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APPLICATION OF STREAM CURRENT ANALYZER AND PARTICLE COUNTER TO COAGULATION CONTROL IN WATER TREATMENT

Marcin KŁOS [a], Jolanta GUMIŃSKA [b], Krzysztof BARBUSIŃSKI [c]

[a] Dr.; SEEN Technologie & Faculty of Energy and Environmental Engineering, The Silesian University of Technology, Konarskiego 18A, 44-100 Gliwice, Poland
E-mail address: *marcin.klos@polsl.pl*

[a] Dr.; SEEN Technologie & Faculty of Energy and Environmental Engineering, The Silesian University of Technology, Konarskiego 18A, 44-100 Gliwice, Poland
E-mail address: *jolanta.guminska@polsl.pl*

[c] Prof.; Faculty of Energy and Environmental Engineering, The Silesian University of Technology, Konarskiego 18A, 44-100 Gliwice, Poland
E-mail address: *krzysztof.barbusinski@polsl.pl*

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Abstract

In water treatment plants (WTP), flocculation is carried out on the base of jar testing which is the basic method to determine optimum operating conditions, i.e. the range of effective doses of reagents, times of rapid and slow mixing and mixing gradients. However, the procedure for these tests, although of high technological reliability, also reveals some defects. One of the most important is that it is time-consuming. This means that we get all results with several hours' delay. The problem also concerns the hydraulic parameters of flocculation and separation. Jar test procedures and technical limitations of the equipment used in these tests only allow for a very approximate assessment of the required intensity and time of rapid mixing and flocculation. Taking into consideration the above limitations of jar tests so to get full control over the coagulation system, it is necessary to apply the system which allows to obtain full information about the course of all unit processes. The main element of the proposed system structure is a Stream Current Analyzer (SCA) cooperating with a pH analyzer. Taking into consideration measurement used in determination of treatment effectiveness, the most useful are spectrophotometric measurements of absorbance UV254 as an indicator of organic matter and particle number analyses as an indicator of suspended particles concentration.

Streszczenie

W praktyce wodociągowej proces ustalania parametrów technologicznych koagulacji realizowany jest na drodze testów zlewkowych, które stanowią podstawową metodę określania optymalnych warunków prowadzenia procesu tj. zakres skutecznych dawek reagentów, czasy szybkiego i wolnego mieszania oraz gradienty mieszania. Jednak procedura tych testów, mimo dużej wiarygodności technologicznej ma także pewne wady. Do najważniejszych należy zaliczyć to, że jest ona czasochłonna. Oznacza to, że ewentualne wyniki uzyskujemy czasami z kilkugodzinna zwłoką. Istotnym problemem jest również prawidłowy dobór parametrów hydraulicznych procesu flokulacji i separacji zawiesiny pokoagulacyjnej. Procedury testów zlewkowych i ograniczenia techniczne urządzeń stosowanych w tych testach pozwalają jedynie na bardzo przybliżoną ocenę wymaganej intensywności oraz czasów szybkiego mieszania oraz flokulacji. Biorąc pod uwagę powyższe ograniczenia testów zlewkowych, aby uzyskać pełną kontrolę nad przebiegiem procesu koagulacji wymagane jest zastosowanie systemu pozwalającego na uzyskanie możliwie pełnej informacji o przebiegu poszczególnych procesów jednostkowych. Głównym elementem proponowanego systemu jest Analizator Prądu Strumieniowego (SCA) współpracujący z analizatorem pH. W zakres pomiarów wejdą pomiary absorbancji w nadfiolecie przy długości fali 254 nm jako wskaźniki zawartości materii organicznej (UV254) oraz mętność (M) lub alternatywnie liczba i wielkość cząstek (LC) jako wskaźnik zawartości cząstek zawieszonych.

Keywords: **Flocculation; Stream Current Analyzer; Absorbance; Particle number analyse.**

1. INTRODUCTION

In water treatment a key factor determining the effectiveness of technological system are the properties of post-coagulation suspensions. Floc size and strength determine flocs susceptibility to their separation by flotation, sedimentation and filtration. Considering flocs strength in the process of filtration it is of less importance, since in this case, the separation of suspensions is based on several mechanisms and involves not only the physical separation of phases. The mechanism of particles removal in filter bed is mainly dependent on the size of particles of post-coagulation suspension. It is also determined by the change of filter bed properties at the time of its operation [1].

