MONITORING WATER FILTRATION PROCESSES FOR OPTIMAL PARTICLE REMOVAL

John Gregory
Department of Civil and Environmental Engineering,
University College London, Gower Street, London WC1E 6BT, UK

ABSTRACT

Filtered water is routinely monitored for particles, usually by turbidity measurements. In recent years, concern over certain parasitic protozoa in drinking water has led to the use of more sensitive particle monitoring techniques. Although particle counting instruments are suitable for such purposes, it is shown that a simpler, but very sensitive technique, based on turbidity fluctuations, may also be acceptable.

KEYWORDS: Filtration; Monitoring; Particles; Turbidity; Water.

THE NEED FOR PARTICLE MONITORING

Monitoring of filtered water quality by turbidity measurement is routinely carried out in water treatment plants. Originally, such measurements were mainly for aesthetic reasons - a visibly cloudy or turbid water is undesirable and turbidity provides a quantitative measure of this property. However, turbidity monitoring also provides an indication of particle removal.

Several outbreaks of water-borne disease caused by *Cryptosporidium* [1] have prompted a re-appraisal of turbidity measurements as a means of detecting very low concentrations of particles in water. *Cryptosporidium* oocysts are nearly spherical in shape, with a diameter of 4-5 μm. They are highly resistant to disinfection by chlorine and are considered significant at concentrations of 1 per litre or less, which means that physical removal of oocysts by water treatment processes needs to be highly effective. There are no on-line methods that can specifically detect oocysts at the very low concentrations of interest. However, it is likely that removal of *Cryptosporidium* oocysts by typical processes, such as coagulation/flocculation and filtration is comparable to that of other particles in the same size range. Consequently, by monitoring the removal of particles generally, it should be possible to estimate the degree of oocyst removal. The problem is that very low concentrations of particles in water may need to be monitored in filtered water, which presents difficulties for conventional turbidity methods. More sensitive methods may be required and there are several possibilities.

Particles in water may be detected by various methods, but not all are suitable for the very low concentrations found in high-quality filtered water. Some techniques have been developed for specific applications, such as the 'Silting Index', which is based on the clogging of pores in a membrane filter. This is very sensitive, but not well suited to continuous, on-line measurements. The vast majority of practical methods are based on optical measurements, which depend on the light scattering properties of particles. These include all turbidity methods and optical particle counters.

LIGHT SCATTERING AND TURBIDITY

Basics

Particles in water scatter light, giving turbidity. Detailed accounts of light scattering theory can be found in many texts [2] [3]. The amount of light scattered (and hence turbidity) depends on the concentration, size and refractive index of particles, as well as on the light wavelength used. In all cases, light scattering leads to (a) an angular distribution of scattered light and (b) a reduction in intensity of transmitted light. It is possible to measure the amount of light transmitted through the sample or the light scattered at one or more angles to the incident beam.

Light transmission

When transmitted light is measured, turbidity, τ, is defined by the following equation:

$$I = I_0 \exp(-\tau L) \tag{1}$$

where I_0 and I are the incident and transmitted light intensities and L is the optical path length. For uniform particles, the turbidity is given simply by $\tau = NC$, where N is the number concentration of particles and C is the *light scattering cross-section* of a particle. C is related to the geometrical cross-sectional area of the particle by a factor Q, which is the *light scattering coefficient*. So, for a spherical particle, radius a, $C = Q\pi a^2$. If the concentration of particles is expressed as the *volume fraction*, $\phi = (4/3)\pi a^3 N$, then we get a simple expression for the *specific turbidity* (i.e. the turbidity per unit concentration):

$$\frac{\tau}{\phi} \cong \frac{3Q}{4a} \tag{2}$$

This shows that for a given volume (or mass) concentration, the turbidity will depend on the scattering coefficient Q and inversely on the particle size.

