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Particle monitoring techniques for water treatment applications

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Abstract—A simple optical technique based on fluctuations in light transmitted through flowing suspensions has proved useful in two distinct water treatment applications. The first of these is the monitoring and control of coagulation/flocculation processes, where information on optimum coagulant dosages as well as on the dynamics of floc formation can be derived. The method is suitable for a very wide range of particle concentrations, up to levels found in highly turbid river waters. The second application is as a very sensitive monitor of particles in filtered water. Such monitoring can help to ensure the effective removal of pathogens such as *Cryptosporidium* from drinking water. Brief accounts of these techniques are given, together with some examples of their use.

Keywords: *Cryptosporidium*, coagulation, flocculation, fluctuations, monitoring, particles, water treatment.

1 Introduction

Particles in natural waters are often too small to be effectively removed by these separation techniques. The process of coagulation/flocculation causes fine particles to aggregate into larger units (flocs) which can be more easily separated. In water treatment salts of aluminium and iron are commonly used as coagulants, which destabilise the particles and cause flocs to form. In many cases, the formation of an insoluble metal hydroxide plays an important part in the process, which is then known as "sweep flocculation". It is important to add the correct dosage of coagulant and to adjust chemical conditions (especially pH) to give optimum floc formation. In some applications, high molecular weight polymers are used as flocculants, which act by "bridging" particles together. These may be used either alone (primary flocculants) or in combination with conventional coagulants to give stronger hydroxide flocs.

Under optimum conditions flocs should be effectively removed and the finished water, after filtration, should contain very few particles. Recent problems with the protozoan parasite *Cryptosporidium*, including a very serious incident of water-borne disease in Milwaukee (Mackenzie, 1994), have led to much greater concern over the levels of particles in treated water. Particles of around 5 μm in size, are of special interest, since this is about the size of *Cryptosporidium* oocysts. *Cryptosporidium* is not easily inactivated by conventional disinfectants, such as chlorine, so that physical removal of oocysts is essential.

It is recognised that in order to reduce particulate contamination to a minimum, coagulation/flocculation conditions need to be optimised and the filtration process should operate with high efficiency. Both of these aspects can be addressed by appropriate particle monitoring techniques.

2 Flocculation tests

In some cases, raw water quality does not change appreciably over long periods and, once the optimum coagulant dosage is established, it need only be checked occasionally. However, there are many river waters that are subject to rapid changes, for instance as a result of flash flooding. In such cases the coagulant dosage needs to be adjusted frequently and, ideally, some form of on-line monitoring and dose control should be used, but it is much more common to carry out periodic off-line tests, such as the widely used jar test procedure.

2.1 Jar tests

In the water treatment field jar tests have become standard for determining optimum coagulation conditions. The subject has been reviewed by Dentel (Dentel, 1991). The whole procedure can be quite time-consuming and requires large quantities of sample. Although the jar test is very useful in determining optimum coagulant dosages, it may not give a good indication of the degree of clarification that is achieved in a full-scale treatment plant. This is because the hydrodynamic conditions during rapid mixing and slow stirring in a jar of 1—2 L capacity cannot match those in a full-scale plant. Nevertheless, provided that this limitation is appreciated, the jar test can still give very valuable guidance in the operation of a water treatment plant.

2.2 Turbidity fluctuations

It has been shown by Gregory and Nelson (Gregory, 1986) that a simple technique based on measurements of fluctuations in light transmission through flowing suspensions can give very useful information on the state of aggregation of particles.

So far, the implementation of this technique has been such that the information derived is of an empirical, or semi-quantitative character. Nevertheless, it has proved possible to optimize coagulant dosages and investigate the effect of mixing conditions, different additives and many other factors on flocculation of a wide range of suspensions.

By improvements to the optical arrangement it is possible to derive more quantitative information on floc size and density. Although there is a need to make assumptions about the floc size distribution and the light scattering properties of aggregates (Gregory, 1995a).

Since the suspension is flowing, there are random variations in the number of particles in the illuminated volume leading to fluctuations in the intensity of transmitted light. The number fluctuations follow the Poisson distribution, so that the variance about the mean is equal to the mean number of particles in the light beam. The transmitted light intensity shows corresponding fluctuations about a mean value. The root mean square value of the fluctuating (ac) signal can be derived and this is usually divided by the mean (DC) value of intensity, to give a ratio value. This depends on the square root of the particle concentration, because of the Poisson distribution. It can also be shown (Gregory, 1995a) that the ratio value always increases when particles aggregate and this gives a very useful method for monitoring flocculation.

