The Evaluation of Polymeric Organic Coagulants for Potable Water Treatment by Dissolved Air Flotation

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Preface

I hereby declare that this entire dissertation is my own work, unless otherwise stated in the text, and that it has not been submitted, in whole or in part, for a degree to any other Institution.

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Abstract

Historically inorganic coagulants were the coagulants of choice for DAF treatment of potable water. Water treatment practitioners using DAF technology preferred ferric chloride, an inorganic coagulant. Ferric chloride formed light, floatable flocs at relatively low flocculation intensities and detention times. The inorganic coagulant was also more forgiving during incidents of overdosing and raw water and pH variability.

A literature survey indicated that some researchers obtained good results with organic coagulants for potable water treatment on a laboratory jar test scale. Although there were some anecdotal reports of full-scale use of organic coagulants as primary coagulants for DAF in Finland and other Scandinavian countries, nothing significant has been cited in the literature.

The aim of this work was to investigate the application of polymeric organic coagulants for DAF treatment of potable water on a continuous pilot plant scale. The objective of the research was to compare the performance of polymeric organic coagulants against a control inorganic coagulant (ferric chloride) with respect to coagulant dose, water quality, filterability, sludge characteristics and chemical treatment costs.

Due to the large matrix of variables in the treatment process, namely, coagulation, flocculation and DAF operating parameters, preliminary

investigations to identify the more important variables that affect DAF final water quality were conducted on a laboratory batch scale flotation jar tester. Those variables found to have a significant effect on DAF performance were optimised on the DAF pilot plant. The other parameters that had no effect on DAF performance were set on the pilot plant, at values obtained from the literature. The geometry of the flocculation and flotation vessel was set to produce superficial velocities that correlated with appropriate values in the literature.

Optimisation of the operating parameters for the DAF pilot plant was based on the measurement of the DAF clarified water turbidity and pH. The coagulant trials were run under optimised flocculation and DAF conditions using ferric chloride as the control coagulant. The trial was then repeated under identical conditions using each of two polymeric organic coagulants. The DAF clarified water quality, filterability, sludge characteristics and DAF operability, were indicators of the effectiveness of the coagulants evaluated for DAF treatment of potable water.

The inflow to the DAF pilot plant was constant at the design flow rate of 1 m^3/h. Raw water was relatively clean, characterised by low turbidity (<10 NTU) and organic loading (TOC concentration < 5 mg/l). Raw water quality was consistent for the duration of the coagulant evaluation trials and there was no significant change in coagulant demand.

Coagulation and flocculation with both ferric chloride and the polymeric coagulants were relatively insensitive to physical conditions of mixing. Both jar test and pilot plant optimisation trials indicated that coagulation and flocculation were dependent on chemical changes (coagulant type, dosage and pH) and was insensitive to physical conditions of mixing time and intensity. Jar tests showed that treated water quality was not compromised even when the rapid mixing stage was excluded in the process. Pilot plant optimisation results showed that low flocculation intensities (<20 s^{-1}) and short detention times (5 to 10 minutes) were adequate for the production of good quality water. The range of values obtained compared favourably with specified DAF design guidelines. Coagulation mixing time and coagulation mixing intensity were set at 60 seconds and 200 s^{-1} respectively. Flocculation time and intensity were set at 10 minutes and 40 s^{-1} respectively. The saturated air-water recycle was set at 7%.

From the pilot plant optimisation trials, it was observed that the performance of the coagulants, ferric chloride and the polymeric coagulants, PolyA and PolyB did not appear to be affected by or sensitive to any particular mixing matrix. This implied that one set of operating conditions could be used for both the inorganic coagulant (ferric chloride) and the organic polymeric coagulants (PolyA and PolyB). It was possible to choose a set of operating parameters for the DAF pilot plant that suited all the coagulants evaluated. The coagulant dose was optimised on the pilot plant. The pH of the raw water and DAF clarified water was monitored to ensure that the pH was within the optimum efficiency range of the coagulant.

The polymeric organic coagulants, PolyA and PolyB were compared with ferric chloride with respect to a number of performance criteria that included treated water quality, filterability of the DAF clarified water, DAF float layer characteristics and chemical treatment costs.

DAF treated water quality, in terms of turbidity, produced by PolyB compared favourably to that produced by ferric chloride. DAF clarified turbidities using PolyB and ferric chloride were 2.5 and 2.8 NTU respectively, while the corresponding turbidities after filtration were 0.28 and 0.35 NTU. PolyB also achieved turbidity removals (60% removal based on DAF clarified turbidity) comparable to ferric chloride. In contrast, PolyA, produced DAF treated water with relatively higher residual turbidities (4.1 and 0.50 NTU on the DAF clarified water and filtered water respectively) and lower turbidity removals (42% based on DAF clarified water).

Generally all the coagulants, both the inorganic and organic coagulants, produced DAF clarified water (floated) turbidities that were acceptable as clarified water feed for sand filters.

From the measurements of UV absorbance @ 254 nm on the treated water and the reduction in absorbance relative to raw water, it was concluded that ferric chloride achieved better organic removal (62%) than the polymeric organic coagulants (53%). The higher organic removal efficiency of ferric chloride over the polymeric coagulants may be attributed to the mechanism of sweep flocculation, where the precipitated ferric hydroxide species provide a larger surface or adsorption sites for organic removal.

Lower doses of polymeric organic coagulants (PolyB) were required to produce final water turbidities comparable to turbidities of the ferric treated water. The optimum ferric chloride dose was 12 mg/l (expressed as ferric chloride) while the optimum doses for PolyA and PolyB were 5 and 3 mg/l respectively. Overdosing with ferric chloride was more forgiving than (overdosing with) polymeric organic coagulants.

Ferric chloride imparted more acidity into the water, relative to the polymeric coagulants. Depending on the buffering capacity of the raw water, the ferric treated water may have a significantly higher demand for pH correction chemicals.

Although ferric chloride produced marginally better quality DAF treated (filtered) water, all the coagulants (both organic and inorganic coagulants) produced final water that met Umgeni Water's minimum standards for potable water.

Ferric chloride produced a voluminous float that appeared to be less dense and occupied a larger volume compared to the more compact and 'drier' float produced by the polymeric organic coagulants. The stability of the float layer strongly impacted on the DAF run time. Stability tests based on DAF run times indicated that the DAF pilot plant could be operated continuously for three days before desludging, when polymeric organic coagulants were used. The ferric float started became unstable after ten hours of continuous operation, resulting in rapid deterioration of DAF clarified water.

Dry solids concentration of sludge generated by the polymeric organic coagulants was twice as high as the concentration of the ferric sludge. The dry solids concentration of the float layer generated by ferric chloride was 6.6%(m/m) and the dry solids in the float layer produced by PolyA and PolyB were 14.6 and 13.6%(m/m) respectively. Depending on the mode of sludge treatment and disposal, the large volume of relatively 'thin' sludge generated by ferric chloride, may have significant cost implications.

Filterability tests showed that PolyB, produced DAF treated water with the best filtration characteristics. Significantly longer filter run times were achieved for sand filtration of floated water pre-treated with PolyB relative to the ferric chloride treated water. Steady state filter run times achieved with ferric and PolyB were 40 minutes and 90 minutes respectively. The lower terminal headloss at turbidity breakthrough (160 minutes for ferric chloride and 240 minutes for PolyB) and steeper gradient of the headloss versus time relationship for the ferric chloride treated water (2.8 for ferric chloride and 1.8 for PolyB), was further evidence that ferric chloride produced flocs that had less favourable filterability characteristics compared to flocs generated by PolyB. The filterability characteristics of PolyA were marginally better than those of ferric chloride.

A chemical cost comparison based on average coagulant doses and budget chemical costs indicated that the polymeric organic coagulants were more cost effective than ferric chloride.

Comparison of optimisation data generated from batch scale jar test trials and DAF pilot plant trials indicated that there was very good agreement in the optimum coagulant dose determined using the jar test and the pilot plant for both ferric chloride and the polymeric organic coagulant (PolyA). Similar DAF treated water turbidities were achieved on the jar test and pilot plant.

There was no significant correlation in mixing conditions with respect to mixing intensity for optimum coagulant dose, between the jar test and the pilot plant. It was evident from batch scale jar tests and the DAF pilot plant trials that mixing conditions on a jar test may not be directly applicable to full-scale environments.

For DAF treatment of raw water with low turbidity and organic loading, polymeric organic coagulants will produce treated water of the same quality as that produced by ferric chloride, more cost effectively.

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Abbreviations / Nomenclature

SYMBOL	ABBREVIATIONS / NOMENCLATURE
abs	absorbance
DAF	Dissolved Air Flotation
DOC	Dissolved Organic Carbon, mg/l
nm	Nanometres
NTU	Nephelometric Turbidity Units
UVA	Ultra Violet Absorbance
$\mathrm{A_p}$	Theoretical Solubility of Air, mg/l
D	Impeller diameter, m
G	Mean Velocity Gradient, s^{-1}
g	Gravity constant (9,81m/s^2)
N	Rotational speed, rpm
n	Molar concentration, mol/l
P	Pressure of precipitated air, kPa
P	Mixer Power Input, watts, W
$\mathrm{P_o}$	Power Number
P(a)	Gauge pressure , kPa
Re	Reynolds Number
R	Universal gas constant (8,314J/mol.K)
S	Solubility constant, mg/(l.kPa)
$\mathrm{S_T}$	Solubility of air in water at temperature, T, mg/(l.kPa)
T	Temperature, ^{0}C
t	torque measure at drive shaft of jar stirrer, kg.m
V	Volume, m^3
μ	Viscosity, Pa.s
ν	Kinematic Viscoscity, m^2/s
π	pi = 3.141592..
ρ	Liquid density, kg/m^3

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CHAPTER 1

Introduction

1.1 Background

The most important requirement for the continuance and well-being of all forms of life is the availability of water of a suitable quality primarily for consumption. The quality of water for human consumption must be such that it does not cause ill-health to those that are healthy nor aggravate the health of those that are frail and sick. Because water is consumed daily, it is the most effective carrier of diseases. The classification of potable water as a food is widely accepted and the health regulations governing its production and the quality specifications that the treated water is required to adhere to are as stringent as other food processes and edible products.

Water treatment is primarily concerned with making water safe for consumption. Potable treated water must be free of bacteria, viruses and chemicals that will have an adverse effect on health both in the short term and the long term. Of secondary importance, from a health perspective, is the improvement in aesthetic appeal of the water and the reduction or removal of objectionable taste and odour in the treated water. An efficient water treatment process is one that consistently produces wholesome, safe and aesthetically acceptable drinking water cost effectively.

One of the prime objectives of a water treatment process is to remove finely divided particulate matter which, due to its small size (usually less than 10 µm) will not settle out of suspension by gravity in an economical time frame. Particulates of inorganic origin, such as clay, silt and mineral oxides, generally enter a surface water by natural erosion processes and can decrease the clarity of the water to unacceptable levels. Organic particulates, such as colloidal humic and fulvic acids, are a product of decay and leaching of organic debris and litter, which have fallen into the water source. The particulates impart a colour to the water, which in some extreme cases can be nearly opaque. Removal of these particulate contaminants is required for both aesthetic and health reasons (Montgomery, 1985).

1.2 Sedimentation versus flotation

The separation of particulates or suspended solids from the aqueous phase is conventionally achieved by sedimentation, where the water is preconditioned with the aid of chemicals. Solids separation and consequent clarification is achieved when the solid particles join together to form larger particles that settle by gravity. For the removal of readily settleable solids, sedimentation is a very effective solids-liquid separation process. It is the most widely used pre-filtration process for the production of potable water from surface water requiring chemical treatment (Zabel and Melbourne, 1980). The efficiency of sedimentation, however, is severely impaired if the solids have a low density and or high organic loading.

Often raw water contains low density particles such as algae and light floc formed during the chemical treatment of coloured waters. In particular, difficulties have been experienced when treating nutrient rich, stored waters which, during the summer months, support heavy algal blooms. These algae can pass through the sedimentation stage penetrating the filters or causing filter blocking.

Difficulties can also arise when treating coloured waters. The flocs produced from the chemical treatment of these waters have a low settling velocity, even with the addition of polyelectrolytes especially during the winter months. Large sedimentation tanks are therefore required and floc carryover can occur.

For these reasons, there has been a growing interest in the alternative solids-liquid separation process of dissolved air flotation (DAF) all over the world. In the Scandanavian countries, DAF has been successfully applied to clarification and sludge-thickening for many years. Also pioneering research in DAF clarification of surface waters, was undertaken in the United Kingdom. Case studies of large DAF applications have been reported from the Netherlands, Australia, Brazil, Canada and other countries (Haarhoff and van Vuuren, 1993). For algal removal, lower turbidities were obtained by flotation with alum as coagulant (Edzwald, 1993). DAF research done in Sweden and Finland on algal laden water found that 90% algal removal was achieved by flotation compared to 65% removal by sedimentation. Other advantages of flotation over sedimentation were lower capital costs, less backwashing and drier sludge that required no further conditioning (Rosen and Morse, 1976).

1.3 Brief overview of the different types of flotation

Flotation may be described as the transfer of a solid from the body of a liquid to the surface by means of bubble attachment. Flotation is a gravity separation process in which the gas bubbles attached to the solid particles lower the apparent density below that of water, allowing the bubble-solid conglomerate to float to the surface.

The different methods of producing the gas bubbles, give rise to different flotation processes. These are electro-flotation, dispersed air flotation and dissolved air flotation (Zabel and Melbourne, 1980).

1.3.1 Electro- flotation

Electro-flotation or elecrolytic flotation is based on the generation of gas bubbles of hydrogen and oxygen by the passage of a dc current between two electrodes immersed in a weak aqueous solution. Aluminium or steel sacrificial electrodes are normally used resulting in high replacement costs and maintenance costs due to fouling.

Although not widely used due to high electrical cost, due to the very small bubbles generated by electro-flotation, the process is more efficient under suitable conditions for the removal of low density particles. As the bubble formation does not create turbulence in this system, it is particularly suitable for fragile flocs. The surface loading is usually less than 4 m/h compared with up to 12 m/h for dissolved air flotation.

1.3.2 Dispersed air flotation

There are two different types of dispersed air flotation:

(1) foam flotation and

(2) froth flotation.

In foam flotation, air bubbles are generated by forcing the air through porous media, made from sintered metal, ceramic or plastic. In froth flotation, air bubbles are generated by introducing the air in the proximity of an impeller or turbine and breaking the air into small bubbles by the shearing movement of the impeller or turbine blades. Dispersed air flotation produces relatively large air bubbles, larger than 1mm, compared with bubbles of between 20 and 100 µm for dissolved air or electro-flotation. This mode of bubble formation is unsuitable for fragile flocs that are likely to shear as a result of the high turbulence in the system. Dispersed air flotation is mainly used in the mineral industry for mineral separation. To promote separation, 'collectors' and ' frothing agents' are often employed. Dispersed air flotation is more suitable for thickening than clarification and is thus not applied to potable water treatment.

1.3.3 Dissolved air flotation

In dissolved air flotation, bubbles are formed by the reduction in pressure of a water stream saturated with air. Air is released in the form of tiny air bubbles ranging in size between 20 and 100 µm. The difference between the operating pressure of the saturator and the outlet pressure in the flotation vessel is proportional to the volume of air injected into the system. The three main types of dissolved air flotation are vacuum flotation, micro-flotation and pressure flotation.

1.3.4 Vacuum flotation

In vacuum flotation, the water to be treated is saturated with air at atmospheric pressure. A vacuum is then applied to the flotation vessel, releasing the air as small bubbles. The achievable vacuum limits the amount of air available. Other disadvantages of vacuum flotation are that it is a batch process and that sophisticated equipment is required to maintain the vacuum.

1.3.5 Micro-flotation

In micro-flotation, the entire volume of water is subjected to the increased pressure. This is achieved by passing the water down and up a shaft approximately 10 m deep. In the down flow section, the water is aerated and the amount of air dissolved in the water increases due to the increase in the hydrostatic pressure. As the water rises in the upflow section, the hydrostatic pressure decreases and some of the air is released in the form of air bubbles. The depth of the shaft provided determines the amount of air available.

1.3.6 Pressure flotation

Pressure flotation is currently the most widely used dissolved air flotation process. In pressure flotation, air is dissolved in water under pressure. The air bubbles are formed when the pressure is reduced to atmospheric, resulting in the release of air in the form of fine air bubbles.

Three basic pressure flotation devices are used.

(a) full flow pressure flotation

(b) split flow pressure flotation and

(c) recycle flow pressure flotation.

In full flow pressure flotation, the entire influent is pressurised and aerated. In split-flow pressure flotation only a fraction of the influent is subjected to pressurisation, while the remainder flows directly to the flocculation / flotation tank. This is a more cost effective arrangement than the full flow pressure flotation system, as the saturator and the feed pump only handle a fraction of the full flow.

Both the systems are unsuitable if a flocculation step is required, because any floc formed prior to the air release facility, will be destroyed owing to the high shear during pressure release.

The recycle flow flotation process is the most widely used system. Part of the clarified effluent is recycled, pressurised and saturated with air. The pressurised, recycled water is introduced into the flotation vessel through a pressure release device and mixed with the flocculated water. Fine air bubbles (20 to 100 µm diameter) are released when the pressure is reduced to atmospheric pressure. The air bubbles attach themselves to the floc and the bubble- floc conglomerate floats to the surface.

1.4 Application to the water industry (wastewater and potable water treatment)

Pioneering work on DAF for clarification in potable water treatment and sludge thickening in wastewater treatment was started some 30 to 35 years ago.

In the UK there are about 100 DAF plants and the implementation rate is about 5 to 10 new ones every year. The biggest plant has a capacity of 18750 m^3/h. Finland has more than 30 years experience with DAF and the number of full – scale DAF plants is the highest in the world. Since the 1970's all potable water plants (with a clarification step) for surface water treatment were DAF plants.