In the process of separation of post-coagulation suspensions by sedimentation the problem of flocs strength is not the problem of great importance, because velocity field is relatively homogeneous, so flocs are not generally vulnerable to rupture. However, this is of particular importance in case of dissolved air flotation. In this process much smaller flocs are required in comparison to flocs separated in sedimentation. These flocs should also be resistant to breakage what is of particular importance in the mixing zone of the flotation tank, where post-coagulation suspension produced in the flocculation tank contacts with air bubbles produced in decompression of recycled water. In this zone the values of mixing gradient may reach up to 1000-3000 s^{-1} and shear stresses may cause flocs rupture if the strength of inter-particle forces are lower than forces which tend to their breakage. Similar problems may appear in devices with recirculation of post-coagulation suspension where flocs may break during their transport from sedimentation tanks to flocculators.

Mechanisms of breakage is dependent on the type of stress acting on a floc: fragmentation is caused by tensile stress (pressure gradient), and erosion by shearing stress. Surface erosion results in the removal of small particles from the floc surface and as a consequence an increase in the small particle size ranges. Large-scale fragmentation is the breakage of flocs into pieces of a similar size. The dominant mechanism of degradation depends on the floc density. Flocs of compact structure i.e. higher D value (fractal dimension) are more susceptible to breakage through the surface erosion, while those with a loose structure (low D value) usually split into fragments [2, 3].

Flocs strength is defined as the energy necessary for the floc rupture and is directly linked to its structure, which arises during its formation. During the process of flocculation floc growth is controlled by floc breakage. Therefore, the rate of aggregation is a balance between floc formation and floc breakage. In the initial phase of flocculation, microflocs agglomeration dominates over the process of their breakage, however, the importance of the breakage increases with the increase of floc size until it achieves steady floc size distribution for the specified stress conditions. When the tension rises above the critical value flocs break-up in order to achieve a new steady state. Finally, higher stress can lead to a situation that a furher floc growth is impossible, and hence effective treatment is unreachable [2,3].

In addition to the hydraulic parameters the composition of the treated water is also important for flocs properties. During the removal of humic substances from water flocs of various structures and of different susceptibility to separation can be formed. The structure and properties of flocs are determined by the pH and alkalinity of water. These parameters affect the resulting flocs size, as well as their density. Floc density is very important in aspect of its strength. The research conducted by Wang indicates that the flocs formed during the hydrolysis of aluminium sulphate at pH 5.0 have a more compact structure if compared to the flocs formed at pH 7.0 [4]. The studies also showed that the strength of the post-coagulation suspension increases with the increase of polymerized species in coagulant. The analysis of factors affecting floc size and structure and to assess the significance of these parameters on separation efficiency shows that these factors are very important elements that determine to a large extent, both the efficiency of flocculation and floc separation [4-9].

The fundamental difference between sedimentation and flotation as methods of separation of post-coagulation suspension, is the size of removed flocs. In case of sedimentation flocs spontaneously settle under gravity. Sedimentation runs the faster the larger size and weight of flocs are and the lower the viscosity of the liquid. Therefore, optimizing of coagulation for sedimentation process aggregates produced in the flocculation units should show good sorption properties and relatively large size and weight. As a result of particle agglomeration, the settling rate of single floc is always higher than the speed of sedimentation of a set of particles. It results from the fact that a certain amount of water is floated by flocs. However, the increase of particle size is limited by its breakage. As it reaches a critical size a floc can break into smaller particles. These flocs are of "cirrus" structure and they contain a significant amount of water. Specific gravity of hydrated flocs can be approximately calculated theoretically, but in order to determine the parameters of the sedimentation of the suspension it is necessary to carry out laboratory tests.

If sedimentation is used in place of flotation, operating conditions of the process must be changed. The optimum size of floc for flotation is smaller than required in conventional systems where sedimentation is applied and it is about 30-40 micrometers. This means that flocculation process should be conducted in such a way to increase the absorbing floc surface not by an increase in floc size, and thus the mass of individual floc, but by increasing the amount of smaller aggregates in the mass of treated water. Dissolved air flotation is one of flotation methods, which is based on the phenomenon of producing a stable agglomerate composed of dispersed phase (aggregates of post-coagulation suspensions) and gas bubbles. Bubbles in DAF process are generated in decompression of water, which was earlier saturated with air under increased atmospheric pressure. Agglomerates consisted of flocs and bubbles have a density less than water density and hence they float to the water surface. In the flotation systems the separation of post-coagulation suspensions is much shorter than in sedimentation. It lasts from 5 to 15 minutes and depends on concentration and type of pollutants.

