeter determine its color sensitivity spectrum. The closer to a single wavelength the color sensitivity spectrum is, the more consistent will be the scatter pattern produced.

Optical Design Limits

There is a relationship between the total suspended solids in the liquid and the light intensity due to particle scattering. This relationship can be determined through the development of a working curve for each specific sample (see Figure 3). This relationship holds up to a transition point where the rate of scatter intensity no longer increases with an increase in the quantity of undissolved particles. This point is the maximum limit of the optical design of a turbidimeter. Light which is detected by the photocell that is not caused by the scattering of light by suspended particles is called “stray light.” The lower limit of the optical design of a turbidimeter is dependent on the amount of stray light. Causes of stray light include reflections, scattering by dust, scratches or fingerprints on the sample cell, or imperfections in the glass.

OPTICAL MEASURING CONFIGURATIONS

Single-Beam Method

This basic instrument design uses a single light source and a single photodetector located at a 90 degree angle to the transmitted light, as shown in Figure 4. This design, which has been in existence for many years, has some inherent problems. Commencing immediately after the light source is turned on, it slowly begins to burn out, which reduces its intensity. Since instrument calibration is based upon light intensity, this reduction in luminosity necessitates frequent

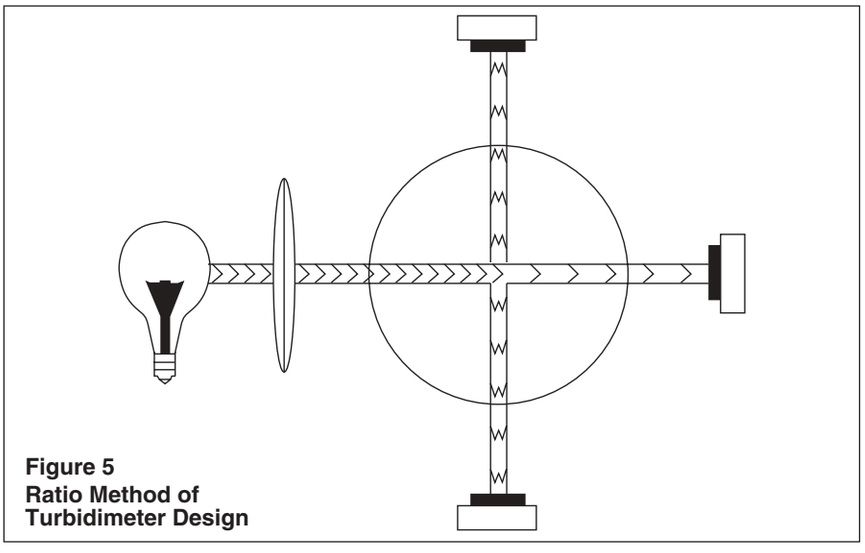

Figure 5
Ratio Method of Turbidimeter Design

calibration to re-establish a new value of the scattered intensity.

Another problem is the measurement of colored liquids. The presence of any color will absorb some of the light, thereby reducing the light intensity. As a result, the detector senses less scattered light, providing a false, lower-than-actual turbidity reading. The single-beam method also lacks the ability to provide a stable measurement reading at higher levels of turbidity.

Ratio Method

The ratio method expands upon the single-beam concept. In addition to the one photodetector positioned at a 90° angle to the transmitted light, additional detectors can be added at other angles, as shown in Figure 5. Using a ratio of the multiple detector system increases the stability of the measured turbidity values. This design also cancels the effects of light intensity reduction when measuring colored liquids, thus making the turbidimeter color-compensated. Although a multiple detector design using a ratio measurement method is an improvement over the single-beam detector design, the problem with light source decay and the need for frequent calibration still exist.