DAF is also very widely used for the production of industrial water in Finland. The DAF plants used for this purpose number 33, the largest plant with a capacity of 3600 m^3/h (Flotation Information Forum, 2000).

In South Africa, with scarce and often highly eutrophic water sources, there has been a keen interest in the development and application of DAF dating back over 30 years. The DAF process has been accepted as a viable alternative since the late seventies as evidenced by the substantial increase in full-scale DAF plants since the early eighties (Haarhoff and van Vuuren, 1993).

1.5 Research Objectives

Dissolved air flotation is an effective solid – liquid separation process for the removal of low density, light flocs, characteristic of algal or coloured water. It has been shown that DAF was not feasible for raw water turbidities greater than 100 NTU but produced better results than sedimentation when treating low turbidity waters (Valade *et al*, 1996).

The performance of a DAF process is primarily dependent on efficient chemical pre-treatment for the generation of stable flocs (Malley Jr *et al*, 1991). Particle destabilization was more important than floc size (Edzwald *et al*, 1992).

Coagulant dose and pH have a stronger influence on DAF performance than physical conditions (Malley *et al*, 1991).

Inorganic coagulants, especially alum, ferric chloride and ferric sulphate, are historically the most widely used coagulants. They are preferred primarily due to their application to a wide range of water types, conservative energy requirements and availability. Alum and suitable ferric salts are still widely used in most of the first and third world countries (Losasso, 1992).

DAF chemical pre-treatment using ferric chloride is more popular than alum because it is effective over a wider pH range and the flocs formed are more amenable to flotation. It has also been shown that under favourable conditions of pH and ferric chloride dosing, the removal of dissolved organic matter and the consequent reduction of THM formation potential can be maximised (Offringa, 1990).

1.5.1 Umgeni Water's experience with polymeric coagulants for conventional potable water treatment plants

Umgeni Water, in the KwaZulu Natal province of South Africa, is a bulk water treatment authority serving a population in excess of 7 million people in a supply area more than 21 000 square kilometres. Umgeni Water's three large water treatment plants (between 350 and 1000 megalitres per day capacity) and a number of smaller and older plants have successfully changed over from alum to polymeric organic coagulants, with no negative effects on water quality (Nozaic *et al*, 2000). All the Waterworks using polymeric organic coagulants have 100% compliance with Umgeni Water's potable water standards, which are considered more stringent than the guidelines specified by the Department of Health and the Department of Water Affairs and Forestry.

1.5.2 Encouraging results from other researchers on a laboratory batch scale

As early as 1973 it was shown that cationic polyelectrolytes were able to replace inorganic coagulants completely as primary coagulants for both low and high turbidity surface waters when G values greater than 400 s^{-1} were applied (Morrow and Rausch, 1974). Optimum coagulation with cationic polyelectrolytes using high energy mixers occurred in less than two minutes and an increase in the velocity gradient decreased the retention time and polyelectrolyte dosage necessary to effect colloidal destabilization (Morrow and Rausch, 1974). From another study, using a synthetic raw water and a standard jar tester, it was concluded that cationic polymeric coagulants were more efficient than alum for the removal of bacteria (Jidal and Singh, 1986).

1.5.3 Some advantages of polymeric coagulants over inorganic coagulants

A study of the long-term effects of polymeric coagulants at Umgeni Water found that polymeric coagulants had significant advantages over inorganic coagulants (Nozaic *et al*, 2000). Polymeric coagulants produce significantly lower volumes of 'drier' sludge. Polymeric coagulants also have less effect on the treated water pH than the inorganic coagulants, which impart a higher acidity to the water, thus necessitating the use of larger quantities of pH correction chemicals and more dosing facilities along the treatment line. Polymeric organic coagulants do not increase the TDS of the water and do not introduce metal ions. Operation in the charge neutralization zone allows the use of streaming current detectors for automatic dosage control by means of a feedback control loop. This form of control has been found effective over nearly two orders of magnitude of incoming turbidity without requiring reversion to manual control of coagulant dosage (Nozaic *et al*, 2000).

1.5.4 Aim

The aim of this project was to investigate the application of polymeric coagulants for DAF treatment of potable water on a continuous pilot plant scale.

1.5.5 Objective

The objective of the research was to compare the performance of polymeric organic coagulants against a control inorganic coagulant (ferric chloride) with respect to final water quality, filterability, sludge characteristics and chemical treatment costs.

1.6 Approach

The DAF treatment process has a number of operating variables that could affect treated water quality. These include raw water characteristics and flow rate, coagulation and flocculation parameters and DAF operating parameters. The chemical parameters that affect coagulation and flocculation include coagulant type, coagulant dose and pH. The physical parameters are coagulation time, coagulation intensity, flocculation time, and flocculation intensity. DAF operating variables include DAF geometry and volume of the air/water mixture, necessary for flotation.

The large matrix of variables was considered both cumbersome and time consuming to optimize on a pilot plant scale. The literature cites a wide range of operating parameters applicable to different raw water characteristics. It was assumed that some variables may be site specific with respect to raw water characteristics.

A pilot plant was used to generate data for the evaluation of polymeric coagulants for potable water treatment by DAF.

Preliminary tests were conducted using a laboratory-scale DAF jar Tester to determine the sensitivity of DAF performance to operating variables.

Those operating parameters found to have a significant effect on DAF performance were optimised on the DAF pilot plant. The other operating parameters, were set at conservative values guided by literature (Haarhoff and van Vuuren, 1993).

Due to differences between the jar test and pilot plant with respect to size, geometry and mode of operation (batch versus continuous), absolute values obtained from the jar test were not directly applicable to the pilot plant. Therefore, interpretation of jar test results were based on trends rather than absolute values.

DAF pilot plant operating parameters were optimised for each of the coagulants. The performance of the DAF pilot plant was monitored over a period of time, under constant, optimised conditions.

CHAPTER 2

Theory of coagulation and flocculation

2.1 Introduction

Because DAF for potable water treatment is a solid-liquid separation process, its efficiency is dependent on a constant inflow of flocculated water containing small stable flocs. In general coagulation and flocculation requirements for solid-liquid separation by DAF are very similar to requirements for sedimentation. This chapter deals with the practical and theoretical aspects of floc formation, including a brief summary on the coagulation and flocculation mechanisms for inorganic coagulants and polymeric organic coagulants. The important aspects of mixing for optimum floc formation are also discussed.

2.2 Particles in water

Particles in natural water vary widely in origin, concentration and size. Some particles have their origin from land or atmospheric sources (e.g clay, silt, pathogenic organisms), while some are produced by chemical and biological processes within the water source (e.g. algae, precipitates of calcium carbonate, iron and manganese). Particle size may vary by several orders of magnitude, from a few tens of nanometers (e.g. viruses) to a few hundred micrometers (e.g zooplankton).

Humic substances are the major organic constituents of unpolluted waters. They are derived from soil and are also produced within natural water and sediments by chemical and biological processes such as the decomposition of vegetation.

Water treatment is primarily a solid–liquid separation process and the process of coagulation and flocculation as practised in water treatment can be considered as three separate and sequential steps:

(1) coagulant formation;

(2) particle destabilization, and;

(3) inter-particle collisions (Amirtharajah and O'Melia, 1990).

2.3 Definition of coagulation and flocculation

The definition of coagulation and flocculation is complex. Coagulation is considered to encompass the overall process of particle aggregation within a water being treated (Amirtharajah and Tambo, 1991). These include chemical particle destabilization and inter-particle physical contacts. The coagulation process is usually accomplished with two types of tanks arranged in series: rapid mixing tank for coagulant addition, coagulant formation, particle destabilization; and flocculation tanks to promote inter-particle contact and agglomeration. The physical process that facilitates particle-particle contact is termed flocculation.

In order to avoid confusion a simpler definition that separates the two terms, coagulation and flocculation, will be adopted in this work. Coagulation is defined as the process whereby the destabilization of the particles take place. Flocculation is the process whereby the destabilised particles are induced to come together and form larger agglomerates (Bratby, 1980)

2.3.1 Stability of colloids

Most particles in water have electrically charged surfaces, that are usually negative. Figure 2.1 shows a negatively charged colloidal particle, with a cloud of ions (diffuse layer) around the particle. Because the particle is negatively charged, an excess of ions of opposite charge (positive) accumulate in the interfacial region. Ions of opposite charge accumulating in the interfacial region together with the primary charge form an electrical double layer. When a particle moves in an electrical field, some portion of the water near the surface of the particle moves with it. This gives rise to the plane of shear of fluids around the particles. The electrical potential between the shear plane and the bulk solution can be determined by electrophoresis measurements and is termed the zeta potential or electrokinetic potential (Montgomery, 1985; Penniman, 1981).

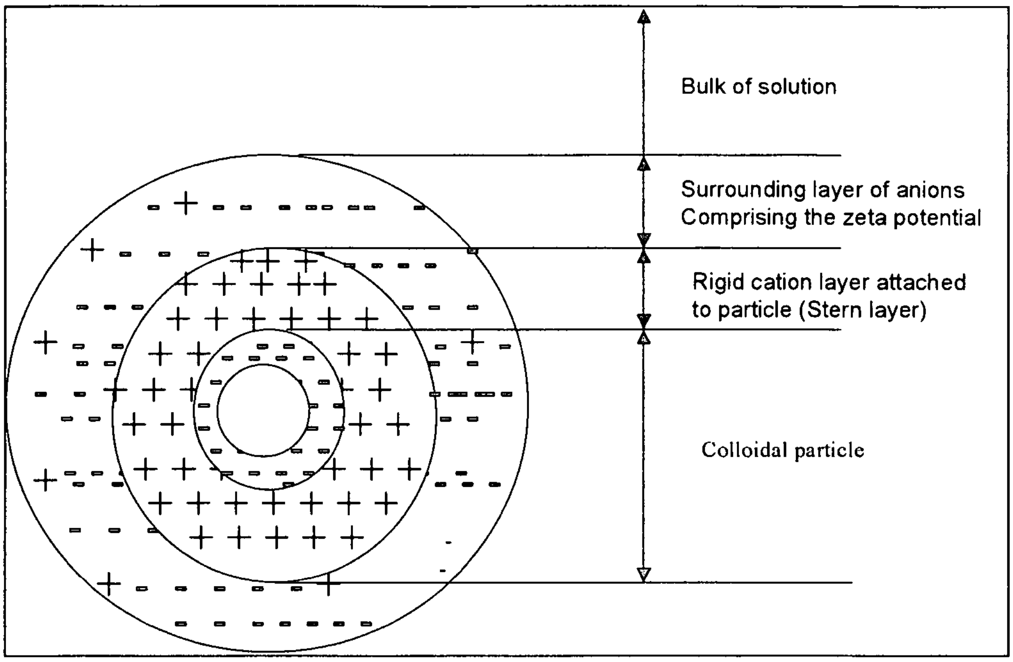


Figure 2.1: Representation of a colloidal suspension in a solution, showing the electric double layer (Penniman, 1981)

The charges cause the particles to repel one another. The more negative or higher the zeta potential, the greater the repulsion and, therefore, the greater the stability. As the zeta potential approaches zero, the negative charge becomes less effective and conditions approach optimum for flocculation and consequent aggregation (Penniman, 1981).

2.3.2 Chemistry of coagulation

The two primary functions of coagulation chemicals are particle destabilization and strengthening of flocs to reduce floc breakup. Chemicals serving one or both of these purposes must also satisfy several practical constraints, including low cost, ease of handling, availability and chemical stability during storage. In addition, the coagulant must form highly insoluble compounds or be strongly adsorbed on to the particulate surface, thus minimizing the concentration of soluble residuals (coagulant) that may pass through the treatment plant.

Selection of the type and dose of coagulant depends on the characteristic of the coagulant, the particulates and the water quality. Although the interdependency of the stated variables is well understood, it is not yet possible to predict the type of coagulant and the optimum dose for a particular combination of particulates and water quality. A standard jar test apparatus is used for the bench-scale testing of coagulant dose and type. The apparatus and its application to water treatment will be discussed in more detail in chapter 4.

Pilot plant testing or finally full-scale testing may be required to refine the optimum coagulant combinations and doses because of the limitations of the jar test in simulating the hydraulic conditions in full-scale facilities.

2.3.3 Chemistry of inorganic coagulants and coagulation mechanisms

The two principal inorganic coagulants used in water treatment are aluminium sulphate and ferric chloride. In the United States, the predominant water treatment coagulant is aluminium sulphate or alum. For DAF treatment of potable water, however, ferric chloride, is the most widely used.

The aqueous chemistry of aluminium and ferric ions is complex. Both aluminium and ferric ions can undergo a series of reactions with the hydroxyl ion (OH^-), forming both monomeric and polynuclear species which in turn react with the particulate surfaces. The hydrolysis products, not the aluminium or ferric ion, cause particulate destabilization through charge neutralization (Amirtharajah and Tambo, 1991).

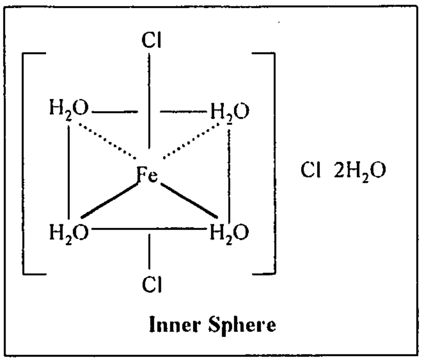
When ferric or aluminium ions are added to water, parallel and sequential reactions occur, the rates of which depend on several solution parameters, including pH, ionic species in the water, temperature, type and concentration of particulates, concentration of the coagulant and the mixing conditions at the point of coagulant addition. All of these factors will influence the quantity of coagulant needed to achieve destabilization of the particulates. Of these solution parameters affecting coagulant-particle interaction, pH plays the dominant role.

Coagulation of turbidity by iron(III) and aluminium salts occurs predominantly by two mechanisms:

(1) adsorption of hydrolysis species on the colloid causing charge neutralization, and;

(2) sweep coagulation where interactions occur between the precipitating metal hydroxides and the colloidal particles. Using alum as an example, it has been shown that the reactions that precede charge neutralization are extremely fast and occur within milliseconds without formation of Al(III) polymers and within 1 second if polymers are formed. This implies that for charge neutralization using inorganic coagulants (alum or ferric chloride) rapid dispersion (less than 0.1s) of the coagulant in the raw water stream is imperative so that the hydrolysis products that form between 0.01 and 1 second will cause destabilization of the colloid.

For sweep coagulation, where the hydroxide formation is in the range of 1 to 7 seconds, extremely short dispersion times and high intensities of mixing are not as crucial as in charge neutralization (Amirtharajah and Tambo, 1991). A simple diagrammatic representation of ferric chloride hydrolysis in water is presented (Gonzalez, 1992).



Inner Sphere

Figure 2.2: Ferric Chloride Hydrolysis

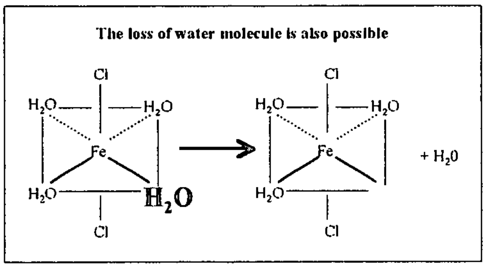
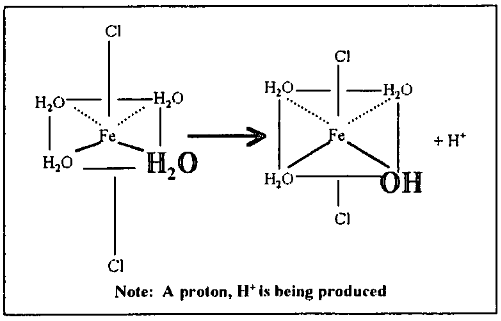

The loss of water molecule is also possible

Figure 2.3: Ferric Chloride Hydrolysis



Note: A proton, H$^+$ is being produced

Figure 2.4: Ferric Chloride Hydrolysis

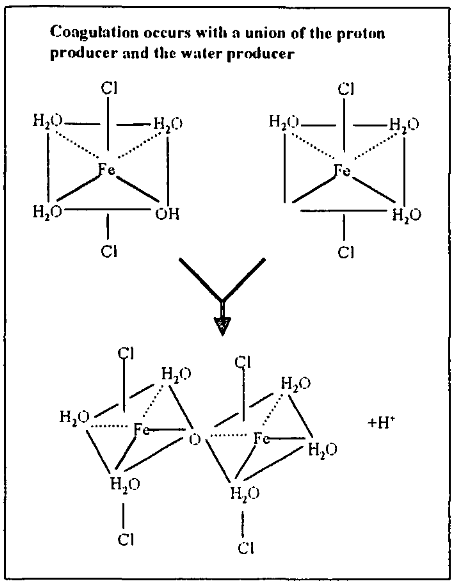

Coagulation occurs with a union of the proton producer and the water producer

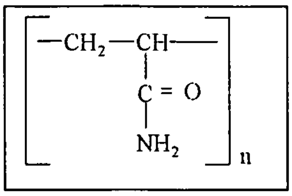
Figure 2.5: Ferric Chloride Hydrolysis

2.3.4 Chemistry of organic coagulants and coagulation mechanisms

Organic polymeric coagulants are long chain molecules consisting of repeating chemical units. The chemical units usually have an ionic nature that imparts an electrical charge to the polymer chain. When used as primary coagulants, polymers, in contrast to aluminium or ferric ions, do not form voluminous floc volumes.