In the paper the assumptions to the steering system of coagulant dosing at real time with the usage of a controlling system based on the Streaming Current Analyzer (SCA) were presented. The proposed structure of the system control is based on quality analysis of raw water and pre-selection of optimal dose. The main element of the structure is a Stream Current Analyzer (SCA) cooperating with a pH analyzer.

2. FLOCS UNDER SHEAR

There are many different measurements used as the representative characterisation of floc size. A simple measure of floc size is the floc longest dimension. However, this measurement is of limited use as it only gives an indication of floc size in one dimension. More common is two-dimensional measurement based on the longest dimension of the floc in both horizontal (d_{hor}) and vertical (d_{vert}) planes. Floc size is usually determined by a floc equivalent diameter measurement rather than an absolute value [10]. Equivalent diameters should be used for comparative purposes. The use of equivalent diameters allows the particle to be defined as a sphere or circle that is in some way equivalent to the particle. The largest sizes (d_{max}) are determined by the balance of floc growth and rupture within the fluid regime. Many studies have demonstrated that the upper cut-off size (d_{max}) complies with the empirical dependence

$$d_{\max} = CG^{-m} \tag{1}$$

in which G is the velocity gradient and C and m (>0) are constants. Here, the velocity gradient is defined by:

$$G = \left(\frac{\varepsilon}{\nu}\right)^{1/2} \tag{2}$$

where

G – the average velocity gradient (s^{-1});

ε – the rate of energy dissipation per unit mass of fluid (N m s^{-1} kg^{-1})

ν – kinematic viscosity [m^2 s^{-1}]

The maximum floc size is proportional to the Kolmogorov length scale which is defined by:

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \tag{3}$$

The Kolmogorov length defines the smallest length scale of turbulent motion and is location dependent [11].

Bache (1999) stated that for humic flocs $d_{max}/\eta \approx B$ where B is a constant (~1). It shows the d/η ratio is constant irrespective of the G value and that the upper floc sizes are controlled by the magnitude of the Kolmogorov length (Table 1).

Table 1.
Turbulence parameters and computation of strength [11]

G(s^{-1})	d(μm)	η(μm)	d/η	σ(Nm^{-2})
50	238	141	1.69	0.08
90	182	105	1.74	0.16
160	143	84	1.71	0.29
230	120	66	1.82	0.42

σ – the floc strength [N m^{-2}]

From the perspective of the effectiveness of separation of post-coagulation suspensions it is necessary to optimize the flocculation process. It should ensure two things:

- Obtaining the required characteristics of separated flocs (size, density, etc.),
- Maximising the removal of organic impurities.

In practice, in water treatment plants (WTP), this process is carried out on the base of jar testing which is the basic method to determine optimum operating conditions, i.e. the range of effective doses of reagents, times of rapid and slow mixing and mixing gradients. However, the procedure for these tests, although of high technological reliability also reveal some defects. One of the most important is that it is time-consuming. This means that any results we get with several hours' delay. If the quality of supplied water is stable it does not really affect the efficiency of the process. But it often happens that its quality varies very quickly, especially during periods of heavy rain or during periods of thaw. Another negative factor is the problem with the transfer of parameters determined in the laboratory scale tests to the technical system. In case of technological parameters of coagulation (the dose of reagents, the range of pH adjustment), these problems are not so important. The optimum doses of reagents determined by jar testing are usually confirmed in the technological system of the WTP.

The problem concerns the hydraulic parameters of flocculation and separation. Jar test procedures and technical limitations of the equipment used in these tests only allow for a very approximate assessment of the required intensity and time of rapid mixing and flocculation. This is due to the large influence of hydraulics and design of the mixing tank and mixers characteristics on the course of flocculation.

Taking into consideration the above limitations of jar tests so to get full control over the coagulation system, it is necessary to apply the system which allows to obtain full information about the course of all unit processes. The system should meet several conditions, which define its structure, the range of measurements and the assumptions to algorithms transferring the results of physical - chemical parameters into changes of various technological parameters. The basic conditions include:

- the need of operating in real time,
- process flexibility which allows for adjustment to varying quality of raw water and to different configurations of unit processes,
- assessment of the correctness of the process course and its effectiveness in relation to predefined parameters,
- automatic and semi-automatic working mode.