2.3 Laboratory tests

A very convenient laboratory application is the continuous monitoring of a flocculating suspension in a stirred vessel. This is essentially a jar test procedure, but giving much more detailed information than the traditional test. Sample is continuously monitored through transparent tubing by a peristaltic pump and passed through a monitor (PDA 2000, Rank Bros, Cambridge, UK), which gives signals corresponding to the transmitted light intensity and the ratio value defined above. In some cases, R is referred to as the flocculation index and given the symbol FI.

2.3.1 Dilute suspensions

Flocculation of fairly dilute suspensions in a stirred vessel gives a monitor response which varies with time in the manner shown in Fig.1. This behaviour can be reasonably well understood in terms of the kinetics of flocculation and floc break-up in stirred reactors (orthokinetic flocculation). In the early stages flocs are very small and collision rates are low. With increasing floc size, Smoluchowski theory (Elimelech, 1995) predicts an increasing collision rate and hence more rapid flocculation. As flocs grow larger further growth is restricted by the effective shear rate in the stirred vessel and the strength of the flocs. Flocs grow to a limiting size determined by the shear rate, the nature of the coagulant and the size of the primary particles.

It is not possible to provide a fundamental analysis of curves like that in Fig.1. Gregory and Hiller (Gregory, 1995b) found that curves of FI vs time, t, can be very well represented by a

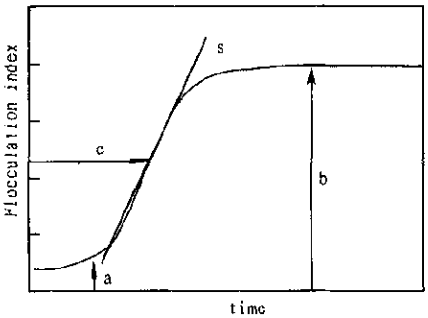

Fig. 1 General form of sigmoid curve, representing the change of Flocculation Index with time. The significance of various parameters is discussed in the text

number of mathematical forms, such as a simple sigmoid curve, from which various parameters can be derived:

The parameter *a* is simply the value of *FI* initially, before any flocculation. In the results given here this value is always very low. The value of *b* reflects the plateau level, achieved after a sufficient period of flocculation. *c* is the time required to reach the inflection point of the curve (maximum slope) and *s* is the slope at this point. The parameters *b*, *c* and *s*, could all be important in the flocculation process. The ultimate floc size should be related to *b* and the greater this value the larger the flocs. The time to achieve the maximum rate of increase, *c*, is a function of the stirring rate and also the nature of the coagulant. In the case of hydrolysing salts some time required to form hydrolysis products and for these to become adsorbed on particles. There is often a characteristic "lag time" before flocculation begins. The slope, *s*, should be closely linked to the maximum flocculation rate.

A primary aim of flocculation tests is to establish optimum chemical conditions (dosage, pH etc.) and the parameters discussed above could all be useful in deriving such information. The optimum might, for instance, correspond with the maximum floc size achieved under standard shear conditions or the maximum rate of flocculation or the minimum "lag time" before the onset of flocculation. In fact, it has been found (Gregory, 1995b) that the maximum slope, or the parameter *s*, gives a good correlation with the residual turbidity after a standard jar test procedure, both for aluminium and ferric coagulants. The higher the slope is, the lower the residual turbidity. The plateau value, *d*, indicating the limiting floc size, is also a good indicator of the residual turbidity, as expected. However, this is a less convenient parameter than the slope, since the latter can be determined fairly quickly, soon after the addition of coagulant.