2.3.4.1 Types of polymers

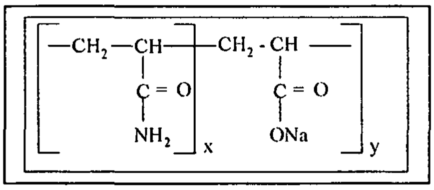
Synthetic organic polymeric coagulants are made either by homopolymerization of the monomer or by copolymerization of two monomers. Polymer synthesis can be manipulated to produce polymers of varying molecular weight, charge groups, number of charge groups per charge chain (charge density), and structure (linear or branched). Polymeric coagulants that carry no charge are called nonionic e.g polyacrylamide (Montgomery, 1985).



$$\left[-CH_2-\underset{\substack{|\\C=O\\|\\NH_2}}{CH}-\right]_n$$

Figure 2.6: Nonionic – polyacrylamide

Subsequent hydrolysis of the polyacrylamide under basic pH conditions, produces a polymer with anionic charges.



$$\left[-CH_2-\underset{\substack{|\\C=O\\|\\NH_2}}{CH}-\right]_x\left[-CH_2-\underset{\substack{|\\C=O\\|\\ONa}}{CH}-\right]_y$$

Figure 2.7: Anionic polymer – Partially hydrolysed polyacrylamide

The third type of polymer has a cationic or positive charge group incorporated in the polymer chain. These are the most widely uses organic polymers in the potable water industry. The poly(DADMAC), Poly(diallyldimethylammonium chloride) or poly(DMDAAC), Poly(dimethyldiallylammonium chloride) is one of the most widely used primary coagulants. They are chlorine resistant and the charge density is not pH sensitive.

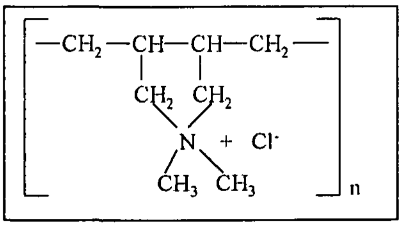


Figure 2.8: Cationic poly(DADMAC) or poly(DMDAAC) polymers

Also widely used as primary coagulants are the cationic quarternized polyamines. These have properties similar to poly(DADMAC).

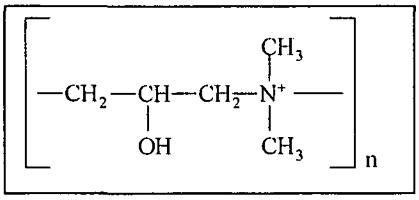


Figure 2.9: Cationic Quarternized polyamines

Over recent years, the use of blended polymeric coagulants gained popularity, where a poly(DADMAC) is blended with an inorganic polyaluminium chloride or polyaluminium sulphate. This resulted in the polymeric coagulants (blended) being applicable to wider water types at reduced costs.

2.3.4.2 Coagulation mechanism

Because most particulates in natural water are negatively charged (clay, humic acids, bacteria), cationic polymers achieve particle destabilization through charge neutralization by adsorbing onto the particulate surface. This results in a reduction in electrostatic repulsion such that particles may attach to each other following induced collisions. Generally the optimum dose is reached when the particulate surface is only partly covered with polymer (less than 50%). Overdosing will cause restabilization.

Destabilization by bridging occurs when segments of a polymer chain absorb on more than one particle, thereby linking the particles together. When a polymer molecule comes into contact with a colloidal particle, some of the reactive groups on the polymer absorb at the particle surface, leaving other portions of the molecule extended into the solution. If a second particle with some vacant absorption sites comes into contact with the extended loops and tails of the polymer, attachment can occur. A particle-polymer-particle aggregate is formed in which the polymer serves as a bridge.

2.3.5 Flocculation

The second stage of the overall process of solid-liquid separation is flocculation. In this stage physical processes transform smaller particles into larger aggregates or flocs. The rate of aggregation in this transformation is determined by the rate at which particle collisions occur. Destabilised colloids must be brought into contact with each other for aggregation to occur. Three physical processes transport particles so that the inter-particle collisions can occur. These contacts lead to the formation of particle aggregates. The three transport processes are:-

i. Brownian diffusion (perikinetic flocculation): This results from the random motion of the particles caused by their continuous bombardment by surrounding water molecules. Brownian motion affects the movement of colloidal particles but has only a minor influence on particles larger than 1um. Compared to most chemical reactions in solution, Brownian flocculation is a relatively slow process.

ii. Fluid shear (orthokinetic flocculation): In order to influence particles greater than 1um and speed up the flocculation process, mixing from external sources is required. This causes velocity differences or gradients in laminar or turbulent flow situations resulting in inter-particle contacts. The velocity gradient, G, is directly related to the energy dissipated per unit mass of the fluid.

iii. Differential settling produces vertical transport of particles resulting in collisions. The driving force is gravity and the settling velocity is the parameter controlling the mechanism.

2.4 Mixing requirements

Mixing intensity is expressed as mean velocity gradient, G

$$\text{Velocity Gradient, } G = \sqrt{\frac{P}{\mu V}} \qquad \text{.........(Eq. 2.1)}$$

P = Power Input, Watts, W

μ = fluid viscosity, Pa.s

V = Volume, m^3

2.4.1. Mixing for Coagulation

In the coagulation/flocculation process, two modes of mixing are required. Coagulation mixing or rapidmixing is required for the initial dispersion of the coagulant into the raw water stream for particle destabilization and flocculation mixing or slowmixing where mixing is required to accelerate the formation of aggregates (Amirtharajah and Tambo, 1991)

Recently attempts have been made to distinguish between the requirements for coagulation mixing intensity on the basis of the major modes of coagulation.

2.4.1.1 Coagulation mixing intensity for inorganic salts

Destabilization of colloids by inorganic salts occurs predominantly by two coagulation mechanisms; viz, sweep coagulation and charge neutralization.

Coagulation mixing intensity for sweep coagulation: In sweep coagulation, physical interaction occurs between the voluminous (iron or aluminium) precipitates and the raw water colloids. Under these circumstances, the chemical conditions for the precipitation of the hydrolysis and subsequent flocculation, are more important than the transport interactions between the colloid and hydrolysis product during destabilization (Amirtharajah and Tambo, 1991). When sweep coagulation is dominant, coagulation is not dependent on rapid mixing conditions (Amirtharajah and Mills, 1982).

Coagulation mixing intensity for charge neutralization: For charge neutralization, there has to be transport or collisions between the rapidly formed hydrolysis products and the colloid. Under these circumstances, high intensity mixing (G values of 3000 to 4000 s^{-1}) and of short duration (<0.1 s) may be beneficial (Amirtharajah and Tambo, 1991). However, experimental results for inorganic coagulants (alum and ferric chloride) showed that for the best destabilization, the mean velocity gradient should be in the range of 700 to 1000 s^{-1} or greater than 3500 s^{-1}. Velocity gradients between 1000 and 3500 s^{-1} are in the region that have a minimum destabilization rate (Amirtharajah and Trusler, 1986).

2.4.1.2 Coagulation mixing intensity for polymeric organic coagulants

The mechanism of coagulation with organic polymers are charge neutalization and inter-particle bridging. Since the competing reactions of adsorption on to the colloids and precipitation as a hydroxide, which occur simultaneously with inorganic coagulants, do not occur with organic polymers, it can be assumed that high mixing intensities are not necessary for organic polymers (Amirtharajah and Tambo, 1991). From a study of mixing with polymer in a baffled tank it was found that the optimum coagulation/rapid mixing intensity was between 250 and 750 s^{-1}. The corresponding mixing times were 60 s for the lower G value and 30 s for the higher G value (Keys and Hogg, 1978).

2.4.2 Mixing for flocculation

Flocculation is defined as the process whereby the destabilized particles make contact with other destabilised particles to form aggregates that are large enough to be removed by sedimentation or flotation. There are three main modes of flocculation: random flocculation, contact flocculation and pellet flocculation.

Random flocculation is the most common in a flocculator used for water treatment. Flocs of different sizes form as the initial destabilized colloid collides with others in the flocculation vessel. A balance between floc growth due to random flocculation and floc breakup due to agitation establishes an equilibrium floc size distribution that is attained after a certain duration of mixing (Amirtharajah & Tambo, 1991).

Contact flocculation can be characterised as a mode of flocculation where larger floc particles adsorb incoming minute flocs on to the surface. Contact flocculation is seen in solids contact clarifiers and partly in conventional flocculators with back mixing. Because of the presence of grown flocs with high concentration, C, the required duration of flocculation can be considerably reduced.

A lower G value causes the rate of formation of flocs to be slower and the size of the flocs formed to be larger. These floc characteristics support tapered flocculation, where higher G values are applied in the first flocculation compartment, followed by progressively lower G values in the other three cells of a 4-cell flocculator. The higher G values cause a rapid transformation of the primary particles into high density flocs, and the lower G values cause the build up of larger size flocs for better settling (Amirtharajah & Tambo, 1991).

The literature shows that a wide range of coagulation and flocculation conditions exist. Some researchers reported that high mixing intensities were applicable under certain circumstances while others showed that lower mixing intensities were sufficient under other circumstances (Kawamura, 1973). This seems to indicate an inter-dependency between coagulant dose, coagulant type and raw water characteristics.

2.5 Local experiences and trends

In a DAF plant survey of 14 South African DAF plants for clarification, it was noted that more than half the plants surveyed used inorganic coagulants as primary coagulants with organic polymers as coagulant aids. About half the plants used alum while the other half used ferric chloride as primary coagulants. In-line blenders and weirs were used for rapid mixing while less than 20% of the plants used mechanical stirrers. 50% of the plants used stirred flocculation tanks where the flocculation time varied between 6 and 120 minutes. Flocculation intensities of G values of 130 to 150 s^{-1} were applied. 20% of the plants used pipes and baffled channels while the rest used flow through turbulent un-mixed tanks for flocculation (Haarhoff & van Vuuren, 1993).

2.6 Overseas experience and trends

Malley and Edzwald (1991) presented a conceptual model of DAF where the dependence of DAF performance on effective pre-treatment by coagulation and flocculation was shown. The model re-affirms the findings of previous workers (Richards and Packham, 1975) that good coagulation conditions yield good flotation conditions. Bench-scale DAF tests by other Researchers indicated that excellent clarification by flotation is achieved with small pinpoint floc and that large floc need not be prepared for flotation (Edzwald, 1994). In the same study it was found that an 8 minute flocculation time gave similar results to a 16 minute flocculation time.

Studies on a low turbidity river water in Sweden showed that DAF was a robust process and only short flocculation times (5 minutes) were required to produce excellent flotation and filtration performance (Montgomery,1985). The researchers concluded that coagulation chemistry has a stronger influence on DAF performance than physical flocculation parameters (Kitchener *et al*, 1981).

2.7 Current trends in chemical pre-treatment for DAF

Using a synthetic water spiked with *E.coli*, it was shown that polyelectrolytes are more efficient in removing bacteria than alum. In the same work, it was found that turbidity removal with alum was slightly better than cationic polyelectrolytes (Jindal and Singh, 1986).

Bunker et al (1994), working with two different water types, humic and non humic waters, studied flocculation time and flocculation mixing intensity. They found that good residual turbidities were achieved at a flocculation time of 5 minutes with little or no improvement if the flocculation time was increased to 16 minutes. All mixing intensities (20, 55, and 140 s^{-1}) produced turbidities less than 1 NTU. With alum and ferric chloride lower turbidities were produced with increasing flocculation mixing intensities.

In the same work, the workers found that turbulent mixing conditions occur at the bottom of flotation tanks, where the recycle flow is injected, in full-scale plants. If fragile flocs are prepared by use of low flocculation mixing intensities, the turbulent mixing may shear the floc particles producing micron size particles. This would yield poorer flotation performances compared to particles tens of microns in size. If higher mixing intensities were used in flocculation, small pinpoint flocs (tens of microns) that are stronger and more resistant to shear may be formed. It was shown that good flotation performance occurs at higher mixing intensities than are used in flocculation systems in sedimentation plants.

Vlaski *et al* (1996), working on bench-scale experiments with an algal laden model water using ferric chloride as coagulant found that low flocculation intensity (G of 10 s^{-1}) resulted in the highest DAF particle removal efficiency although the flocs were of a weak structure. They showed that the common statement that DAF requires high flocculation G values in order to produce small, strong shear resistant flocs may not always apply.

In an earlier study, cationic polyelectrolytes were able to replace inorganic coagulants completely as primary coagulants for both low and high turbidity surface waters when G values of greater than 400 s^{-1} were applied (Morrow and Rausch, 1974). A comparison of the sludge produced by cationic polyelectrolytes and inorganic coagulants indicated that polymer sludge has a greater density, more rapid settling, improved dewatering characteristics and significantly lower volumes (Kitchener and Gochin, 1981).

CHAPTER 3

Theory of DAF

3.1 Introduction

A dissolved air flotation plant for potable water treatment consists of three independent unit processes. First in the treatment chain is the flocculation vessel where the inflow is pre-conditioned for the formation of stable flocs. An air-water saturator system is the source of air bubbles and a flotation vessel that facilitates the intimate contact between pre-formed flocs and the air bubbles and provides the required environment for the separation process to take place. Ideally, the floc-air bubble conglomerate, due to its acquired buoyancy and suitable hydraulics, moves to the surface of the flotation vessel and accumulates as a sludge float layer, while the clarified water moves to the bottom of the vessel where it is collected for final filtration.

3.2 Solids separation by flotation

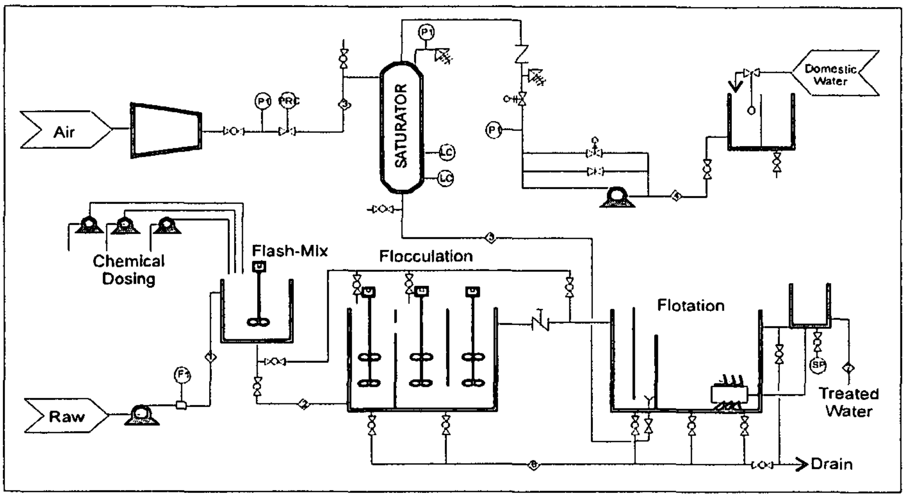


Figure 3.1: Schematic Representation of a DAF Process

Flotation is more complex than other phase separation processes, in the sense that there are three phases involved: the solid phase (particles), gas phase (air bubbles) and the liquid phase (water) (Haarhoff and van Vuuren, 1993).

The first stage in flotation is the **contact zone** where intimate contact takes place between the pre-formed particles in the water and air bubbles. Favourable conditions in the contact zone result in the formation of stable particle-bubble agglomerates that have the required buoyancy for efficient solid-liquid separation (by flotation). The second stage is the **flotation zone**, where the solid particles are physically separated from the bulk liquid by virtue of the hydraulics in this zone and the difference in density between the particle-bubble agglomerate and the bulk liquid. The source of air bubbles is an air-water saturator, where water and air is allowed to mix under suitable pressure conditions.

3.2.1 The contact zone

The bulk liquid carrying pre-formed particles and a stream of water saturated with air meet in the contact zone. Air bubbles precipitate out of solution due to the drop in pressure experienced by the incoming saturated air-water stream. Close contact between the particles and the air bubbles results in air bubble- particle attachment.

There are four models for air-bubble-particle attachment that have been proposed by various workers for the formation of a stable air-bubble agglomerate (Kitchener and Gochin, 1981; Shade, 1982; Vrablik, 1959).

a) Adhesion of bubbles to preformed flocs: Preformed flocs are attached to the surface of the air bubbles, when the particle penetrates the surface of the air bubble. This contact is only possible after the water separating the particle and air bubble is swept away by 'hydrodynamic thinning'. The probability of collision and adhesion is proportional to the particle diameter. The particle surface must be hydrophobic for the particle to stick to the air bubble. Haarhoff and van Vuuren, (1993) concluded that this model will dominate when very small particles (20 µm diameter or less) are successfully floated by bubbles that are of comparable size (40 µm).

b) Enmeshment of the air bubbles into the floc particle: The bubbles become trapped in the rough and jagged structure of a floc particle that is many times larger than the individual bubbles. Because there may be no adhesion, bubbles can be dislodged from the particle. Therefore, the collision efficiency during enmeshment is lower than that for adhesion.

c) Incorporation of the air bubbles into a floc particle. If there is floc breakup and consequent re-flocculation in the contact zone or flocs are still in the process of being formed while air bubbles are introduced into the contact zone, air bubbles may be incorporated into the growing floc.

d) Growth within flocs: It is based on the principle that supersaturated air will preferentially precipitate out on existing nuclei when pressure is gradually reduced. When saturated air was introduced over a layer of iron flocs, after a few minutes, small air bubbles started to grow within the floc (Kitchener and Gochin, 1981).

Under normal operating conditions, stable, preformed flocs are introduced into the contact zone. Therefore bubble-particle agglomeration by adhesion and enmeshment are considered dominant contact mechanisms.

3.2.1.1 Bubble size

There is consensus in the field that small air bubbles (between 40 µm and 170 µm) are best for DAF, due to the following reasons: For small bubbles, a larger number of bubbles can be generated from the same quantity of air. Smaller air bubbles move more slowly to the top and increase particle-bubble contact time and opportunity for attachment between particle and bubble. Larger bubbles will cause disruption of the float layer (Haarhoff and van Vuuren, 1993).