Dual-Beam Method

To minimize the effect of light source decay, the dual-beam method was developed, shown in Figure 6. This method uses a single light source which is split by an oscillating mirror into two beams: a measuring beam and a reference beam. The measurement is made differentially, with a single photodetector registering the different light intensities of both beams. This method reduces the need for frequent calibration and, in fact, when used with a monochromatic light source totally eliminates the need for calibration. Although the dual-beam method minimizes or eliminates the need for frequent calibration, it does not address the problem of unstable readings at higher turbidity levels.

Modulated Four-Beam Method

The modulated four-beam method uses two light sources and two photodetectors. As Figure 7 illustrates, these components are spaced at 90° intervals around a circular sample chamber. Every half second, the sensor accomplishes two measurement phases, and a microprocessor calculates a turbidity reading.

In the first phase, Light Source 1 momentarily pulses a light beam directly into Photodetector 2. Simultaneously, Photodetector 1 measures the light scattered at 90°.

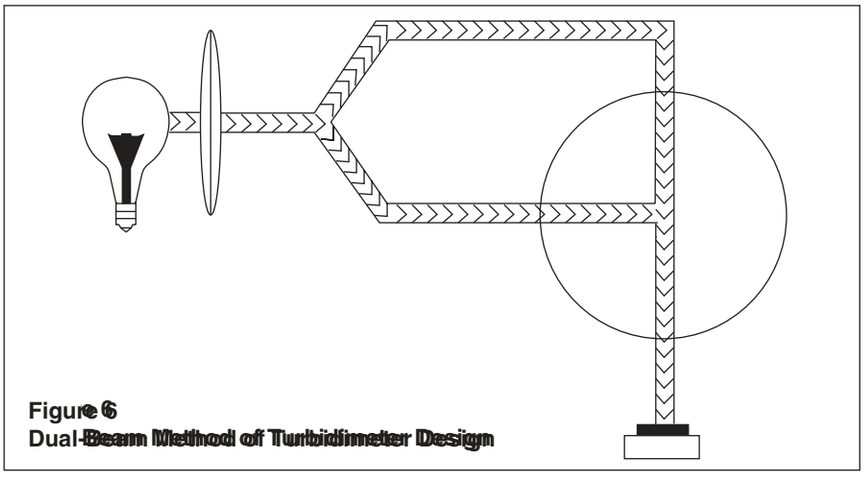

Figure 6
Dual-Beam Method of Turbidimeter Design

In the second phase, Light Source 2 momentarily pulses a light beam directly into Photodetector 1. Simultaneously, Photodetector 2 measures the scattered light at 90°.

Every time a light source is activated, it provides both an active signal and a reference signal. The two light sources are alternately pulsed. Likewise, the two photodetectors alternate reading the active signal and the reference signal.

This two-phase measurement provides four independent measurements from two light sources, using both direct strength readings and 90° scattered light readings received by two detectors. The microprocessor uses a ratiometric algorithm to calculate turbidity value from these four readings. Mathematically, this means that all error effects appear in both the numerator and the denominator — and thus are cancelled out.

The modulated four-beam method cancels all error terms derived from aging or fouling of components, and reduces errors due to color factors. This method also offers the practical advantage that light sources and detectors need not be matched for there to be accurate measurements.

Calibration Standards

Every turbidimeter, regardless of its optical configuration, must be calibrated with a known standard, a reference to which the measured values can be compared. The most widely used measurement unit for turbidity is the FTU (Formazin Turbidity Unit). This unit can be used for all turbidimeters which employ the polymer formazin as the calibration standard. The USEPA uses formazin, but states its