So defined conditions practically determine the range of possible applications for the measurement of two components:

- spectrometric measurements (without the usage of any reagents), as an element of the removal efficiency control of a specific group of contaminants,
- measuring the electrokinetic potential as a factor assessing the correctness of determination of a coagulant dose.

3. APPLICATION OF UV/VIS SPECTROPHOTOMETRY IN COAGULATION CONTROL

Control of coagulation process requires the use of measurements, which allow to analyze changes of water quality in the technological system in real time. As one of the tasks of coagulation is to remove organic pollutants, a necessary element of control of this process is the measurement of this group of compounds. At this moment there is a number of analytical methods commonly used to assess water contamination with organic compounds. However, in practice all of them are ex-situ measurements. The only solution that allows for the quantification of organic compounds in real time is ultraviolet and visible spectrophotometry (UV/VIS).

UV/VIS Spectroscopy is used in analysis of water and sewage from the 20th century. Particularly, it is widely used in the – middle UV range (200-300 nm), which allows to determine organic compounds, especially those with unsaturated binding in their structure, without usage of any reagents. The results of many studies showed that there are correlations between the absorbance measured at 254 nm (UV254) and several typical indicators such as total organic carbon, chemical oxygen demand and the specific parameters, such as THM formation potential. UV measurements are used in determination of water colour and turbidity [12, 13].

An important factor which decides about the possibility of application of this method in real-time is the compensation of the impact of other water contaminants, which can interfere with the measurement results. The most important contaminants are suspended solids (turbidity). Compensation of this factor can be done in two ways. The first way is filtration of the sample before measurement by a spectrophotometer. The second one is the program compensation of results based on parallel made measurements of turbidity or particles number.

Absorbance measurements are also used widely in the development of automation of the process of coagulation. The results of earlier studies have shown that they are essential elements of many models for the prediction of coagulant type and dosage.

3.1. Proposals for solutions of coagulant dosing and coagulation control

We can distinguish two basic types of systems for prediction of coagulant dosage and control of this process. The first one is based on the analysis of raw water quality data, while the second, takes into account changes in the quality of water during treatment and the effectiveness of this process. It is very difficult to decide which one is better. However, analyzing their advantages and disadvantages, it can be noticed that the first system is more resistant to disturbances arising from the course of the process [14].

If in prediction of the dose, only raw water quality is involved, the disturbances in the process caused by defects of mixers, problems with water distribution, local increases of mixing gradient etc., will be treated as the effects of improperly determined coagulant dose. The second approach, which takes into account the effects of coagulant dosing can not only identify possible problems at the implementation stage of the process, but first of all it allows to assess coagulation in terms of its dominant mechanism. This is particularly important in case of contaminated water with high concentration of organic matter, which may only be removed by sweep coagulation what allows to obtain required efficiency of removal, in particular, precursors of disinfection by-products and to ensure water biostability. Therefore, it seems that the latter approach has the potential to develop in future.

However, to ensure the proper operation of the system, the basic problem should be solved. The problem of control of process chemistry, defined as doses of reagents (coagulant, flocculent, adjustment of pH) and monitoring of the process must be considered. The key to ensure the proper system operation is the right structure of the measuring system which takes into account the selection of the type of individual measurements and their location, and the method of signal processing and applied algorithms of control.

3.2. System structure

The proposed structure of the system control and process control of coagulation is shown in Figure 1. It is a two-step solution. The first step is a system of quality control analysis of raw water and pre-selection of optimal dose. The main element of this step is a Stream Current Analyzer (SCA) cooperating with a pH analyzer. Basing on the collected measurements, these devices, working with the system of feedback control of the SCA and coagulant dosing proportional to the flow of water, can ensure:

- dosing of reagents in the amount appropriate for a specific raw water quality,
- correct dosing of coagulant regardless of the changes of quality or flow of raw water,
- the appropriate dosing regardless of changes of concentration of coagulant solution,
- maintaining the pH at the level required for optimal coagulation process.

There are two operational scenarios for the I step of the system:

1. Initial reference dose of coagulant will be adjusted as indicated by the SCA,
2. SCA will determine the coagulant dose, aiming at neutralization of electrokinetic potential and the dose will be adjusted based on the measurements of selected physical – chemical parameters.

The second stage of the system will operate with application of devices which will analyze the changes of water quality in treatment system. The range of measurements will involve the following indicators:

1. measurements in raw water:
   – turbidity (T) or alternatively the number and size of particles (PC),
   – ultraviolet absorbance at 254 nm (UV254),
2. post-flocculation measurements:
   – number and size of particles,
3. post-sedimentation (post-flotation) measurements:
   – turbidity, or alternatively, the number and size of particles,
   – absorbance (UV254).