3.2.1.2 Particle size

There is a wide variation in particle size suitable for efficient particle-bubble attachment and subsequent flotation. There appears to be a certain minimum size below which the particles are not affected by the upward mobility of the bulk water and bubbles in the contact zone and therefore not suitable for flotation. Above the maximum particle size, the particle may be too heavy to be floated. Particle density also plays an important role in the floatability of particles. Theoretically particle diameters between 10 and 50 µm were ideal for DAF water treatment applications (Edzwald *et al.,*1990). In practice, however, particles with much higher diameters are effectively treated by DAF (Haarhoff and van Vuuren, 1993).

3.2.1.3 Detachment

Turbulence and gravitational forces in the contact zone result in some particles being detached from the bubble as they move through the water up the contact zone (Haarhoff and van Vuuren, 1993). Large particles are more likely to be detached due to their higher inertia and a greater strain on the particle-bubble linkage.

The contact zone design should allow for sufficient time for particle bubble attachment. Enough turbulence should be created to facilitate collisions between particles and air bubbles. Excessive turbulence should be avoided due to floc shear.

3.2.2 Air- water saturator system

The most convenient way of introducing air bubbles into the contact zone of the flotation vessel, is in the form of a stream of water saturated with air. Air and water are pumped into a pressure vessel maintained at an elevated pressure. Since air solubility in water increases with pressure, mass transfer from the gas phase into the liquid phase takes place resulting in a supersaturated air-water mixture. An equilibrium shift is experienced by the mixture when it is released under atmospheric pressure into the flotation vessel, resulting in the precipitation of small air bubbles. Air solubility is dependent on three factors :

i) Temperature; Solubility of air in water decreases as temperature increases.

ii) Pressure; Air solubility increases linearly with pressure and

iii) Air composition; Atmospheric air consists mainly of nitrogen and oxygen in the proportion of 79% to 21% respectively. Because oxygen is twice as soluble in water than nitrogen, the air above the saturator becomes deficient in oxygen while the nitrogen concentration increases. At equilibrium, the air concentration in the saturator is 88% nitrogen and 12% oxygen. Saturator air will therefore be about 9% less soluble than atmospheric air. It was therefore concluded that theoretically, saturator efficiency only reaches 91% on the basis of atmospheric air (Haarhoff and van Vuuren, 1993).

In practice, air requirements for clarification by DAF are met by recycling a small fraction of the DAF treated water into a saturator, operated at a high pressure. The saturated water stream is then injected into the contact zone via suitably chosen nozzles. The volume of the recycle is expressed as a percentage of the inflow as recycle percent. Unlike DAF application for thickening, where air requirement is a function of particle concentration and is expressed as an air:solids ratio, for clarification, air requirement is generally expressed as the mass of air per volume of raw water being treated (mg/l). The quantity of air required for clarification generally varies between 5 and 10 mg/l.

3.3 South African experience

Haarhof and van Vuuren (1993) conducted a comprehensive survey of the South African DAF plants. Fourteen DAF plants that operated in the clarificarion mode participated in the survey. There were 6 different contact zone configurations. The hydraulic loading varied between 50 and 120 m/h with the retention time between 1 and 4 minutes. The crossflow velocity between the contact zone and the flotation zone was generally below 50 m/h. Some plants also operated at crossflow velocities up to 100 m/h. The hydraulic loading in the flotation zone was on or below 8 m/h with a minimum loading at about 4 m/h.

For DAF clarification applications, vertical, packed saturators are used. These are generally operated at pressures between 350 and 550 kPa and at hydraulic loadings varying between 60 and 100 m/h. The air-water recycle rates vary between 6 and 22% translating to an air concentration ranging from 5 to 13 mg/l.

CHAPTER 4

Experimental

4.1 Introduction

The DAF process for potable water treatment is a combination of three unit processes viz. Air-water saturation, coagulation/flocculation and flotation. The cost effective production of high quality DAF treated water depends very much on the performance of the individual unit processes.

From the literature survey, which was conducted, it may be concluded that for both local and overseas applications of DAF:

- Inorganic coagulants, especially ferric chloride, are the preferred coagulants.
- There is a wide variation in the applied mixing intensities for coagulation and flocculation.
- Laboratory scale investigations indicate that cationic polymeric coagulants may be used as primary coagulants for DAF (Morrow and Rausch, 1974).

The objective of the research was to investigate the performance of organic polymeric coagulants relative to that of an inorganic coagulant, ferric chloride for the treatment of potable water by dissolved air flotation. Ferric chloride was used as the reference coagulant because historically it is the coagulant of choice.

4.2 Definition of 'optimised' operating parameters

There are a number of variables in the DAF treatment process that affect the quality of the final water. These include the coagulation/flocculation variables: rapid mixing time, rapid mixing intensity, flocculation time, flocculation intensity and the flotation parameters: percent air/water recycle, contact zone upflow rate and residence time, crossflow velocity (between the contact zone and the flotation zone) and hydraulic loading or downflow rate.

All these parameters need to be set or optimised in such a manner that potable water of the desired quality is produced cost effectively. A generic definition of an optimum operating parameter viz. 'optimum coagulant dose', 'optimum rapid mixing time', 'optimum air-water recycle percent' etc. is the lowest value of the operating parameter that will results in the highest benefit to the quality of the final product, cost effectively.

The processes of coagulation/flocculation and flotation are primarily solids separation processes. Therefore measurement of efficiency of the DAF process were based on solids removal. Turbidity, is widely accepted in the water industry as an indirect pseudo-measurement of the presence of particulates in water. Turbidity measurements were used for optimization of the operating parameters for the DAF pilot plant.

Practical application of 'optimum' operating conditions are, in reality, dependent on local potable water quality guidelines and costs. The DAF trial was conducted at the Umgeni Water Process Evaluation Facility (Wiggins Road, Mayville, Durban). An optimum coagulant dose in terms of the Umgeni Water potable water guidelines, can be defined as the lowest coagulant dose that is required to achieve a consistent final water turbidity less than 0.5 NTU. For the DAF trial, final water turbidity was obtained by filtering the DAF clarified water through a Whatman no1 filter paper using the normal laboratory gravity filtration technique. The filter paper had a pore size of 7μm.

4.3 Criteria for comparison of coagulant performance

The performance of a polymeric organic coagulant under optimized conditions of coagulation and flocculation and saturated air-water recycle, will be compared to the performance of ferric chloride under similar conditions. The criteria for comparison included: potable water quality; coagulant dose; filterability; sludge characteristics and economics.

4.3.1 Potable water quality

The most important outcome of any water treatment process is potable water quality. The success of DAF for potable water treatment relies on a coagulant and its application conditions. The main aspects of potable water quality for which the coagulant is responsible are:

i) removal or reduction of particulate matter in water;

ii) removal or reduction of organic pollutants including colour;

iii) pH effects.

4.3.1.1 Turbidity

Turbidity measurement is based on the principle of light scattering by colloidal particles at right angles to an incident light that impinges on a body of water (containing colloidal particulate matter commonly referred to as suspended solids). The intensity of the scattered light is proportional to the amount of suspended material and is expressed as turbidity. For a water body containing particulates of fairly uniform size and colloidal type (physical-chemical) and relatively low concentration, there is an approximate linear relationship between turbidity (NTU) and suspended solids (mg/l). The raw water turbidity during this investigation was consistently lower than 10 NTU, typically in the 3 to 7 NTU range.

Turbidity was measured using a laboratory bench top Hach turbidimeter model 2100 N.

4.3.1.2 UV Absorbance @ 254 nm

Organic compounds that are aromatic in structure have conjugated double bonds that absorb ultraviolet (UV) light. UV absorbance is often used as a simple surrogate measurement for DOC (dissolved organic carbon). Edzwald (1993) used UV measurements expressed as specific UV absorbance (SUVA) defined as UV absorbance per metre of absorbance path length per unit concentration of DOC in mg/l. UV absorbance was measured using a double beam variable wavelength spectrophotometer, Milton Roy 1200.

UV absorbance @ 254 nm, was measured in a 50 mm flow through cell and expressed as absorbance per metre (path length).

4.3.1.3 pH

pH is one of the most fundamental and the most important measurement of the properties of water. The pH of the raw water can greatly affect the performance of a coagulant and more importantly the coagulation mechanism (See also section 2.3.3). Johnson and Amirtharajah (1983) conducted intensive studies with alum and ferric chloride and their dependence on pH. By plotting the concentration and solubility of the metal ion hydrolysis product species against solution pH, regions corresponding to optimum reduction or removal of colour or other organic constituents, were mapped out.

The pH of the final treated water needs to be within a specified range to be suitable for human consumption and stability. The corrosivity of the water, which can affect concrete and other pipes in contact with water, is a function of pH. Therefore, the control of pH in water treatment is of paramount importance.

The performance of the coagulants will be evaluated under prevailing raw water pH conditions. The impact of the coagulants on the final water pH will be assessed by comparison with the specified pH ranges for potable water.

pH was measured with a bench top Beckman pH meter model number 45, equipped with a glass electrode and automatic temperature compensation.

4.3.2 Sludge/float layer characteristics

Solids separation inevitably leads to the generation and accumulation of sludge. Because in DAF treatment of potable water, the sludge accumulates as a float layer on the surface of the water, sludge characteristics play an important role in the stability of the DAF process. Coagulant effects on sludge characteristics will be investigated under the following headings:

4.3.2.1 Sludge volume

A qualitative assessment will be made on the basis of the thickness of the sludge, and the amount of sludge generated.

4.3.2.2 Sludge stability

Under normal operating conditions, sludge stability may be defined as the time the float layer takes to break up and fall into the flotation vessel. The net result of sludge instability will be a deterioration in DAF treated water (floated) turbidity.

In order to evaluate sludge stability, the DAF pilot plant was allowed to run under optimised conditions for each coagulant until an irreversible deterioration in floated water turbidity, due to disintegration of the float layer, was recorded. The DAF run time corresponding to the onset of deterioration in floated water turbidity was used as an indirect measure of float layer stability.

4.3.2.3 Dry solids

Sludge samples were taken from the top of the flotation vessel above the water level at 4 equidistant points along the length of the vessel. The samples were composited before analysis. Depending on the mode of sludge disposal, dry solids concentration may be important. In most cases, waterworks sludge is transported off-site for disposal to landfill or municipal waste water plants. To reduce sludge treatment costs, a 'drier' sludge will be more beneficial. The sludge dry solids concentration was determined by drying a known mass of homogeneous representative sludge float in a constant temperature oven maintained at 105^{0}C. The dry solids concentration was calculated from the weight loss after drying.

4.3.3 Filterability

Filtration following clarification (by flotation) is the final polishing step in a conventional treatment chain. Bernhardt and Schnell (1993) used a floc filtration test apparatus to investigate effects of energy input during orthokinetic aggregation on the filterability of generated flocs. Tekippe and Ham (1971) compared the results of jar tests with sedimentation to those of jar tests with filtration and concluded that a sedimentation jar test is most appropriate to describe the sedimentation behaviour of the generated flocs whereas the filtration behaviour of the flocs can be ascertained in the filtration tests.

Dominant mechanisms involved in removal of suspended solids during rapid sand filtration depend on chemical and physical characteristics of the suspension, media, rate of filtration and the chemical characteristics of the water. The particles deposited in the filter are held in place by the attractive forces between the media and floc particle that are opposed by the drag forces (hydraulic shearing forces). As the deposits build up, velocities through the voids increase and the shear forces increase. Ultimately, breakthrough of the particles occur when the drag forces overcome the attractive forces (Cleasby, 1990).

The effect of chemical and physical characteristics of the floc may be determined from filterability tests where the other critical parameters that affect filtration (media, rate of filtration and water characteristics) are kept constant.

The nature of the floc particles in the floated water will impact on the performance of the sand filter. Thus the filterability of the flocs generated by the coagulants were investigated. The filter headloss with time and the filtered turbidity change with time were measured and compared for each coagulant.

A simplified and modified version of the Bernhardt and Schnell (1993) filtration test apparatus was used for the filterability tests. The filtration apparatus was only used for filterability tests on DAF pilot-scale tests and not for jar tests.

4.3.3.1 Laboratory Sand Filtration Apparatus

The small scale filtration unit (Figure 4.1) consists of a 1 metre long column, 43 mm ID. The column is graduated in 1 mm intervals for accurate measurement of the headloss development.

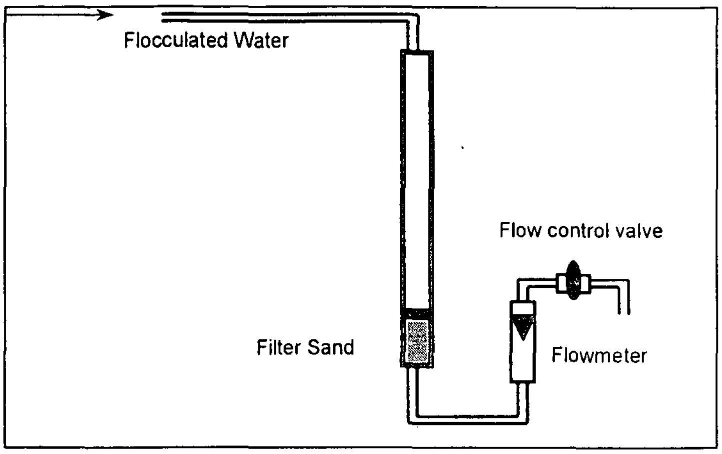


Figure 4.1: Laboratory sand filtration apparatus

4.3.3.2 Laboratory Sand Filter Description and Operation

Sand with an average particle size of 0.5 mm, was washed and then dried in an oven maintained @ 105 °C. The filtration unit was charged with 150g dry sand, which occupied a height of 50 to 60 mm in the column. The filter head loss development and turbidity were measured during the filtration cycle at 10 minute intervals until turbidity breakthrough was reached.

Filtration tests were run under controlled conditions with respect to media and flowrate. Suspended solids in the clarified water treated with each of the three coagulants were similar (between 5 and 6 mg/l). The filtration process was assumed to be stable when the incoming flowrate of the clarified water was equal to the filtered water flowrate.

After filtration, sand was removed from the column and replaced with new sand. The batch and the mass of sand added into the column were kept constant for filterability tests conducted for each of the three coagulants tested.

4.3.4 Economics

A simple cost comparison was made on the basis of coagulant dose. A qualitative cost assessment for the three coagulants was undertaken with emphasis on the following contributory factors.

- Dosage/coagulant cost comparison
- pH correction chemical costs.
- Sludge treatment and disposal
- Coagulant storage requirements

4.4 Experimental Method

The objectivity of the investigation was dependent on the following operating constraints:

- Constant raw water quality – Wide variation in raw water quality can seriously affect comparison of coagulant performance especially if it results in a significant shift in the 'optimum dosage' and final water quality.
- Analytical instruments – Testing equipment need constant calibration and the measurements must be reliable and reproducible.
- The variation in the performance of the jar tester and DAF pilot plant, under constant operating conditions, was quantified so that performance changes due to a process variable change can be distinguished from normal plant performance with a reasonable degree of confidence.

Each unit process in the DAF has a number of operating variables that may need to be optimised. Conservative saturator and flotation operating parameters were chosen from the literature (Haarhoff and van Vuuren,1993). The DAF trials were conducted under constant saturator and flotation operating parameters. The air-water recycle (percent) was optimised on the pilot plant.

To reduce the number of variables to be optimised on the pilot plant, the effect of the operating parameters on final quality were investigated on the batch scale laboratory (DAF) jar tester. Those operating parameters, to which the treated water turbidity was found to be sensitive, were optimised on the pilot plant.

The following experimental procedure was adopted for the initial jar test trials using each of the two coagulant types (ferric chloride - inorganic coagulant and an organic polymeric coagulant):

- Coagulant dose under standard jar test conditions
- Determination of variation in turbidity under standard operating conditions.
- Effect of coagulation mixing time on treated water turbidity
- Effect of coagulation mixing intensity on treated water turbidity
- Effect of flocculation time on treated water turbidity
- Effect of flocculation intensity on treated water turbidity

4.4.1 Thesis organization

- Chapter 5 - The results of the jar test optimisation of coagulation and flocculation operating parameters are presented
- Chapter 6 - describes the DAF pilot plant and commissioning; calibration of stirrers for coagulation and flocculation and determination of saturator efficiency.
- Chapter 7 - details the DAF pilot plant optimisation of coagulation and flocculation conditions for each of three coagulants, ferric chloride (control coagulant) and two polymeric organic coagulants, PolyA and PolyB.
- Chapter 8 - presents the results of the evaluation of the coagulants under optimised operating conditions.
- Chapter 9 - A comparison of the performance of the coagulants for DAF potable water treatment is made based on performance criteria identified and discussed in chapter 4.
- Chapter 10 – Conclusions drawn from the study and recommendations are presented.

4.5 Raw Water characteristics

4.5.1 Raw water source

The work on coagulants for DAF was conducted at the Umgeni Water Process Evaluation Facility situated on the site of Wiggins Waterworks in Mayville, Durban. The raw water used in the investigation was an impounded surface water supply from a relatively new dam (11 years old), the Inanda

Dam. The dam with a capacity of 258 000 megalitres, is situated on the Mngeni River, which is the main source of water for the Mngeni catchment area. Water from the dam gravitates a distance of 50 kilometres to Wiggins Waterworks through a series of tunnels. Raw water from Inanda Dam is supplied to the Process Evaluation Facility via an off-take just before the inlet to the Wiggins Waterworks.