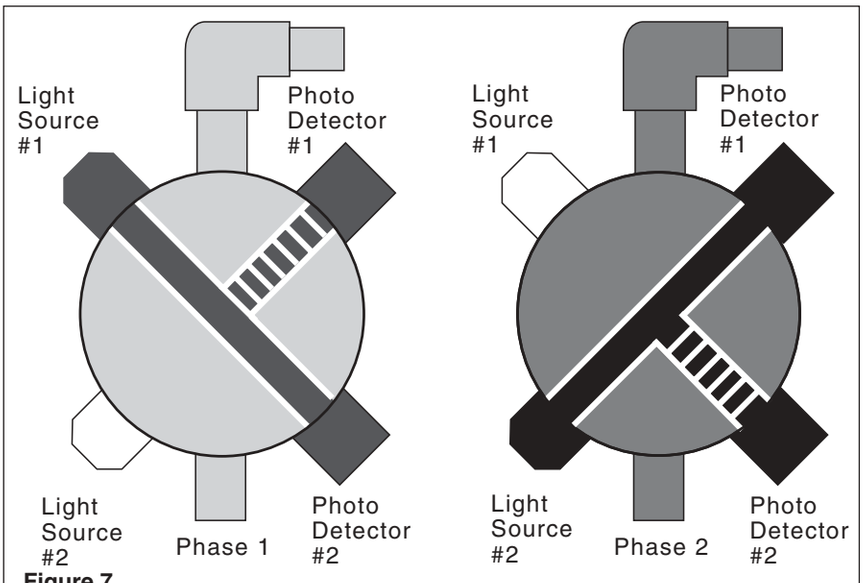

Figure 7
Optical Diagram of Modulated Four-Beam Method

measuring units as NTU (Nephelometric Turbidity Units). ISO refers to its units as FNU (Formazin Nephelometric Units).

A formazin suspension is created by the polymerization of hexamethylenetetramine and hydrazine sulfate under strictly controlled conditions. Although formazin offers advantages over sane or diatomaceous earth, it still lacks the long-term stability and reproducibility necessary in order for a substance to function as a universally accepted primary standard.

Formazin is most commonly manufactured in a 4000 FTU (Formazin Turbidity Unit) suspension. Reproducibility of this suspension using the same hexamethylenetetramine and hydrazine sulfate is ±1%. (Suspensions using different brands, lots, etc. of hexamethylenetetramine and hydrazine sulfate have a ±15% reproducibility.) Subsequent dilutions of this suspension to lower turbidity values render the compound more unstable with greater dilution. It is recommended that diluted calibration suspensions be used immediately and then be disposed of promptly and properly.

Most modern turbidimeters are equipped with a secondary calibration standard. These standards are used to standardize the instrument or to check calibration to determine when calibration with formazin is necessary. Secondary standards made of liquids or gels are still unstable and must be replaced each year.

This only absolutely stable standard is turbid glass. A glass calibration standard has small particles uniformly suspended in a specially formulated glass cube. The turbidity value of this glass cube is permanently fixed. It cannot be affected by time, temperature or, most importantly, by any change in who's performing the calibration.

Standard Specifications

There are two standard specifications for turbidity measurement which are generally in use worldwide: the international standard ISO 7027 (1984 edition) and the USEPA 180.1. The specification for the ISO standard is more stringent and requires the use of a monochromatic light source. This specification allows for greater reproducibility of measured values and greater agreement between measuring instruments. These two standards are compared in Figure 8.

Conclusion

Turbidity is a very complex analytical measurement which can be affected by many factors. To choose the best measuring system for a specific application, all factors must be carefully considered before selecting the appropriate turbidimeter.

An important consideration is the comparison of readings between different instruments calibrated using the same standard. For reasons elaborated in this bulletin, it is unreasonable to expect different instruments to indicate the same value, even for the same sample. On-line process instruments should be used for trending information rather than for absolute values.

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	USEPA 180.1 Standard	ISO 7027 Standard
Wavelength	Tungsten lamp operated at color temperature between 2200 and 3000K	860 nm
Special Bandwidth	Not Specified	60 nm, no divergence, convergence of 1.5 degrees or less
Measuring Angle	90 ± 30	90 ± 2.5
Aperture angle in water sample	Not Specified	20 to 30
Distance traversed by incident light and scattered light within the sample	10 cm	Not Specified
Calibration Standard	Formazin or AEPA-1	Formazin

Figure 8
Comparison Between USEPA and ISO Turbidity Standards