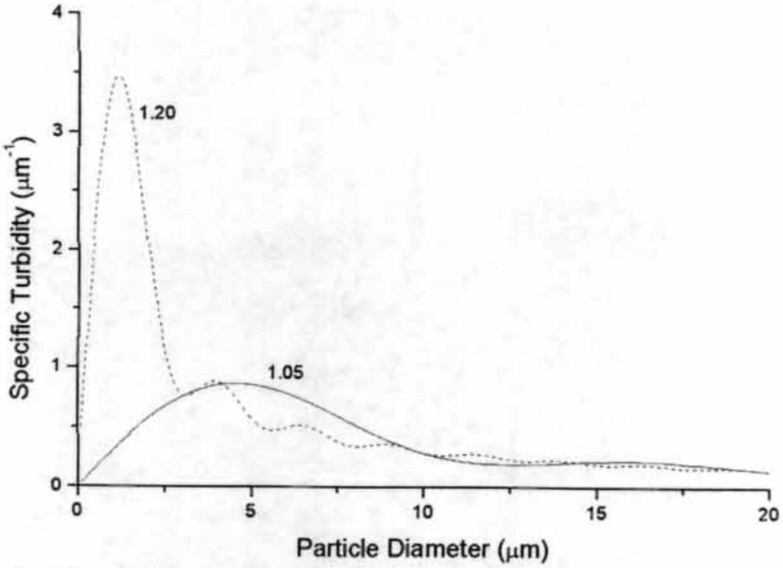

Fig 1 Specific turbidity vs particle size for different m values

Values of Q typically range from almost zero up to values of around 5 or more. Typically, the turbidity increases with particle size, passes through a maximum and then decreases. Figure 1 shows the specific turbidity for spherical particles as a function of their diameter, for two values of *relative refractive index*, m (ratio of particle refractive index to that of water). The values pass through a maximum and then decline with increasing particle size.

For low turbidities the transmitted light is only slightly less than that for pure, particle-free water and it is necessary to measure a very small voltage difference. Random electronic noise, drift and 'fouling' of optical surfaces mean that differences less than about 1 part in 10,000 cannot be reliably measured. So, for a 1 cm path length, turbidities less than about 10^{-4} cm^{-1} cannot be easily measured. High quality filtered water would have a much lower turbidity. This problem can be avoided by measuring scattered, rather than transmitted light.

Turbidity measurements by scattered light

Practical turbidimeters for water treatment applications are based on some form of scattered light measurement. Although light scattered in any particular direction is only a tiny fraction of the total amount of scattered light, sensitive detectors, such as photomultipliers can be used, allowing measurement of very low intensities. Even very low turbidity samples give measurable amounts of scattered light and the intensity increases with increasing turbidity. The problem of resolving small differences between large signals does not arise. Nevertheless, there are some fundamental difficulties with measuring turbidity by scattered light.

Turbidity measurements depend on the precise design of the instrument, for instance the light wavelength, scattering angle, and the acceptance angle of the detector [4]. Different instruments can be calibrated with a suspension (such as Formazin) having an agreed standard turbidity value on an accepted scale (*Nephelometric Turbidity Units – NTU*). However, quite significant differences between standardised turbidimeters are apparent when they are used to measure a range of suspensions. Even different instruments from the same manufacturer give widely varying results [5].

Although scattered light gives a sensitive measure of turbidity, there are still limits when high quality filtered water has to be monitored. A fundamental limit arises from the fact that pure, particle-free water scatters light to a small extent. This is due to random thermal fluctuations and gives an effective turbidity of about 0.03 NTU for pure water. This is well below current drinking water turbidity limits (typically 1 NTU), but restricts the use of turbidimeters for monitoring very low particle concentrations.

Another problem relates to particle size effects. We saw above that turbidity measured by light transmission passes through a maximum value and then decreases as particle size increases. Similar behaviour is found for scattered light, as expected, although the nature of the response depends on the scattering angle. This is significant for water quality monitoring, since conventional turbidimeters respond more sensitively to sub-micron particles. Larger particles, in the *Cryptosporidium* size range (4-5 μm), give a much smaller response.

These difficulties mean that conventional turbidity monitoring of filtered water may not give adequate warning of the breakthrough of larger particles and alternative, more sensitive techniques are of great interest.

TURBIDITY FLUCTUATIONS

This is essentially a development of the basic light transmission method discussed above. The light transmitted through a *flowing* suspension of particles shows random fluctuations, which are due to random variations in the number and size of particles in the light beam. By making the light beam quite narrow (1 mm or less) the fluctuations in transmission (or *turbidity fluctuations*) can become quite significant. The basic principle has been discussed by Gregory [6]. Practical implementation of the method is straightforward, giving in an inexpensive, robust monitor. Simple optoelectronic devices, such as light-emitting diodes and photodiodes are adequate and the flowing sample can be monitored directly in a transparent plastic tube.

The transmitted light signal consists of a large average (dc) component and a much smaller fluctuating (ac) part. It is convenient to derive the root mean square (rms) value of the fluctuating signal and divide this by the dc value, to give a *Ratio* value, R.