4.5.2 Raw water quality variation

Raw water quality remained fairly constant for the duration of the trial. The turbidity was generally less than 7 NTU. The UV absorbance @ 254 nm, expressed as abs/m and pH also showed no significant variation. The alkalinity of the raw water was fairly consistent between 45 and 50 mg/l. Figure 4.2 shows the variation of turbidity, pH and UV absorbance @ 254 nm during the DAF trials. Total organic carbon during the trial period was consistent between 3.2 mg/l and 4.2 mg/l,

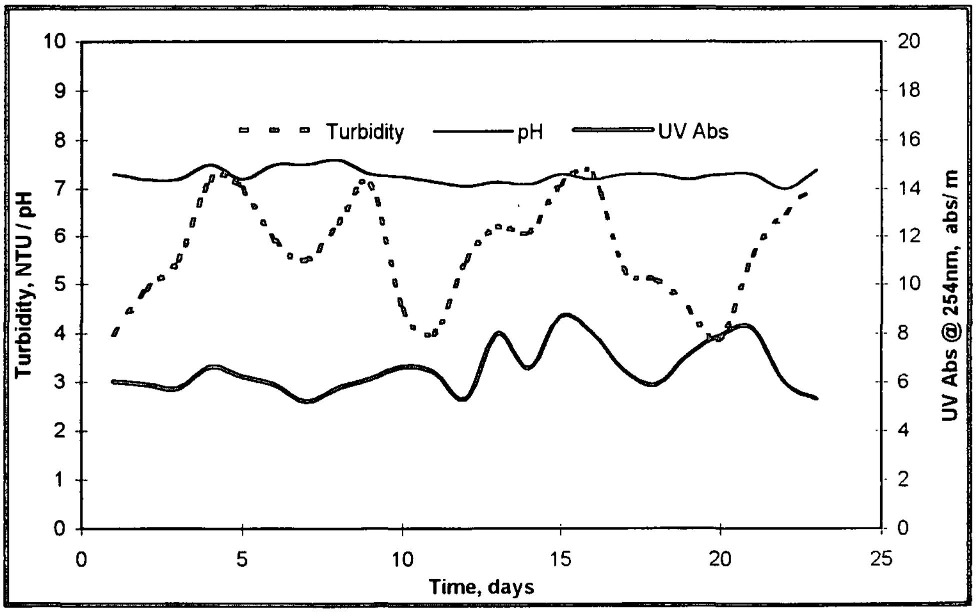


Figure 4.2: Raw water profile during DAF trials

CHAPTER 5

Laboratory Jar Test Trials

5.1 Introduction

The jar test was first developed by Camp in the 1940's when he developed the velocity gradient concept and pioneered the simulation of coagulation and flocculation processes in a beaker (Camp and Steyn, 1943). The technique was further refined and developed into an acceptable technique by Hudson in the 1960's.

5.2 Objectives

The main objective of the jar test trials was to identify the coagulation and flocculation parameters to which DAF treated water turbidity was sensitive.

5.3 Description of DAF jar test apparatus

The apparatus (Figure 5.1) consisted of four identical perspex conical bottom flotation jars which were 100 mm in diameter with a capacity of 1200 ml. Each jar had a bottom drain and two side sampling points. The air/recycle water was introduced at the bottom of each jar via air release nozzles. Recycle water was saturated with air under pressure in a separate saturator and the amount introduced into the jars was controlled by timer operated solenoid valves. Three recycle timers were individually linked to three jars with the third timer controlling the recycle to both the third and fourth jars. Thus in evaluating flotation, three different recycle rates and one duplicate may be examined. To optimize the chemical dose, the different jars can be operated at constant recycle.

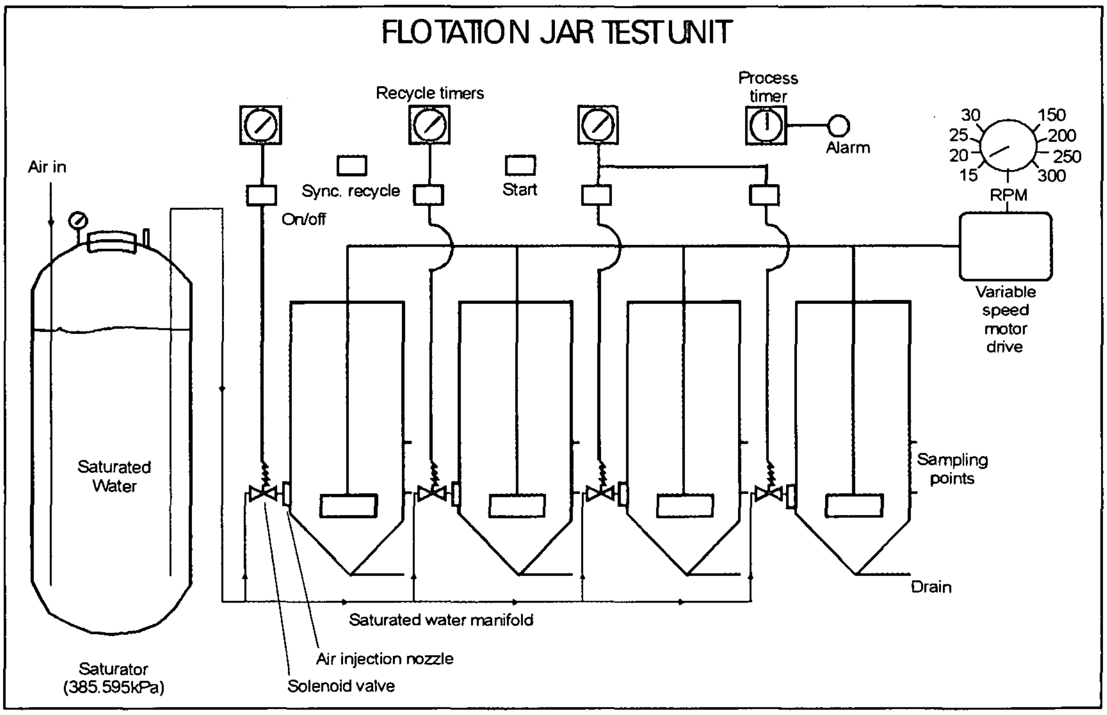


Figure 5.1: Flotation Jar Tester (Zabel and Melbourne, 1980)

Mixing for coagulation and flocculation was provided by variable speed stirrers from a common drive shaft. A flat blade paddle type mixer extended to the bottom of the jar. The speeds were accurately pre-set and can be reproducibly obtained via a multiple position rotary switch. The chemicals can be dosed simultaneously to all jars and a process timer can be variably set to monitor the fast and slow mixing times. A relationship between the mixing speed and the mean velocity gradient, G can be established by measuring the torque at the drive shaft and applying the following relationship modified from (Zabel and Melbourne, 1980) to incorporate SI units.

$$\boxed{G = \sqrt{\frac{20\pi tNg}{60\mu V}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.1)}}$$

Where t = torque measure at drive shaft, kg.m

N = speed of rotation, rpm

V = Volume of water in jar, m^3

G = gravity constant, 9.81 m/s^2

μ = viscosity of water, 10^{-3} Pa.s @ $20^{0}C$

π = pi = 3.141592

5.3.1 Advantages

The jar tester has proved to be one of the most important items of test equipment in a water treatment plant. A properly designed and performed set of jar tests can give the operator a tremendous advantage in determining the correct coagulant and dose for developing the optimum floc. The size and strength of the floc developed will determine the efficiency of the solids removal process. Floc size can easily be observed in the jar test and related to the settling velocity or rise rate in the case of flotation. The sensitivity of the coagulant to physical conditions of mixing during coagulation and flocculation can be determined by varying the rotational speed of the mixers.

5.3.2 Limitations

The laboratory jar test was a batch process and the results did not relate directly to a full-scale continuous water treatment process. The mixing conditions were not accurately matched due to the type of mixing used. Waterworks normally used a 'hydraulic jump' for rapid mixing. Flocculation and settling took place in baffled flocculation tanks or sludge blanket type clarifiers which use a vertical pulsation action for mixing. In a DAF application, the addition of air-water recycle into the flocculated water may not be easily simulated and applied to real plant conditions. The effect of type and number of nozzles and especially the interaction of the nozzles with each other in a full-scale DAF plant may not be simulated with a small, single nozzle in a jar test beaker.

The execution of the jar test was an 'operator intensive activity' and relied, to a significant extent for its accuracy on the reproducible technique of the operator. Therefore, more importance was placed on relative changes rather than absolute results.

5.3.3 Calculation of mixing intensity

The stirring mechanism to turn the impellers, is a magnetic driven unit that can be controlled from 20 to 400 rpm. The magnetic stirrers are fitted with paddle type impellers.

The mixing intensity, expressed as velocity gradient, G, was calculated using the geometry of the impeller, rotational speed of the stirrer, volume and viscosity of the water. The relationship, shown in more detail in Chapter 6, was valid for a particular diameter and type of impeller and water temperature.

The relationship was conveniently expressed in the form of a graph relating impeller speed in rpm to velocity gradient, G, (s^{-1}) (Figure 5.2).

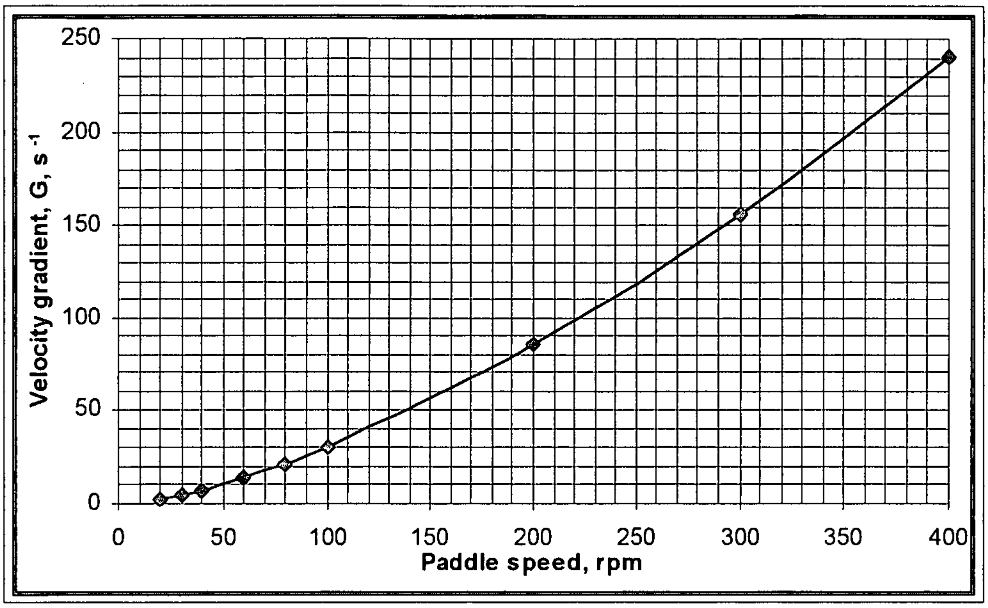


Figure 5.2: Relationship between jar tester paddle speed and velocity gradient

5.3.4 Determination of air-water recycle ratio

Water, saturated with air was produced in a 10 litre pressurized vessel. Water was added into the vessel to about 80% of its total volume and then sealed closed. Compressed air was injected until the vessel pressure reaches the desired saturator operating pressure. Intermittent shaking of the vessel assisted dissolution of air into the water.

The saturator efficiency was assumed to be 100%, based on the manufacturers specifications. The timer based solenoid valves controlled the volume of air-water recycle released into the flocculated water in the beakers. The air injection through each solenoid valve was calibrated by measuring the volume of recycle released for each timer setting. The timer setting corresponding to the required volume of recycle was then determined from a graph of timer setting versus volume of recycle (Figure 5.3).

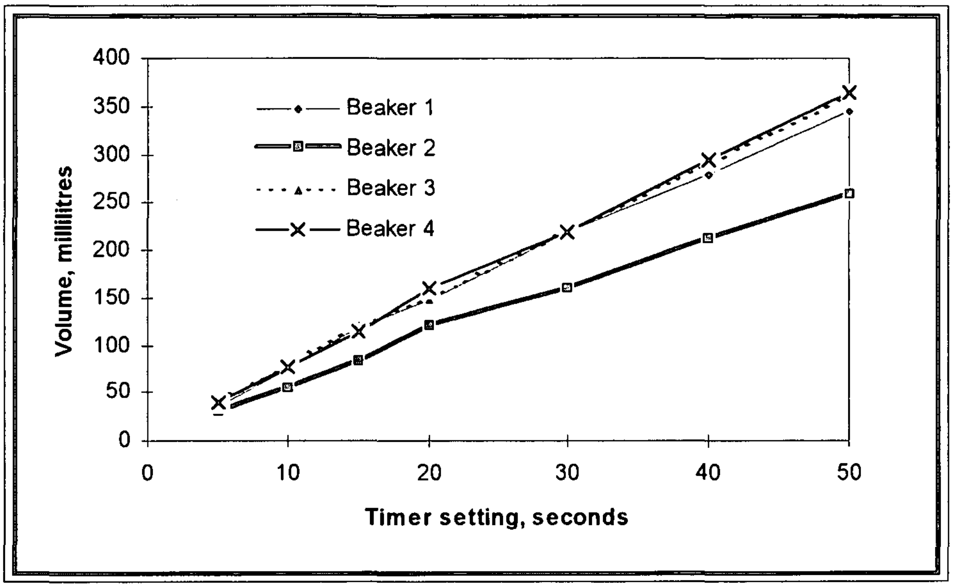


Figure 5.3: Calibration of jar tester solenoid valve timer setting

5.4 Approach

Two sets of operating variables were considered. One set for coagulation and flocculation and the other set for flotation. Most of the operating parameters for flotation were fixed by the batch type nature of the jar tester. Only the air/water recycle ratio can be varied. For the jar test experiments, the air-water recycle was kept constant at a conservative value obtained from literature (Haarhoff and van Vuuren, 1993).

5.5 Method

The first step was the establishment of a coagulant dose that would reduce the turbidity of the filtered water below 0.5 NTU. Turbidity of the DAF treated water (before filtration) was also monitored. The pH of the solution was monitored to ensure it was within the working range of the coagulant.
Physical conditions of mixing intensity and time were conservative values chosen on the basis of experience and historical data. The combination of mixing intensity and duration was kept constant for the determination of 'optimum' coagulant dose for all the coagulants tested.

Having determined the required coagulant dose, the effect of mixing intensity and duration of mixing on DAF treated water turbidity, were determined by keeping the optimised chemical conditions constant and varying the physical parameters.

5.6 Results

5.6.1 Determination of optimum coagulant dose under standard jar test conditions

Table 5.1 shows the jar test operating parameters for the determination of optimum coagulant dose.

Sample size	millilitres	1000
Rapid mix (coagulation)		
Time	minutes	1
Intensity	Velocity gradient, G, s^{-1}	240
Slow mix (flocculation)		
Time	minutes	15
Intensity	Velocity gradient, G, s^{-1}	20
Flotation time	minutes	10
Recycle, percent	Percent (v/v)	10

Table 5.1: Standard jar test conditions

The graphical results, presented in Figures 5.4 and 5.5 are the floated water and filtered water turbidities after DAF treatment, respectively. The optimum ferric chloride dose was 4 mg/l as Fe while the polymeric coagulant dose was 5 mg/l. Differences in the effect of chemical overdosing with respect to treated turbidity were evident from Figure 5.4. While excess inorganic coagulant, (ferric chloride), appears to have no significant effect on filtered turbidity, overdosing polymeric coagulant resulted in a sharp deterioration in final water turbidity. This observation was attributed to the mechanism of coagulation. The dominant mechanism for coagulation using ferric chloride is sweep flocculation. The ferric hydroxide precipitate carries the colloidal particles under it in a 'sweeping' motion. The only limitation is pH. The acidity of ferric chloride can reduce the solution pH and solubilize the ferric precipitate. For the polymeric coagulant, charge neutralization is the preferred mechanism and the deterioration in turbidity with the addition of excess coagulant is due to re-stabilization of the colloidal particles, leading to particle/particle repulsion, poor aggregation with consequent poor flocculation.

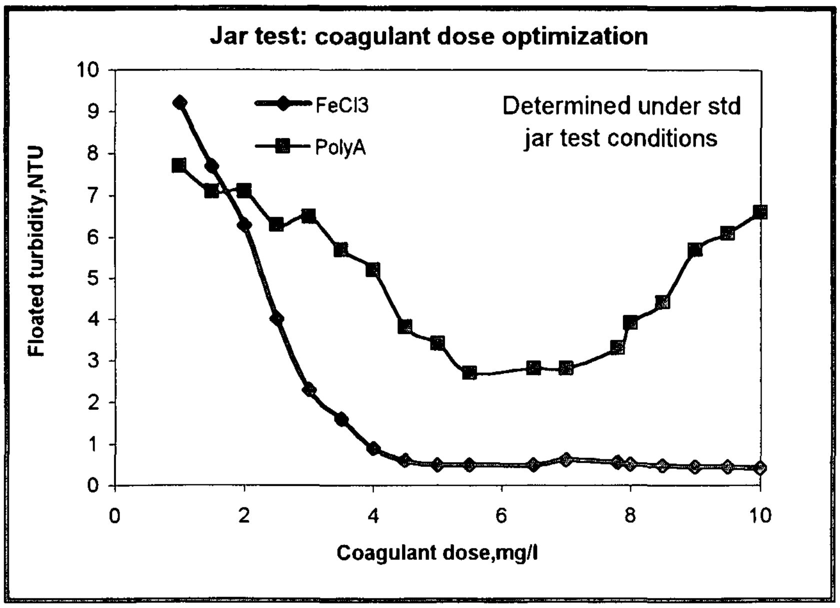


Figure 5.4 : Variation of floated water turbidity with coagulant dose

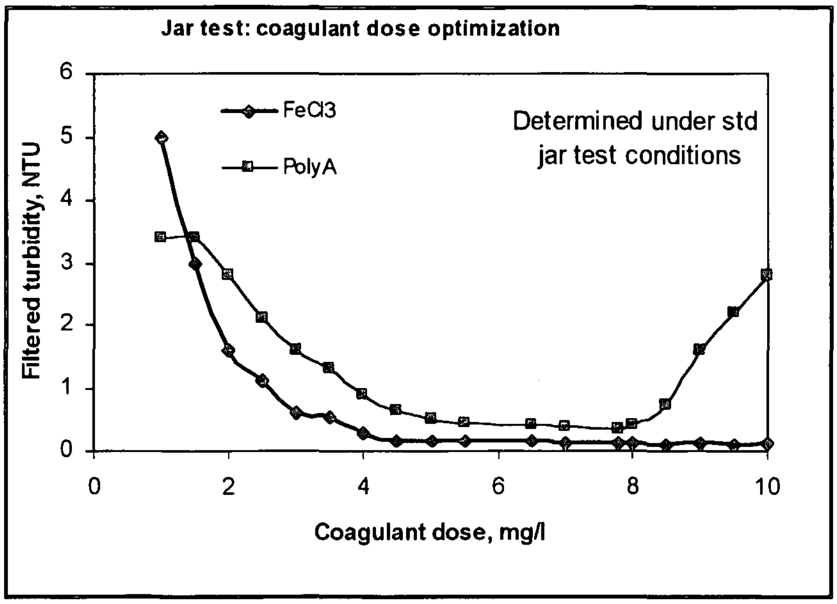


Figure 5.5 : Variation of filtered water turbidity with coagulant dose.