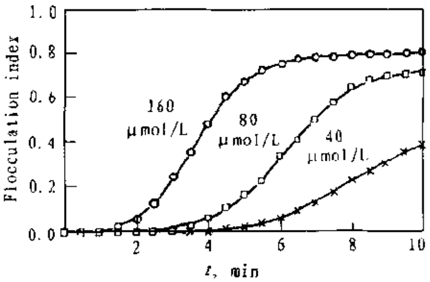

Fig. 2 Change in Flocculation Index with time at various alum doses (μmol Al)

Fig. 2 shows the change in the flocculation index after adding different amounts of aluminium sulphate ("alum") to kaolin suspensions in a stirred beaker. The clay concentrations were 37 mg/L, corresponding to a turbidity of 50 NTU and the pH value (after alum addition) was adjusted to 7.0. There was a 10s period of rapid mixing (300 r/min) after alum addition, followed by 10 min of slow stirring at 50 r/min. Values of the flocculation index at 30s intervals are shown as points and the lines are the best fit sigmoid curves. In all cases there is very good correspondence ($R^2 > 0.998$) between the points and the fitted curve. As the alum dosage increases there is a progressive increase in the rate of rise of the *FI* value and an increasing plateau value, indicating larger flocs. Both the slope and plateau value show good correlation with the residual turbidity, after flocs have settled (Gregory, 1995b).

In all cases, there is a significant lag time before the *FI* begins to show a significant increase.

It has been shown recently (Duan, 1998) that this lag time is closely related to the time required for hydroxide precipitates to grow to an appreciable size. The lag time has no significant effect on the degree of flocculation, provided that sufficient time is allowed for floc formation. However, a more rapid onset of flocculation would generally be beneficial and the dynamic information provided by continuous testing should be useful in practical applications.

Other uses of essentially the same technique in laboratory flocculation testing are reported by Ching *et al*. (Ching, 1994) and Huang and Liu (Huang, 1996a). The additional information on dynamic aspects of flocculation makes this a very useful addition to the standard jar test procedure.

2.3.2 Concentrated suspensions

Flocculation of concentrated suspensions shows very different behaviour. This is relevant to the treatment of high-turbidity waters such as from the Yellow River, which is subject to periodic run-off containing very high levels of fine silt (loess). At high particle concentrations the floc size can pass through a maximum value and then show a significant decline. An example is shown in Fig. 3, for the flocculation of a suspension of kaolin clay at a concentration of 30 g/L, with a high molecular weight cationic polymer. The ratio value passes through a sharp maximum less than one minute after adding the polymer and then declines to a steady value which is much lower than the peak. Fig. 3 also shows the settling rate of flocs at various times after adding the polymer. These values also pass through a maximum at the same time as the ratio values, giving confidence in the turbidity fluctuation method. The effect shown in Fig. 3 may be due to imperfect mixing and the wide range of effective shear rates encountered by growing flocs.

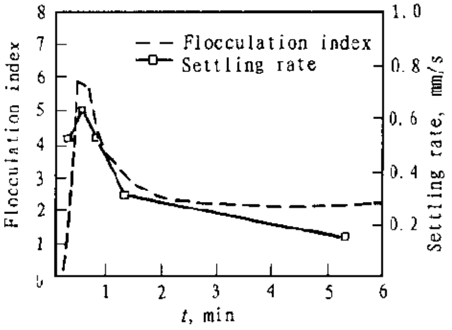

Fig. 3 Flocculation Index (or ratio value) as function of time after adding polymeric flocculant to a 30 g/L clay suspension, stirred at 120 r/min. Settling rate data are also given

2.4 Plant applications

It would be very convenient to have a simple flocculation monitor for use in water treatment plants. The optical monitor described above should, in principle, be applicable to on-line plant application. Water could be sampled soon after coagulant dosing and then passed through the monitor. Some opportunity would have to be given for the formation of small flocs. This could be provided by flow through a length of coiled tubing (Gregory, 1981) or some form of in-line mixing device. The monitor reading would then give an indication of the effectiveness of the coagulant dosage, only a short time (a few minutes) after applying the coagulant. Control of dosing could then be applied with a short feedback loop, allowing a rapid adjustment of dosage, in response to changes in raw water quality.

Control of coagulant dosage on the basis of finished water quality (e.g. after flocculation, sedimentation and filtration), involves a much longer feedback loop (up to two hours), which makes dose control much more difficult.

Another promising means of control, the Streaming Current Detector (Dentel, 1989) gives a still more rapid response, since the electrokinetic change occurs very soon after coagulant dosing and there is no need to wait for any flocs to form. However, the SCD method is only applicable where charge neutralization is the predominant destabilization mechanism, which is not always the case.

The turbidity fluctuation method responds directly to floc formation and hence should be more generally applicable. An early trial of this technique (Brown, 1985) showed that for treatment water containing organic colour, with aluminium sulphate, there was a close correspondence between the degree of colour removal and the flocculation index. A more recent use of the same technique for flocculation monitoring in a water treatment plant is by Huang and Chen (Huang, 1996b).