It can be shown that Ratio value depends on the *square root* of the particle concentration. For uniform particles. In terms of the scattering cross-section, C and the volume fraction, ϕ:

$$\frac{R}{\phi^{1/2}} = \sqrt{\frac{3\pi L}{4A}} Q a^{1/2} \qquad (3)$$

So, for a constant volume concentration, the fluctuating signal, as measured by the ratio R, depends on the square root of the particle size and on the scattering coefficient Q.

For particle-free water, there should be no fluctuating signal, and as the particle concentration increases the fluctuations should increase. These might initially be due to single particles passing through the beam, which is a requirement for optical particle counters (see below). With higher particle concentrations, where there may be many particles, on average, in the light beam, the fluctuations continue to follow eq (3) and the method is still valid. The ratio value R provides a significant advantage over conventional flow-through turbidity measurements, which are subject to the problem of contamination ('fouling') of the cell walls by adhering particles. Since fouling has the same relative effect on both the dc and ac values, the Ratio value is largely unaffected by this problem. In practice, R can be used to derive an empirical index of particulate contamination.

The chief limitation to the turbidity fluctuation technique is random noise, which can be kept to less than 1 part in 10^5 with high-quality opto-electronic devices. By assuming that the lower detection limit for R is twice the noise signal (say, 2×10^{-5}), it is possible to compute the lowest detectable particle concentration. A similar procedure can be carried out for transmission measurements, where the limiting value of I/I_0 is taken as 0.9998, i.e. a difference of 0.02% between incident and transmitted light intensities is the lowest that can be reliably resolved. The results shown in Fig 2 are based on these assumptions and the following values: wavelength = 650 nm, path length L = 5 mm and beam diameter = 0.5 mm. Fig 2 shows the lowest particle concentrations that can be detected for two different refractive index values (m = 1.05 and 1.2), by turbidity and turbidity fluctuation techniques, based on the limits given. It is clear that the fluctuation technique is very dependent on particle size, with a great improvement in sensitivity for particles larger than around 1 μm. For sub-micron particles standard turbidity measurement is more sensitive and there is a characteristic 'crossover' point where the fluctuation method can detect lower particle concentrations. For particles a few microns in size, the turbidity fluctuation method can be more sensitive by a factor of 100 or more and can detect particles at well below 1 ppb by volume. These predictions have been confirmed experimentally [7]. Measurements on a filtered water using this method gave results which closely followed those obtained with a sensitive particle counter [8].

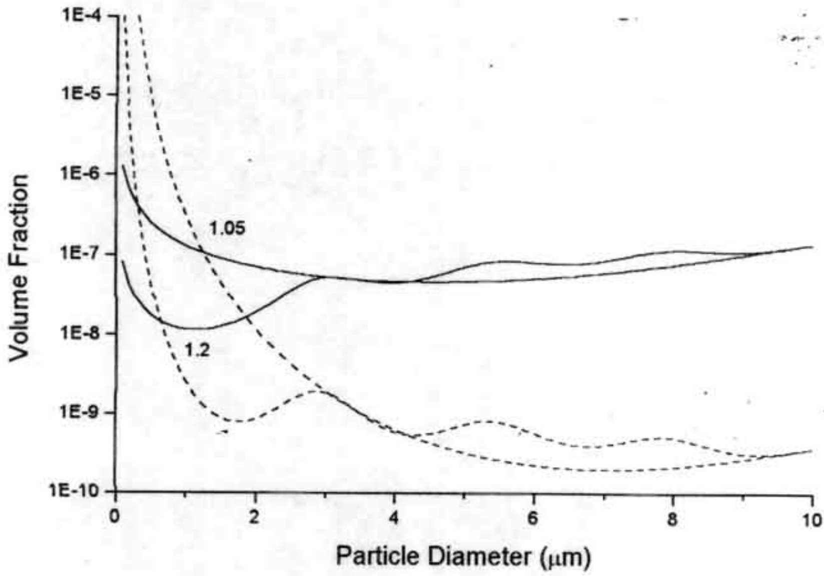

Fig 2 Concentration limits (volume fractions) for particle detection by turbidity (full lines) and turbidity fluctuations (broken lines) for two refractive index values.

PARTICLE COUNTING

General

Particle counters are available which count and size individual particles as they pass through a sensing zone. There are two main types of sensor involved: electrical and optical. However only optical sensors are suitable for routine, on-line monitoring. Optical particle counters sense particles as they pass through a light beam either measuring scattered light or the reduction in transmitted light. The latter technique is most often used for water quality monitoring and is known as the *light blockage* or *light obscuration* technique.