5.6.2 Reproducibility of jar test results

In order to interpret the jar test results obtained from the variation of coagulation and flocculation parameters it was necessary to determine the reproducibility of results of jar tests (run under constant and standard operating conditions). Flotation jar tests were performed on the same batch of raw water sample under standard jar test conditions. Jar test conditions presented in Table 5.2 were applied and kept constant for the duration of the test. The tests were replicated 16 times under identical conditions. The mean and standard deviation were calculated for the results obtained. The variance limits or range for 95% confidence was two standard deviations on either side of the mean. The results for jar tests are presented in Table 5.2.

Coagulant	**Ferric chloride**		**Polymeric organic coagulant**	
	Floated turbidity ntu	Filtered turbidity ntu	Floated turbidity ntu	Filtered turbidity ntu
Mean	1.02	0.20	1.73	0.24
Std deviation	0.15	0.03	0.15	0.02
Variance	0.30	0.06	0.30	0.04
% Variance	29	30	18	17

Table 5.2: Consistency of jar test results

In practical terms, the variance is an indication of the reproducibility of measurements taken under carefully controlled experimental conditions. If one of the variables in the jar test, namely, rapid mixing time, was varied while the other operating parameters were kept constant, then the relative change in turbidity may be regarded as a consequence of the process change (rapid mixing time) if the relative difference in the measurement (turbidity or pH) exceeded the variance. For example, a change in floated turbidity greater than 30% relative to the baseline floated turbidity, may be attributed to a process change. If the change in floated turbidity falls within the 30% variance, then it can be deduced that the variable change had no significant effect on treated water quality.

5.6.2.1 Interpretation of jar test results

Due to the limitations of the jar test technique and minor fluctuations in the raw water turbidity, the comparison of absolute turbidity values from jar test experiments may lead to incorrect conclusions. Interpretations were based on trends and relative changes in water quality measurements.

The percent variance determined under standard jar test conditions for each coagulant was used to aid the interpretation of jar test data.

5.6.3 Effect of coagulation- flocculation parameters on treated water turbidity

Having established the optimum coagulant dose under standard test conditions, the effect of the physical parameters with respect to coagulation and flocculation was investigated.

5.6.3.1 Effect of coagulation time on floated water turbidity

Coagulation time was varied between 0 and 4 minutes. The coagulant doses were set at the optimised values. Other parameters were constant as indicated in Table 5.3.

Sample size	millilitres	1000
Coagulant dose	4mg/l $FeCl_3$ as Fe 5mg/l Polymer PolyA	
Rapid mix (coagulation)		
Time	minutes	1 to 4
Intensity	Velocity gradient, G, s^{-1}	240
Slow mix (flocculation)		
Time	minutes	15
Intensity	Velocity gradient, G, s^{-1}	20
Flotation time	minutes	10
Recycle	Percent (v/v)	10

Table 5.3: Jar test operating parameters

Figure 5.6 indicates that ferric chloride was insensitive to the duration of coagulation, while the polymeric coagulant performance appeared to deteriorate when a coagulation time below 1 minute was applied. The relative percentage change in turbidity observed after the process change (coagulation time) was less than the percent variance (17% for polyA) Thus the results indicate that mixing time had no significant effect on floated water turbidity.

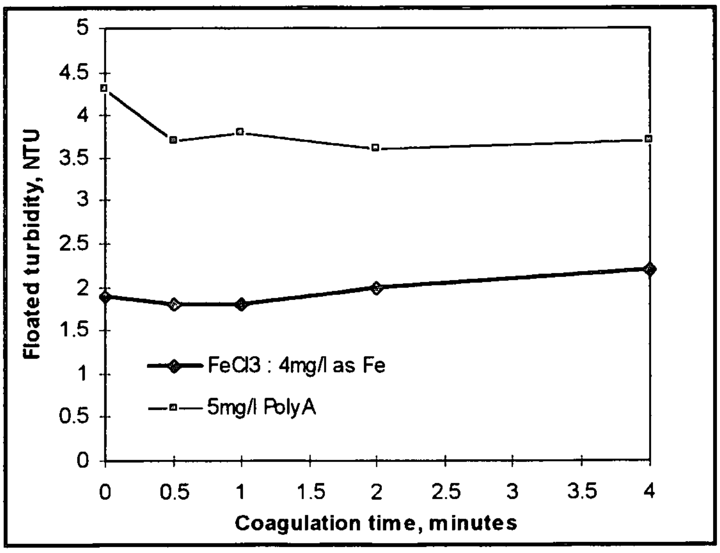


Figure 5.6: Effect of coagulation time on floated turbidity

5.6.3.2 Effect of coagulation time on filtered water turbidity

Figure 5.7 shows that there was no significant change in filtered turbidity for changes in coagulation time when the polymeric coagulant was used as coagulant. Using ferric chloride as coagulant, however, an increase in filtered turbidity was observed for an increase in coagulation time greater than one minute. The turbidity change that resulted from the increase in rapid mixing time was less than the variance in turbidity (30%) determined under constant operating conditions. Therefore, the apparent increase in turbidity with rapid mixing time (for ferric chloride) may be interpreted as insignificant.

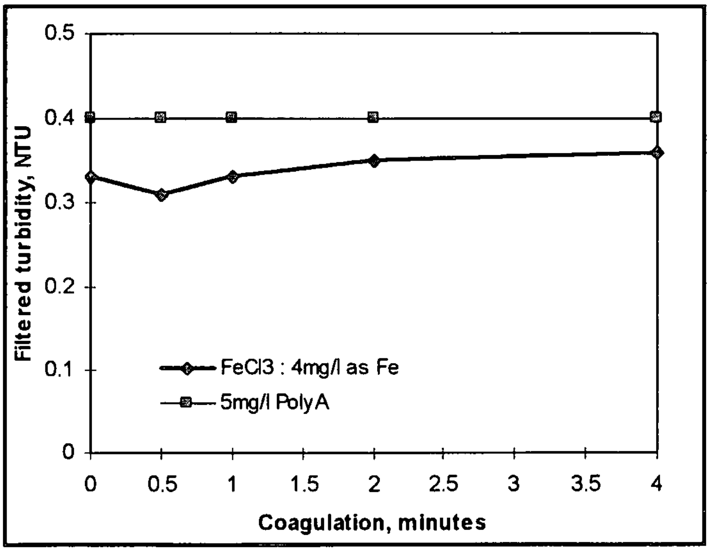


Figure 5.7: Effect of coagulation time on filtered turbidity

5.6.3.3 Effect of coagulation intensity on floated water turbidity

Coagulation/rapid mixing time was reverted to one minute (as in standard jar test conditions) and the rapid mixing intensity was the variable for these set of experiments.

The gradual decrease in floated turbidity with increasing rapid mixing intensity (Figure 5.8) indicates a possible sensitivity to rapid mixing intensity for the polymeric coagulant. However, the percentage change in turbidity is less than the percentage variance determined under constant jar test operating conditions. Therefore, it may be deduced that rapid mixing intensity had no significant effect on coagulation. Coagulation with ferric chloride also showed no sensitivity to coagulation intensity.

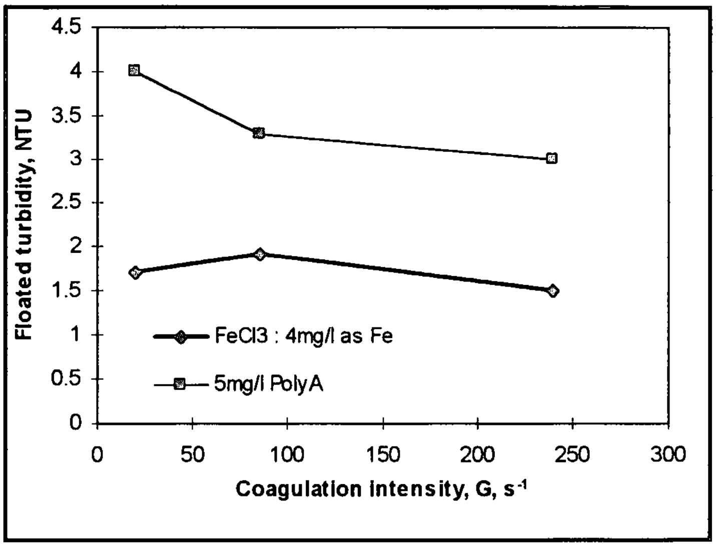


Figure 5.8: Effect of coagulation intensity on floated turbidity

5.6.3.4 Effect of coagulation intensity on filtered water turbidity

Figure 5.9 shows that a coagulation intensity corresponding to a velocity gradient as low as approximately 20 s^{-1} may be sufficient to produce filtered water to acceptable turbidity standards. Further increase in coagulation intensity had no significant effect on filtered turbidity.

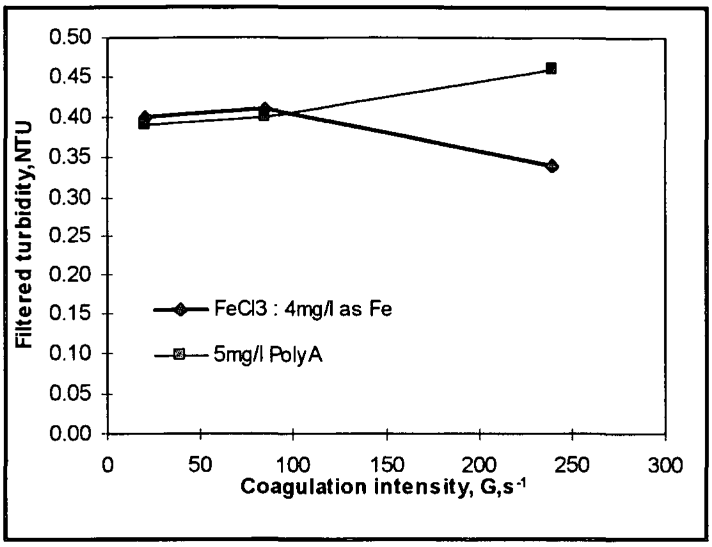


Figure 5.9: Effect of coagulation intensity on filtered turbidity

5.6.3.5 Effect of flocculation time on floated water turbidity

Rapid mixing intensity was reverted to standard jar test conditions (240 s^{-1}). The trend of flocculation time with floated turbidity (Figure 5.10) was similar to the relationship between coagulation time and floated turbidity. Ferric chloride was relatively insensitive to flocculation time, while the performance of the polymeric coagulant indicated an improvement after 5 minutes flocculation time and remained constant for further increases in flocculation time. It is not clear whether the initial decrease in floated turbidity was a consequence of the change in flocculation, because there was no significant difference between the turbidity change (20%) and the variance (18%) in floated turbidity using PolyA under standard jar test conditions.

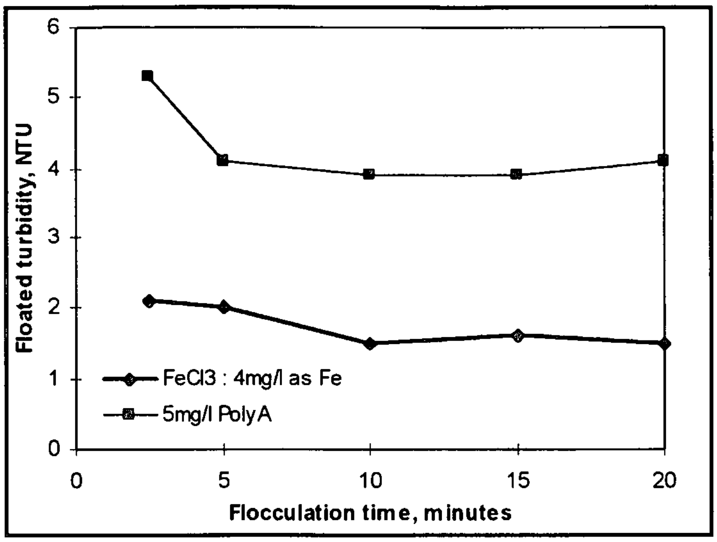


Figure 5.10: Effect of flocculation time on floated turbidity

5.6.3.6 Effect of flocculation time on filtered water turbidity

Although acceptable filtered water turbidities were produced at lower flocculation times (Figure 5.11), the trend indicates that 10 minute flocculation time produced the best results for ferric chloride. When interpreted in relation to turbidity variations for constant jar test conditions (Table 5.3), the graph of filtered turbidity versus flocculation time may appear flat, indicating that, under prevailing conditions, flocculation was not sensitive to duration of flocculation.

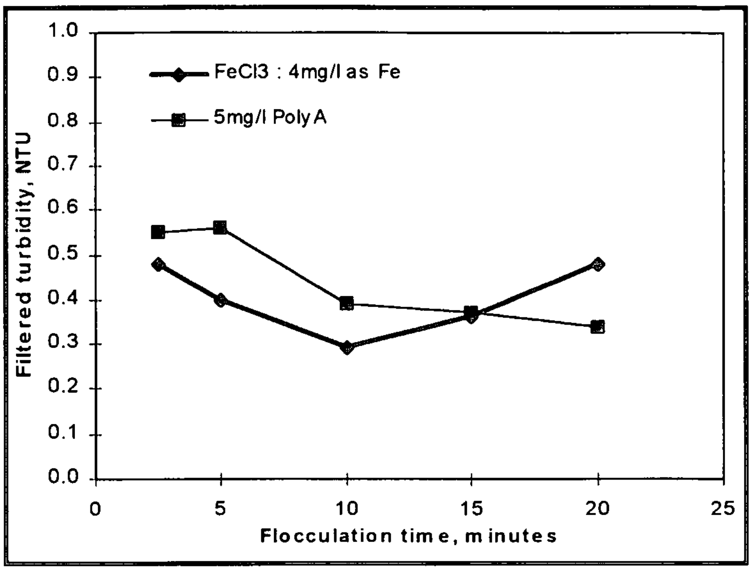


Figure 5.11: Effect of flocculation time on filtered turbidity

5.6.3.7 Effect of flocculation intensity on floated water turbidity

Flocculation time was reverted to 15 minutes as in standard jar test conditions and flocculation intensity was varied between 5 and 240 s^{-1}. As indicated in Figure 5.12, there was a significant improvement in floated water turbidities (for both the coagulants) when the flocculation intensity was increased. Using the polymeric coagulant, DAF performance improved at mixing intensities up to 85 s^{-1}. There was no benefit in increasing the mixing intensity above 85 s^{-1}. For ferric chloride, there was no further improvement in floated water turbidity for velocity gradients greater than 20 s^{-1}.

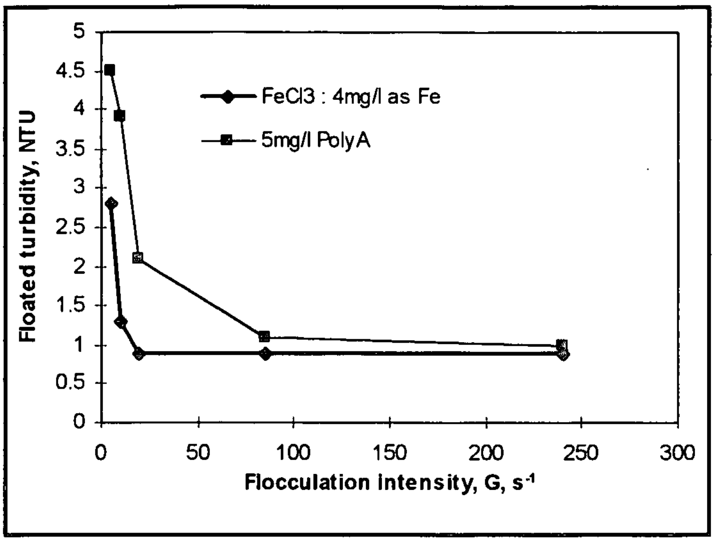


Figure 5.12: Effect of flocculation intensity on floated turbidity

5.6.3.8 Effect of flocculation intensity on filtered water turbidity

Figure 5.13 shows that low mixing intensities (20 to 50 s^{-1}) were sufficient for both the polymeric coagulant and ferric chloride to produce acceptable filtered turbidities. There was a significant deterioration in filtered turbidity at the lower flocculation intensities (less than 20 s^{-1}) when ferric chloride was used as coagulant. For the polymeric coagulant, acceptable filtered water turbidities were achieved with the lowest flocculation intensity tested. For both the coagulants flocculation intensities higher than 20 s^{-1} had no significant effect on filtered turbidity.