When "sweep flocculation" is the operative mechanism, which is very often the case in practice, the flocculation index does not necessarily give a simple indication of the optimum dosage, for instance by passing through a maximum value. This is because the formation of a hydroxide precipitate also causes an increase in the monitor response. Nevertheless, it should be possible to allow for this effect and to establish a relationship between the flocculation index value and the operational optimum conditions for good flocculation.

3 Particle monitoring

As discussed earlier, there is much concern over the presence of pathogenic organisms, especially *Cryptosporidium* in treated water. Specific, on-line monitoring techniques are not yet available and particle monitoring is a convenient, though less satisfactory substitute. If the general level of particulate contamination can be reduced to a very small amount, then it can be reasonably assumed that pathogens will also be largely removed.

3.1 Turbidity

The most common means of monitoring particles in water is by turbidity measurements. Turbidity of treated water is routinely monitored, often on a continuous basis and standards for drinking water must be met. In the European Union the turbidity of drinking water should not exceed 1 NTU. Still lower turbidity standards may be applied in future. The problem is that small numbers of particles around 5 μm in size (typical of *Cryptosporidium* oocysts) contribute very little to turbidity, as conventionally measured by light scattering. Thus a water with a very low turbidity (less than 0.1 NTU) may still have significant numbers of pathogens.

This has led to interest in more sensitive particle monitoring techniques for water treatment applications.

3.2 Particle counting

Particle counters are available which count and size individual particles as they pass through a sensing zone. Those used for treated water are based on optical sensing-either by light transmission ("light blockage") or by measurement of scattered light. Light blockage counters are quite often used, especially in the USA (Hargesheimer, 1992). These can detect particles larger than about 1 μm and provide a much more sensitive indication of such particles than conventional turbidity measurements.

Particle counters give detailed information on particle size distribution, typically as numbers of particles in defined size bands. There is some uncertainty about the actual sizes reported since the light blockage effect also depends on other properties of particles. While detailed information is valuable in certain cases, especially in research studies, a simpler measure of particle concentration may be preferable for on-line monitoring and control of filters. Particle counter results may be converted to a simple number, e.g. total number concentration, or particle counts above a certain size threshold.

3.3 Turbidity fluctuations

A simpler alternative to particle counting is the turbidity fluctuation method, discussed above as a means of monitoring flocculation processes. Gregory (Gregory, 1990) pointed out that this method also could be used as a sensitive monitor of particles in water. It was shown that fluctuations in transmitted light intensity can be used to detect particles larger than about 1 μm and that for larger particles the technique becomes much more sensitive than turbidity measurements. However, for sub-micron particles, simple turbidity monitoring gives a more sensitive indication. Turbidity fluctuations cannot give detailed information on numbers and sizes of particles, but an empirical "particle index" can be derived, which is adequate for many purposes.

Comparison with particle counting data for filtered water at a water treatment plant (Gregory, 1994) show that the particle index is of comparable sensitivity and can give clear indication of deterioration in filtrate quality, before any significant turbidity increase becomes apparent. A commercial Particle Monitor based on the turbidity fluctuation technique is available (Kirby, 1998). This could provide very useful information on filtered water quality and help to protect against the possibility of pathogens such as *Cryptosporidium* entering a drinking water supply.

4 Conclusions

A simple optical technique based on turbidity fluctuations can be very useful in optimizing the removal of particulate contamination from water. The technique can form the basis of a continuous monitor of coagulation/flocculation processes, either in a modified jar test procedure, or for on-line treatment plant applications. By maintaining the coagulant dosage and other chemical conditions close to optimum, the overall particle removal performance can be significantly improved. This will lead to a reduced load on the subsequent filtration process and better quality filtered water.

Monitoring of filtered water for low levels of particles is becoming more important because of the threat of water-borne pathogens such as *Cryptosporidium*. Conventional turbidity measurements are of limited use and more sensitive particle monitoring techniques are needed. Particle counters provide high sensitivity and give detailed information on particle sizes and numbers. A simpler optical method, but with comparable sensitivity, can also be used as a monitor of filtrate quality. The Particle Index derived from this method correlates very well with particle counting data on filtered water in treatment plants.

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