These measurements should be complemented by operational parameters of rapid filtration system (hydraulic load, increase of filter resistance) and the basic indicators of filtrate quality. However, for correct operation of the control system, these data are treated only as an additional element, and can be applied to optimize the coagulation process with a view to increase filtration efficiency and to improve the economics of these processes. In fact, the effectiveness and success of the control system will be determined by the critical conditions that define the

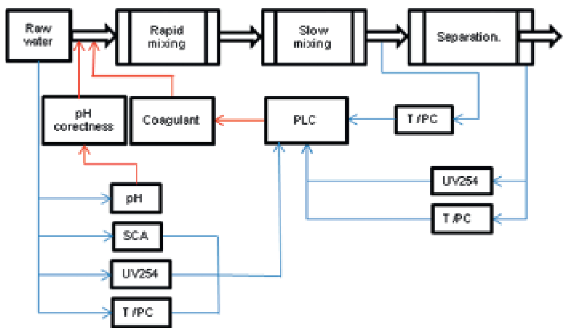

Figure 1.
Scheme of proposed coagulation control system (signatures in text)

required quality of water after the settling or flotation chambers. These conditions should be determined at the stage of preparation of data analysis algorithms. They should take into account not only the required technological effect, but also the influence of the quality of water on the course of further unit processes, particularly rapid filtration and disinfection.

3.3. The system of data processing and modelling

In practice, determination of required coagulant dose in jar tests generates a significant amount of tests, and because of its periodicity and long-term test procedure it does not allow to anticipate problems and the need to change technological parameters of the process [15,16]. Restrictions of such tests can be avoided by using modelling to predict the dose of the reagents. The results of many studies conducted in recent years have shown that it is possible to create a prediction model to the optimum coagulant dose. For the modelling of this problem, different methods are used e.g. the multivariate regression analysis, algorithms based on decision tree theory and the most commonly used neural networks. The proliferation of artificial neural networks (ANN) in solving such problems is due to the fact that in comparison to physical models they have the ability to map nonlinear relationships between different data taken into account in the model.

However, the creation of the model is to be extremely difficult. This is because the unit processes used in water treatment, in particular the coagulation process proceeds by different mechanisms and the relationships between various indicators of quality and technological parameters are rarely linear. Independently of the approved method of data analysis the most important element in creating the proper algorithm is an appropriate choice of input parameters of the model. Depending on the objective and the definition of the tasks of the model, we deal with the two most common situations:

1. the change of treated water quality is anticipated on the basis of data on raw water quality and the technological parameters of the process,
2. the optimal value of one or two technological parameters is determined on the basis of data on raw water quality, the value of some technological parameters of the process and the required water quality after the process.

The first case is commonly used for example in the modelling of water quality changes in water supply networks in terms of monitoring of the concentration of disinfection by-products or control of secondary water contamination in a distribution system. The other situation occurs in the monitoring and control of coagulation combined with a prediction of optimal dosage of the reagents. In this case, inverse process models (inverse process) are used.

In case of artificial neural networks which are mostly used for the prediction of coagulant dosage, the choice of quality and type of input data has a significant influence on the structure of the constructed network and thus the subsequent implementation of the model in practice. Table 2 shows the exemplary, most commonly used, configuration of input and output data models based on neural networks. As shown in the table, Model I is used when it is necessary to predict the effectiveness and process changes depending on the quality of supplied water. Such models are used in the safety assessment of technological processes and determining the criteria for water quality monitoring of raw water, beyond which the problems with the final quality of treated water should be expected.

Model II is used to predict changes in concentration of residual aluminium (so-called residual coagulant) in the water after the coagulation process. With the spread of the pre-hydrolyzed coagulants the problem of residual aluminium is no longer so important. General opinion about this type of reagents was that in a certain range of doses the danger of coagulant overdosing is minimal. Unfortunately, recently research has shown that this phenomenon in treatment system appears and aluminium speciation only changes. Because of high share of polymeric forms, the rate of precipitation is much greater than for conventional coagulants, independently of temperature and pH of supplied water, overdosing of pre-

Table 2.
Configuration of data for prediction models (IN – input parameter, OUT – output parameter) [12]