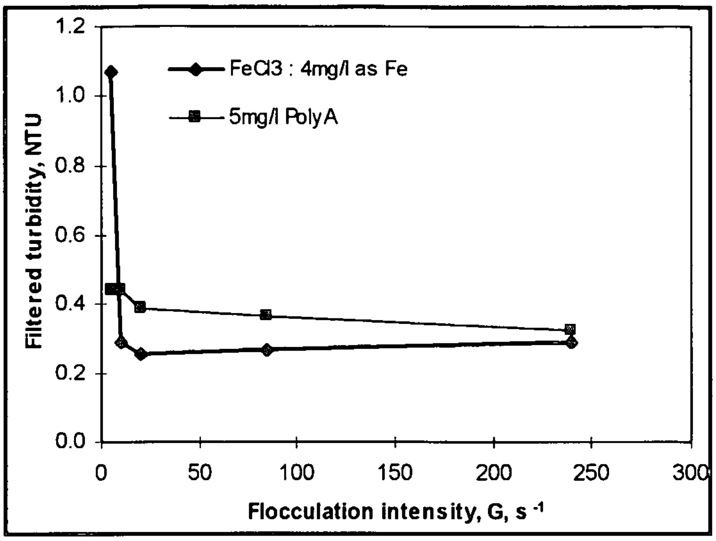


Figure 5.13: Effect of flocculation intensity on filtered turbidity

5.7 Discussion of Results

5.7.1 The effect of coagulant dose on DAF treated water turbidity

Increase in ferric chloride dose beyond the optimum had no effect on treated water turbidity, while a similar increase in polymeric organic coagulant dose resulted in a significant deterioration in turbidity.

Floated turbidity of the ferric chloride treated water was consistently lower than that of the organic coagulant treated water, while a similar comparison of the filtered turbidity showed that the turbidity of the ferric chloride treated water was only marginally lower.

5.7.2 Effects of physical conditions of mixing on coagulation and flocculation

Results of the jar tests indicated that coagulation was insensitive to coagulation intensity and duration, under prevailing raw water conditions and within the limits of the mixing intensities and mixing time tested. The results, shown in Figure 5.7 indicate that fairly good coagulation and flocculation was achieved without rapid mixing. This observation was consistent for both the inorganic coagulant (ferric chloride) and the organic coagulant (PolyA).

Similar observations were made by other workers. Kawamura (1973) found, while studying flocculation of river water using alum in the adsorption-destabilization region, that turning off the rapid mixing impeller had little effect on the final settled water turbidity.

Clark *et al* (1994) stated that although the importance of the initial mixing step in coagulation and flocculation is generally accepted, it may be the single most misunderstood water treatment process. They also found that there was no significant difference in performance over a wide range of rapid mixing intensities (between 0 and 1000 s^{-1}) and that turbidity removal was quite good for a 'no mixer option'.

Variation of flocculation parameters indicated that short flocculation times and low flocculation intensities were adequate.

5.8 Summary

Jar test results indicate that DAF performance was sensitive to coagulant dose, coagulant type and pH. Final water quality was relatively insensitive to physical conditions of mixing. The conclusions drawn from the jar tests are summarised.

- Coagulation was insensitive to mixing intensity and mixing time.
- Low mixing times and intensities were adequate for flocculation.
- Results indicate that a wide range of mixing intensities can be used with no significant effect on treated water.

The optimum coagulant dose and treated water turbidities achieved are shown in Table 5.4.

Coagulant	$FeCl_3$	PolyA
Optimum coagulant dose, mg/l	4.5 as Fe	5.5
Raw water turbidity, NTU	<10	<10
Raw water pH	7.5	7.5
Floated water turbidity, NTU	1.0	3.0
Filtered water turbidity, NTU	0.20	0.24
Filtered water pH	6.5	7.4

Table 5.4 : Summary of coagulant dose optimisation

The coagulation and flocculation operating parameters that produced the acceptable treated water turbidities are presented in Table 5.5

Treatment stage	Flotation		Filtration	
Coagulant	$FeCl_3$	PolyA	$FeCl_3$	PolyA
Optimum coagulant dose, mg/l	4.5 as Fe	3	4.5	5.5
Coagulation time, min	-	0.5	-	-
Coagulation intensity, G, s^{-1}	20	20	20	20
Flocculation time, min	2.5	5	<10	<10
Flocculation intensity, G, s^{-1}	20	75	20	20

Table 5.5: Coagulation and flocculation conditions

CHAPTER 6

DAF Pilot Plant Description

6.1 Introduction

This chapter describes the unit processes that comprise the DAF pilot plant. The initial commissioning of the pilot plant including calibration of flocculator stirrers for comparison of mixing intensities expressed as velocity gradient, G and the determination of the air-water saturator efficiency is also presented.

6.2 Apparatus

The DAF pilot plant, shown in Figure 6.1, is a continuous process with a design capacity of 1 m^3/h. The plant comprises a coagulation (rapid) mixing vessel, three stage mechanical flocculator, flotation vessel and an air-water saturator. The process and instrumentation diagram is shown in Figure 6.2.

The size of the pilot plant was dictated primarily by two factors. The pilot plant had to be small enough for ease of transportation to sites yet large enough to produce reliable data for design of full-scale plants. The square geometry of the mixing vessels for coagulation and flocculation was preferred over the circular design due to better mixing (without baffles) and reduced floor space requirements in comparison with circular tanks.

6.2.1 Coagulation/flocculation

The fixed baffle coagulation/flocculation vessel consists of a rapid mixing (coagulation) compartment and a three stage mechanically stirred flocculator. The unit has been fitted with three dosing pumps for the addition of pre-treatment chemicals and coagulant directly into the rapid mixing compartment. Raw water was pumped into the rapid mixing vessel by a variable speed mono pump. Raw water flowrate was monitored using a magflow meter positioned on the delivery side of the mono pump.

6.2.1.1 Coagulation

The coagulation (rapid mixing) vessel provides a residence time of 60 seconds. Mixing is achieved with a variable speed mixer with a built-in rev counter. The shaft is fitted with an axial impeller with a factory rated power number of 0.3 and is used in the turbulent Reynolds number range (Re > 10 000). The mixer is capable of generating speeds between 20 and 500 rpm.

6.2.1.2 Flocculation

Each flocculation stage had an average residence time of 5 minutes at the design flow rate of 1 m^3/h. The water distribution pipework from the rapid mixing vessel to the flocculator makes it possible to vary the flocculation time from 5 to 15 minutes without changing the inlet flowrate.

The mechanical stirrers are driven by variable speed motors with high torque output and equipped with an electronic speed display. Rotational speeds between 10 and 130 rpm are possible. Two axial impellers were mounted on each stirrer shaft. Mixing speed in rpm is correlated to velocity gradient, G, by equations incorporating energy dissipated to the stirred water and the geometry of the stirrer blades.

6.2.2 Flotation vessel

The flotation vessel was equipped with variable baffles and external supports for flexibility in hydraulic loading in both the contact and flotation zones. The baffles were adjustable for flexibility of varying the flocculated water velocity into the flotation vessel, upflow velocity in the contact zone and final down flow velocity in the flotation zone. The residence time in the flotation vessel was 8 minutes.

A relatively large diameter pipe (100 mm) connected the flocculator to the flotation vessel so that at design raw water flow, flocculated water flow in the interconnecting pipe simulated channel flow. This arrangement helped to reduce turbulence that may cause shearing of the preformed floc.

6.2.3 Air-water saturator system

The saturator system consisted of a pressure vessel, with a 0.25 m internal diameter and a total height of 1.3 m. The vessel was packed with plastic packing saddles (rings) to a height of 0.7 m. Domestic water was pumped from a header tank by a mono pump to the top of the pressure vessel. Compressed air was introduced co-currently to the water feed (Figure 6.2). The saturator pressure was controlled by an air pressure regulator. The liquid level was maintained by level controllers that activated the water feed bypass solenoid valve.

The dissolved air stream (recycle) was introduced into the flotation vessel through a needle valve connected to one of the air injection ports located on the side, near the bottom of the flotation vessel. The pressurized air saturated water injection point (at the bottom of the flotation vessel) was at right angles to the flocculated water feed.

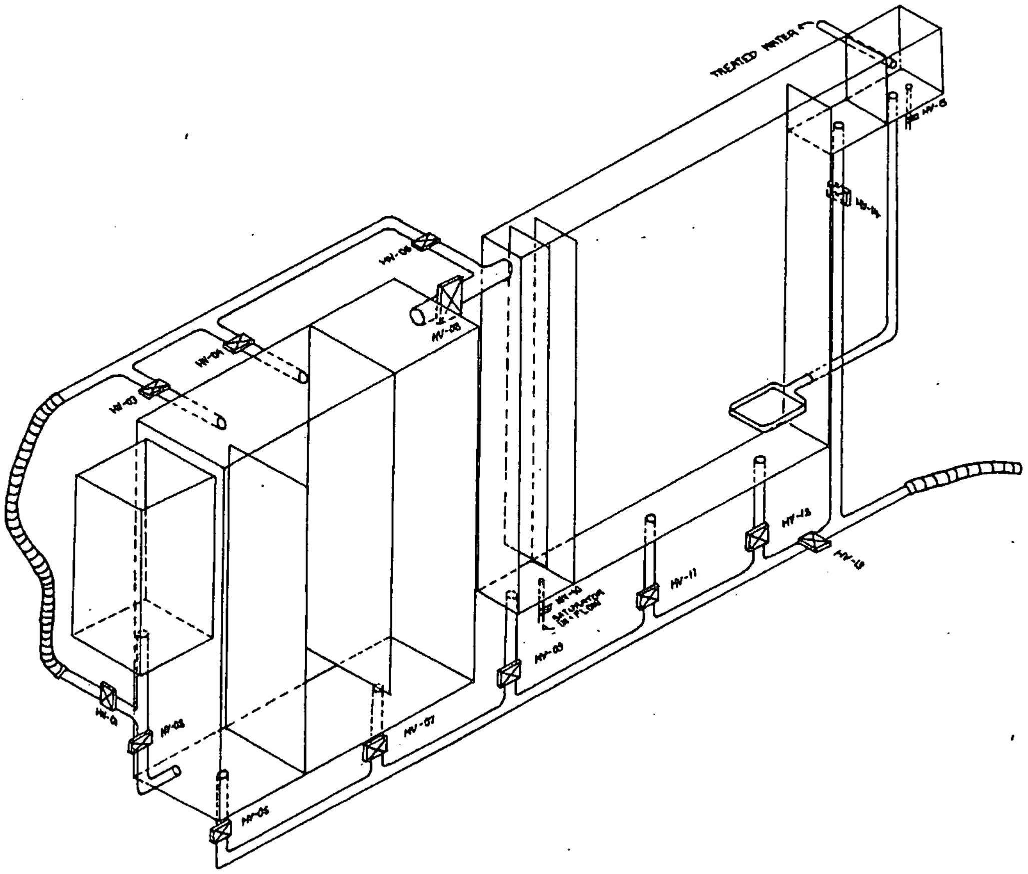


Figure 6.1: Isometic presentation of the DAF pilot plant

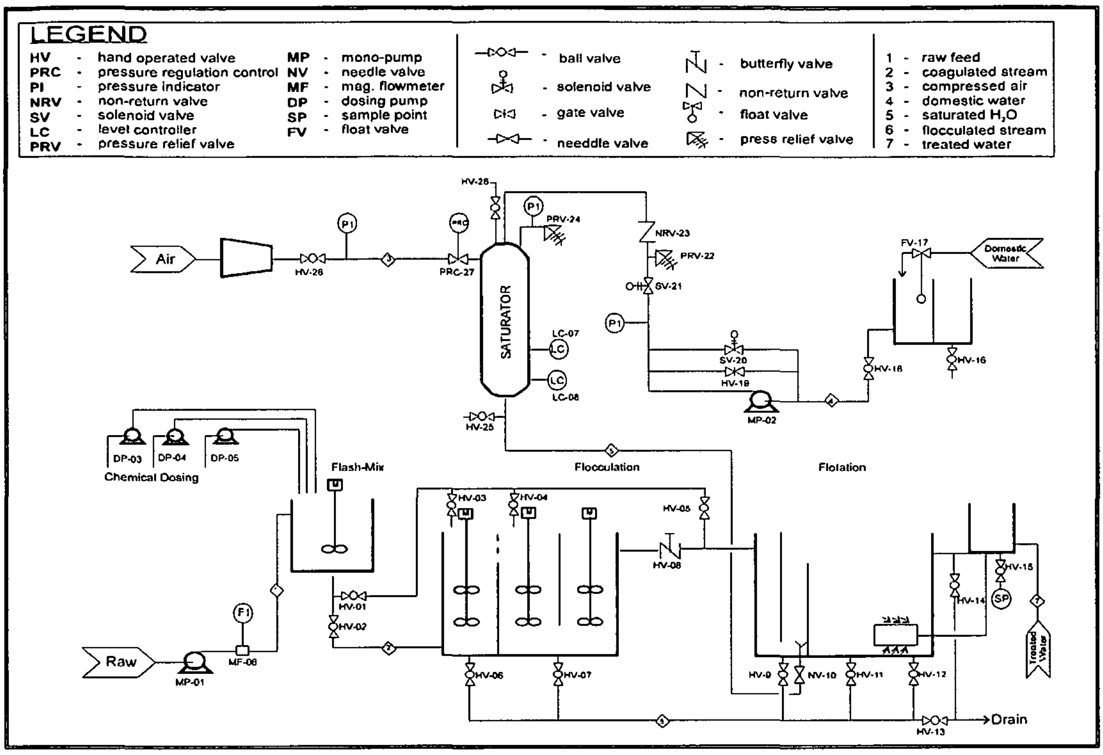


Figure 6.2: DAF pilot plant : Process and instrument diagram

6.3 DAF Pilot Plant Commissioning

6.3.1 Optimisation of flocculator performance

The criterion for optimum flocculator performance was the formation of stable flocs and a filtered turbidity less than 0.5 NTU. The energy input for coagulation and flocculation was optimized by adjusting the rotational speed of the mechanical stirrers. Coagulant was added in the rapid mixing vessel at the point of maximum agitation.

6.3.2 Calibration of the stirrers

The characterization of energy requirements at given operating conditions for agitated tanks can be achieved, quite effectively, by the power number (P_0) and the Reynolds number (Re). The power number can be regarded as the impeller drag coefficient.

$$P_0 = \frac{P}{\rho N^3 D^5} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(6.1)}$$

$$P = P_o \rho N^3 D^5 \quad \dots\dots\dots\dots\dots\dots\dots\dots \text{(6.1.1)}$$

The Reynolds number is a ratio of the inertial to viscous forces, low for laminar flow and high for turbulent. The Reynolds number is defined for impeller agitation as (Godfrey and Amirtharajah, 1986).:

$$Re = \frac{D^2 N \rho}{u} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(6.2)}$$

Where P_0 = Power number

P = Mixer power input

ρ = Liquid density

u = Liquid viscosity

N = Mixing speed

D = Impeller diameter

The flocculator was equipped with special axial impellers with factory calibrated power numbers. The power numbers were valid for turbulent flow which corresponds to Re > 10 000.

From the definition of mixing intensity expressed as velocity gradient, G:

$$G = \sqrt{\frac{P}{\mu V}} \quad \text{........................ (Sect. 2.4)}$$

And substituting $P = P_o N^3 D^5 \rho$

$$G = \sqrt{\frac{P_o N^3 D^5 \rho}{\mu V}}$$

6.3.2.1 Coagulation intensity

The relationship between mixer speed (rpm) and mixing intensity, calculated as the mean velocity gradient, G (s^{-1}) is presented as Figure 6.3.

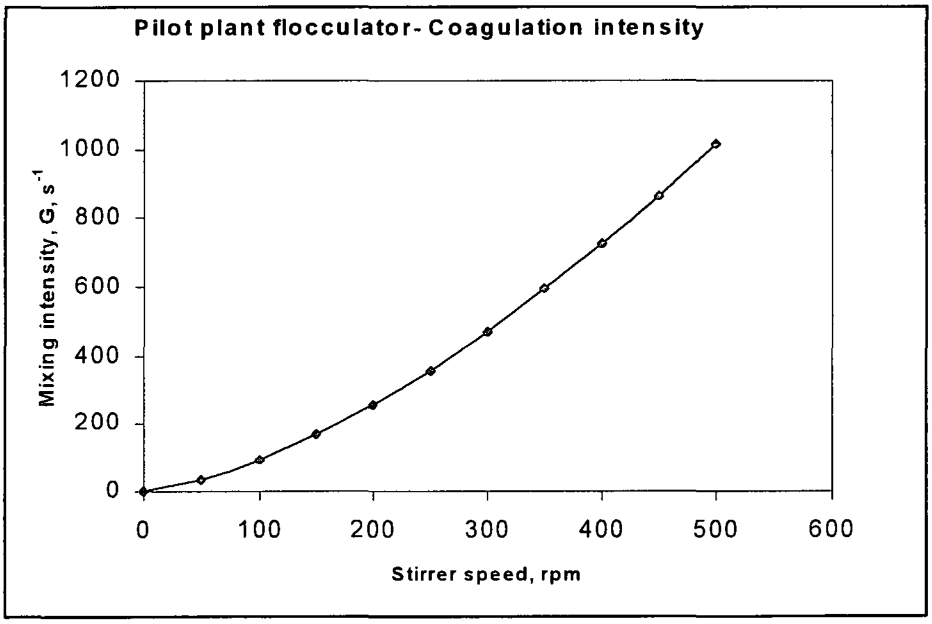


Figure 6.3: Coagulation mixer calibration

6.3.2.2 Flocculation intensity

A calibration graph was plotted for the flocculator mixers. Because the mixers and the mixing environment were similar for the three flocculator compartments, only one calibration graph is shown (Figure 6.4).