A common feature of all particle counters is that they are subject to *coincidence errors*. These arise when the sensing zone contains more than one particle. In that case a single large pulse is generated, rather than two smaller ones. This problem becomes quite serious as the particle concentration increases and considerable sample dilution may be necessary. However, with many instruments, coincidence is not a major concern if the particle concentration is less than a few thousand per mL, which means that filtered waters can be monitored without dilution.

Light blockage counters

These are now widely used in water treatment plants and a very thorough review has been given by Hargesheimer *et al* [9]. Essentially, particles pass one by one through a focused light beam (often a laser beam) and the transmitted light is monitored by a detector (photodiode). Each particle causes a partial blockage of the light beam and gives a corresponding reduction in the photodiode output. This is converted to a voltage pulse, which is related to particle size. Pulse height analysis then allows a form of particle size distribution to be generated.

The amount of light 'blocked' by a particle is proportional to its light scattering cross-section, C. For very large particles this becomes proportional to the geometric cross-sectional area and hence to the square of the particle size. For large particles, the scattering coefficient Q approaches a constant value. However, for particles of a few microns in size, Q depends on the size and the refractive index. There is also a very steep decline in scattering cross-section as the particle size falls below about 1 μm. Particle counters are usually calibrated with latex particles of known size and polystyrene latex has a relative refractive index of around m = 1.2. Particles of lower refractive index, such as bacteria with m ≈ 1.05 and around 1 μm in size, will cause considerably less light blockage than latex particles of the same size. Thus the 'particle size' determined by a light blockage counter, could be misleading if the calibration particles have a different refractive index than the particles being measured. This point is especially relevant for *Cryptosporidium*, as has been pointed out previously [10].

Water samples with a turbidity of around 0.1 NTU are typically found to have a few hundred particles (> 2 μm) per mL. Improvement of the quality of such a water by, for instance, changing filter operating conditions, can be much more reliably monitored by particle counting than by turbidity. There is a large amount of plant experience which demonstrates this point.

CONCLUSIONS

Turbidity measurements are routinely carried out to assess the degree of particulate contamination in water and will continue to play a vital part in water quality monitoring. Drinking water quality standards include turbidity as a regulated parameter and limits are likely to become more stringent. However, turbidity values cannot be interpreted in terms of particle concentrations or particle size and techniques become unreliable for high quality waters.

Alternative techniques are available, the most common of which involve particle counting and sizing, using a light blockage principle. This can give very detailed information, although there are fundamental difficulties in interpreting the results in terms of particle size, because of the varied nature of particles in natural waters. Nevertheless a total particle count provides a very useful index of particulate contamination, at least for larger particles. Particle concentrations cannot exceed a value where coincidence corrections become significant.

A simpler technique, of comparable sensitivity to particle counters is the turbidity fluctuation method. This does not give detailed information on particle number and size, but an empirical index of particulate contamination. The method is not restricted to single particles passing through a sensing zone and so is not subject to concentration limits. A 'Particle Index' derived from this technique provides a very useful indication of the quality of filtered water, and can be used for control purposes.

REFERENCES

1. Gale. P, 1998. *Water Science and Technology*, **38**(12),.7-13.
2. van de Hulst, H.C., 1957. *Light Scattering by Small Particles*, Wiley, New York. (Republished by Dover Publications Inc., New York, 1981)
3. Kerker, M., 1969. *The Scattering of Light and Other Electromagnetic Radiation*, Academic Press, New York.
4. Sethi, V., Patnaik, P., Biswas, P., Clark, R.M. and Price, E.W., 1997. *J.Am Water Wks Assn.* **89**(2) 98-112.
5. Gottfried, G.J., 1986. *Proc. AWWA Water Quality Conference*, **13** 583-590.
6. Gregory, J., 1985. *J. Colloid Interface Sci.* **105** 357-371.
7. Gregory, J., 1990. *Proc Vth World Filtration Congress*, Nice, pp 368-374.
8. Gregory, J., 1994. *Filtration and Separation*, **31**, 283-289.
9. Hargesheimer, E.E., Lewis, C.M. and Yentsch, C.M., 1992. *Evaluation of Particle Counting as a Measure of Treatment Plant Performance*, AWWA Research Foundation, Denver.
10. Lewis, C.M. and Manz, D.H., 1991. *J. Env. Eng., ASCE*, **117**, 209-223.