Model SSN	Raw water						After process					Coagulant dose
	Turbidity	Colour	pH	UV254	Alaknility	TOC	Turbidity	Colour	pH	UV254	Al	
I	IN	IN	IN	IN	IN	IN	OUT	OUT	-	OUT	-	IN
II	IN	IN	IN	IN	IN	IN	IN	IN	OUT	IN	OUT	IN
III	IN	IN	IN	IN	IN	IN	IN	IN	-	IN	-	OUT

hydrolyzed coagulants results in the appearance of large quantities of fine particles (size about 10 to 20 micrometers) in the effluent from the settling tanks. These particles can cause an increased load of rapid filters, which in turn reduces the effectiveness of filters and deteriorates economics of the process.

For the prediction of coagulant dosage in response to changes of water quality model III is used. It makes possible to estimate the dose of coagulant on the basis of specific range of the output data with the coefficient of determination greater than 0.9 and absolute error level so low that it allows for the application of the model at the technical conditions [17]. These models have some limitations. The most serious of these is the low flexibility of the model. The adopted methodology for the construction of neural network and its training makes it very difficult to use the network prepared for one application to another object. However, it seems that this is not the most serious disadvantage. The most important is the behaviour of the network in a situation when there are significantly different input values (especially of raw water quality parameters) than those that were used for training of the network. It is not about periodic deterioration of water quality during heavy rainfall, but about permanent change of water quality which affect the coagulation mechanism such as the change of the nature of organic pollutants known as specific absorbance (SUVA), the change of concentration of dissolved organic carbon and precursors of oxidation by-products. In this case, new tests are required to gather information which allows for re-adjustment ANN.

To minimize the above drawbacks of systems based only on qualitative data analysis of raw and treated water, algorithms to predict the dose of reagents in the process of coagulation are proposed as follows:

1. Application of the model in such a way that a coagulant dose is defined by SCA, aiming to neutralize the assumed level of the electrokinetic potential. This dose will be adjusted basing on the measurement of selected physical-chemical parameters. The system will be more versatile and allow to maintain the base dose value regardless of changes of raw water quality. Adjustment of the dose will be made based on the predominant mechanism of coagulation, or by measuring changes in UV254 absorbance value as an indicator of the effectiveness of removal of organic pollutants in the dissolved form or turbidity measurements (particle number) as the rate of removal efficiency of suspensions.
2. In order to identify disorders of the coagulation process the measurement of the amount of particles will be used. Using this type of measurement the creation of models of changes in size distribution of post-coagulation aggregates after individual unit processes is required. These models will mainly work on the basis of tracking changes in the amount of particles with sizes ranging from 1 to 10 micrometers. These measurements of particles number can also be applied to rapid filters. By using this type of measurement not only the course of flocculation can be monitored, but also the presence of unagglomerated small particles formed in coagulation by pre-hydrolyzed coagulants. These small particles are responsible for the concentration of residual coagulant and may also be an indicator of the presence of microorganisms in treated water. This second possibility is extremely important due to the current trend in optimization of treatment for removal of Cryptosporidium.

4. CONCLUSIONS

1. A key factor determining the effectiveness of technological system are the properties of post-coagulation suspensions. Flocs size determines their susceptibility to separation by flotation, sedimentation and filtration.
2. From the perspective of the effectiveness of separation of post-coagulation suspensions it is necessary to optimize the flocculation process. It should ensure obtaining the required characteristics of

separated flocs (size, density, etc.) and maximising the removal of organic compounds.

3. The key to ensure the proper operation of treatment system is the right structure of the measuring system which takes into account the selection of the type of individual measurements and their location, and the method of signal processing and applied algorithms of control.
4. The proposed structure of the control system is based on quality analysis of raw water and preselection of optimal dose. The main element of the structure is a Stream Current Analyzer (SCA) cooperating with a pH analyzer. Based on the collected measurements, these devices, working with the system of feedback control of a SCA and coagulant dosing proportional to the flow of water are able to ensure:

- dosing of reagents in the amount appropriate for a specific raw water quality,
- correct dosing of coagulant regardless of the changes of quality or flow of raw water,
- the appropriate dosing regardless of changes of concentration of coagulant solution,
- maintaining the pH at the level required for optimal coagulation process.

5. Taking into consideration measurements used in determination of treatment effectiveness, the most useful are spectrophotometric measurements of absorbance UV254 as an indicator of organic matter removal and particle number analyses as an indicator of removal efficiency of suspensions.

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