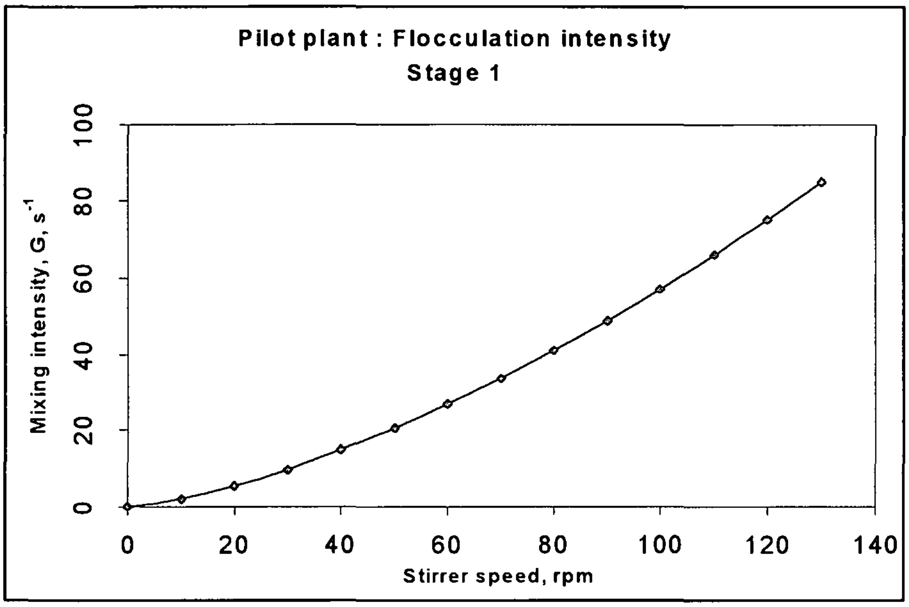


Figure 6.4: Flocculator mixer calibration

Determination of saturator efficiency

6.3.3.1 Calculation for the theoretical solubility

The theoretical solubility of air can be expressed in the form:

$a_p = S*P$ ……………………………………………………(6.3)

With a_p = the excess air concentration in mg/l.

P = Gauge pressure, kPa

S = Solubility constant in mg/l . kPa^{-1}

The following values for S have been reported at 20^0C (Haarhoff and van Vuuren,1993)

S_{20} = 0.242 mg/(l.kPa) for atmospheric air

S_{20} = 0.219 mg/(l.kPa) for saturator air

For temperatures other than 20^0C, the solubility constant was adapted with the following relationship.

$$S_T = S_{20}\left[\frac{293}{273+T}\right] . 10^{-500\left[\frac{1}{293} - \frac{1}{273+T}\right]} \quad \ldots\ldots(6.4)$$

Where S_T is the solubility of air in water at temperature, T

Actual air solubility, calculated from volume of air precipitated was given by :

$$PV = nRT \quad \ldots\ldots(6.5)$$

P = Pressure of precipitated air

= Atmospheric pressure (P_{atm}) – Vapour pressure of water (P_{vap})

V = Volume of air precipitated, m^3

R = Universal gas constant = 8,314 J/mol.K

n = Molar concentration of precipitated air, mol/l

T = Operating temperature, K

$$\%\ \text{Saturator efficiency} = \frac{\text{Actual air solubility}}{\text{Theoretical air solubility}}.100 \quad \ldots (6.6)$$

6.3.3.2 Measurement of saturator efficiency

The efficiency of the saturator was measured at three pressures; 400, 500 and 600kPa. The amount of air precipitated in a known volume of the air-water mixture sampled from the outlet of the saturator, was measured. To calculate saturator efficiency, the actual solubility of air in the saturator was calculated from volume of air precipitated and expressed as a percentage of the theoretical solubility of air for the particular temperature and pressure. The apparatus used to determine saturator efficiency is shown in Figure 6.5.

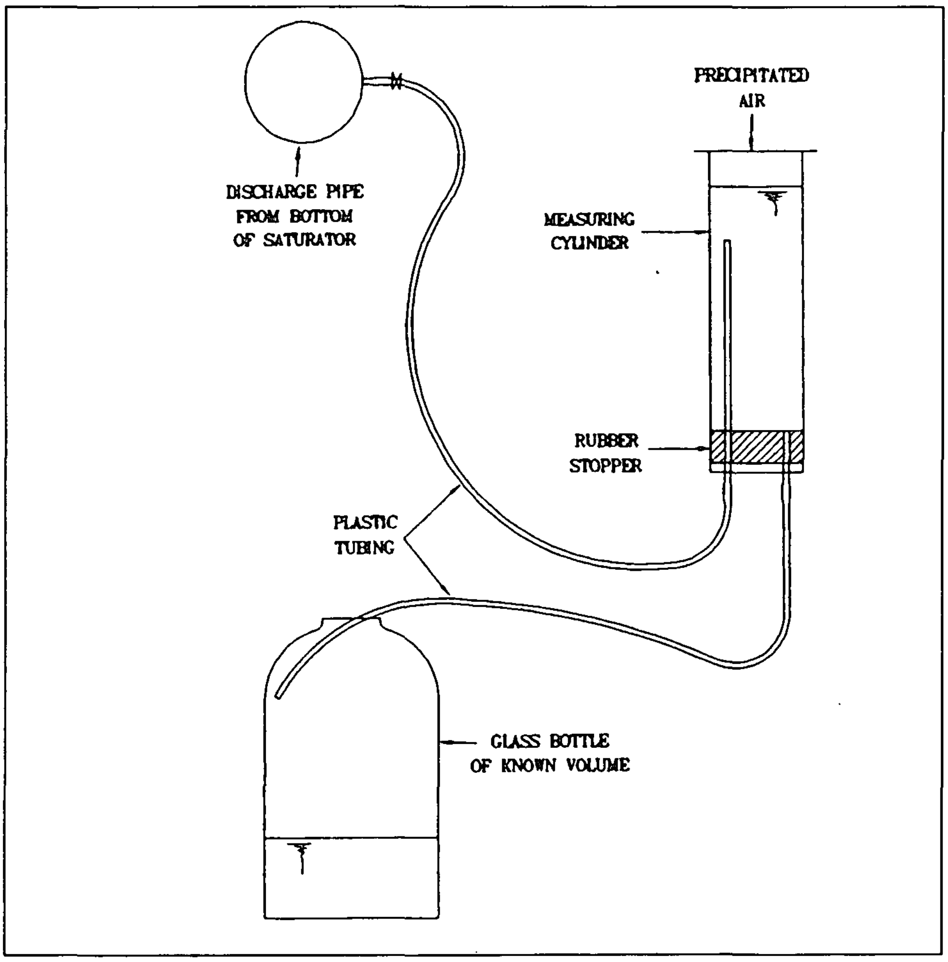


Figure 6.5: Apparatus for measuring air released by pressurised recycle

(Haarhoff and van Vuuren, 1993)

The experimentally determined saturator efficiencies at the three operating pressures (400, 500 and 600 kPa) concur with published data for packed saturators (Haarhoff and van Vuuren, 1993).

Saturator pressure was set at 500 kPa for the pilot plant DAF trials.

Pressure kPa	Precipitated Air volume mls	Water volume mls	Actual air solubility mg/l	Theoretical solubility mg/l	Saturator efficiency percent
400	75	1260	68.9	82.8	83
400	75	1230	70.6	82.8	85
400	75	1250	69.5	82.8	84
Average saturator efficiency @ 400 kPa and 25^{0}C					84
500	110	1420	89.7	103.5	87
500	108	1460	85.7	103.5	83
500	108	1400	89.4	103.5	86
Average saturator efficiency @ 500 kPa and 25^{0}C					85
600	75	820	105.9	124.2	85
600	73	820	103.1	124.2	83
600	75	880	98.7	124.2	80
Average saturator efficiency @ 600 kPa and 25^{0}C					83

Table 6.1: Experimentally determined saturator efficiencies

Chapter 7

DAF Pilot Plant - Optimisation of Flocculation and Flotation Operating Parameters

7.1 Introduction

Jar test results in Chapter 5 indicate that DAF treated water turbidity was not very sensitive to mixing intensities for coagulation (rapid mixing) and flocculation (slow mixing).

The mixing intensities on a batch operation (jar test) and the mixing intensities on a continuous process (DAF pilot plant) may not be easily correlated due to a number of differences in the mixing environment. The jar test beaker was circular and unbaffled while the DAF pilot plant coagulation/flocculation vessels were square based and elongated. The impeller size and geometry were also different. The jar tester had a single flat blade impeller, while the pilot plant was equipped with two axial impellers in each flocculation compartment and a single axial impeller in the coagulation compartment.

The motivation to repeat optimisation of mixing intensity on the pilot plant was further supported by other workers, Clark *et al* (1994) who found that when flocculation tanks were operated at the same G value, sedimentation performance degraded with increasing tank scale. This phenomenon may be more significant when the scale up is from a batch mode (as in a jar test) to a larger continuous operation on the pilot plant.

This chapter presents the optimisation of the DAF operating conditions that include rapid mixing (coagulation) and slow mixing (flocculation) intensity, coagulant dose and air-water recycle on the pilot plant.

7.2. Objectives

The mixing times applied to the DAF pilot plant were conservative values taken from the jar test results (Chapter 5) and literature (Haarhoff and van Vuuren, 1993). Coagulation mixing time was set at 1 minute and the flocculation time was 10 minutes. These mixing times were kept constant for the duration of the coagulant trials.

The objectives of the initial pilot plant experiments were to :-

- Determine the optimum coagulation intensity
- Determine the optimum flocculation intensity
- Determine the optimum saturated air-water recycle
- Use the optimised operating parameters and determine the optimum coagulant dose.

7.3 Method

Flotation and saturator operating conditions were kept constant. Flotation parameters included, reaction zone upflow rate and residence time, flotation zone downflow rate and residence time. The saturator operating pressure was constant.

The setting of these operating parameters were guided by the South African experience (Haarhoff and van Vuuren, 1993).

The optimisation of coagulation and flocculation operating conditions and air-water recycle trials was conducted for each of the three coagulants tested. The coagulant dose was then determined on the pilot plant under optimised pilot plant conditions. Flotation operating parameters are presented in Table 7.1.

Contact zone	Units	Pilot plant set point	Design guidelines
Residence time	S	51	60 – 240
Hydraulic loading	m/h	66	40 – 100
Flotation zone			
Crossflow velocity	m/h	75	20 – 100
Hydraulic loading	m/h	5	5 – 11
Side depth	m	1.2	1.5 – 3.0
Residence time	min	8	
Saturator			
Recycle	Percent (v/v)	10	6 – 10
Saturation pressure	kPa	500	300 – 600

Table 7.1: Flotation operating parameters

7.4 Measurement of treated water quality

For the optimisation of pilot plant operating conditions, turbidity and pH of the DAF treated water were measured. Samples of raw water and DAF treated water (floated water) were taken at half hour intervals for laboratory analysis. A sample of flocculated water was taken at the last flocculation stage prior to DAF treatment. Chemical analyses were conducted on the 'floated' water before and after filtration through Whatman No 1 filter paper. The same filtration technique used in the jar tests was applied.

Trends presented in the graphs were identified accordingly.

7.5 Optimisation of DAF operation using ferric chloride

7.5.1 Determination of pilot plant consistency and stability using ferric chloride as coagulant

The consistency of the pilot plant under constant operating conditions may be defined as the rate of change of performance of the pilot plant over time for operation at constant conditions of raw water, coagulation/flocculation and flotation. Performance was measured by monitoring the turbidity of the floated water and final (filtered water).

The DAF pilot plant was run under constant operating conditions over a period of time similar to experimental run times during coagulant evaluations (on the DAF pilot plant). Theoretically, DAF treated water quality should not change under conditions of constant raw water quality, raw water inflow, coagulation, flocculation and flotation and temperature. In reality, however, conditions can be maintained only within reasonable limits. The fluctuation of operating conditions within these limits dictates the stability or consistency of the pilot plant.

The stability of the pilot plant can be quantified by monitoring plant performance over a suitable period of time while the operating conditions are controlled at a constant level as tightly as possible. The normal experimental time for the DAF pilot plant was between 4 to 8 hours. The average residence time in the pilot plant at the design flowrate was 20 minutes. During normal operation samples were taken 30 minutes after a process change was made. For the consistency test, pilot plant run time was between 4 to 8 hours and the sampling frequency was 30 minutes.

The objective for the determination of variance in the pilot plant performance, under constant operating conditions, was to establish a baseline against which the effect of a process change can be quantified.

Table 7.2 shows the normal variation of the DAF treated water quality in terms of floated turbidity and filtered turbidity.

Ferric chloride	Flocculated and filtered	DAF treated water	
	Turbidity NTU	Floated turbidity NTU	Filtered turbidity NTU
Average	0.14	2.82	0.22
Standard deviation	0.02	0.38	0.04
Variance for 95% confidence	0.05	0.75	0.08
Range	0.1 to 0.2	2.1 to 3.6	0.1 to 0.3
%Variance for 95 % confidence	36	27	36

Table 7.2: Variation of DAF treated water quality at constant operating conditions using ferric

Percent variance implied that there was no significant difference between results lying within the upper and lower limits defined by the statistical variation (from the mean), for a particular set of operating conditions. The statistical presentation of the results also indicate that for the same system of conditions, the effect of a process change (on the pilot plant) would be seen as the difference between a measurement (turbidity) before and after the process change. If the relative difference in measurement was greater than the normal variance, then it may be deduced that the effect (difference in turbidity) was due to the process change. However, the deduction will be valid only when one variable was changed while the other variables were kept constant.

Due to the fact that the conditions of the raw water were continually changing and that only one pilot plant was used (i.e no control experiment could be performed continuously) trends in performance were repeated and comment made as to how significant the trend was relative to a baseline operating condition.

7.5.2 Optimisation of pilot plant coagulation and flocculation parameters

Coagulation and flocculation times were set from guidelines obtained from literature and jar test results. Initial coagulant dose was taken from jar tests.

7.5.2.1 Coagulation intensity

The coagulation mixing intensity, expressed as mean velocity gradient, G, was varied between 50 s^{-1} and 1200 s^{-1}. Table 7.3 shows the pilot plant operating conditions for the DAF pilot plant at a constant flow rate of 1 m^3/h.

Parameter	Units	Setpoint
Coagulant dose	mg/l as Fe	4.5
Coagulation time	minutes	1
Coagulation intensity	velocity gradient, G, s^{-1}	process variable
Flocculation intensity	velocity gradient, G, s^{-1}	50
Flocculation time	minutes	10
Air-water recycle	percent	10
Raw water turbidity	NTU	6 to 9
Raw water pH	pH units	7.1

Table 7.3: Operating conditions for DAF pilot plant using ferric chloride as coagulant

Figure 7.1 indicates that ferric chloride can produce good DAF treated water with relatively low intensity rapid mixing. Low floated turbidities were achieved with rapid mixing intensities as low as 50 s^{-1}. With mixing intensities greater than 200 s^{-1}, the floated turbidity appeared to increase slightly with increasing coagulation mixing. However, this change in turbidity was within the limits of plant variation under constant plant operating conditions and may be interpreted as a 'no change scenario'. At mixing intensities lower than 100 s^{-1}, the turbidity of the floated filtered water deteriorated. Turbidity of the 'flocculated and filtered' sample decreased to a minimum at a mixing intensity of approximately 100 s^{-1} and thereafter remained fairly constant with increasing mixing intensity. The turbidity of the filtered water after DAF clarification ('floated and filtered' in Figure 7.1) was higher than the filtered turbidity of samples taken from the flocculator. This is probably due to some floc shear in the flotation vessel especially in the contact zone. There was no significant difference in DAF treated water turbidity for the range of mixing intensities applied and it may be concluded that coagulation was not sensitive to mixing intensity.

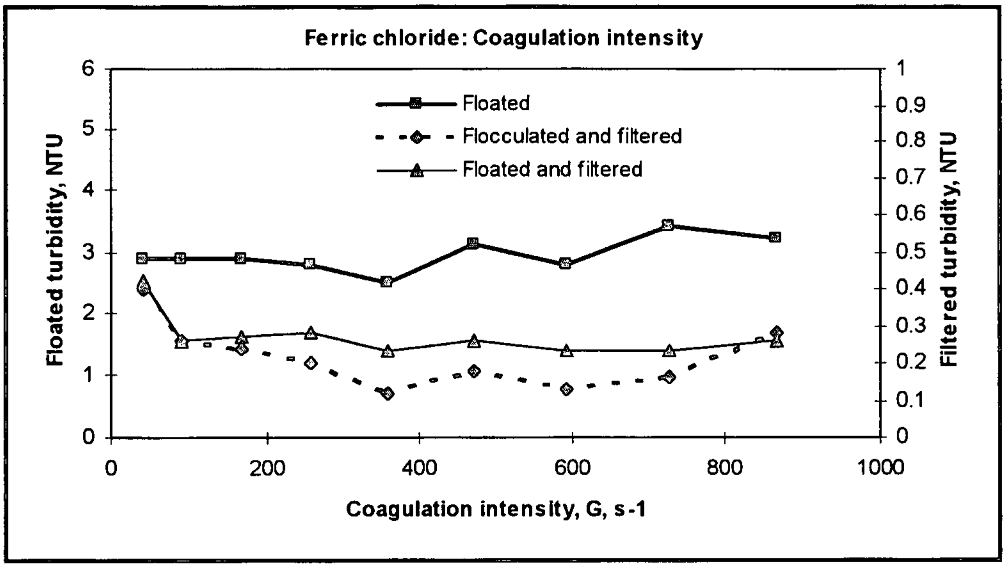


Figure 7.1: Effect of coagulation intensity on DAF treated water turbidity using ferric chloride

7.5.2.2 Effect of flocculation intensity

For the determination of the effect of flocculation intensity, the coagulation intensity was set at a conservative value of 350 s^{-1} and the flocculation intensity was varied between 2 s^{-1} and 104 s^{-1}. Figure 7.2 indicates that the floated turbidity improved with increasing flocculation intensities between 2 and 50 s^{-1}. There was no benefit in increasing flocculation intensity beyond 50 s^{-1}. The filtered turbidities of the flocculated water and DAF clarified water were insensitive to flocculation intensity. An experimentally determined flocculation intensity of 40 s^{-1}, based on the floated turbidity and filtered turbidity, was adequate for flocculation.

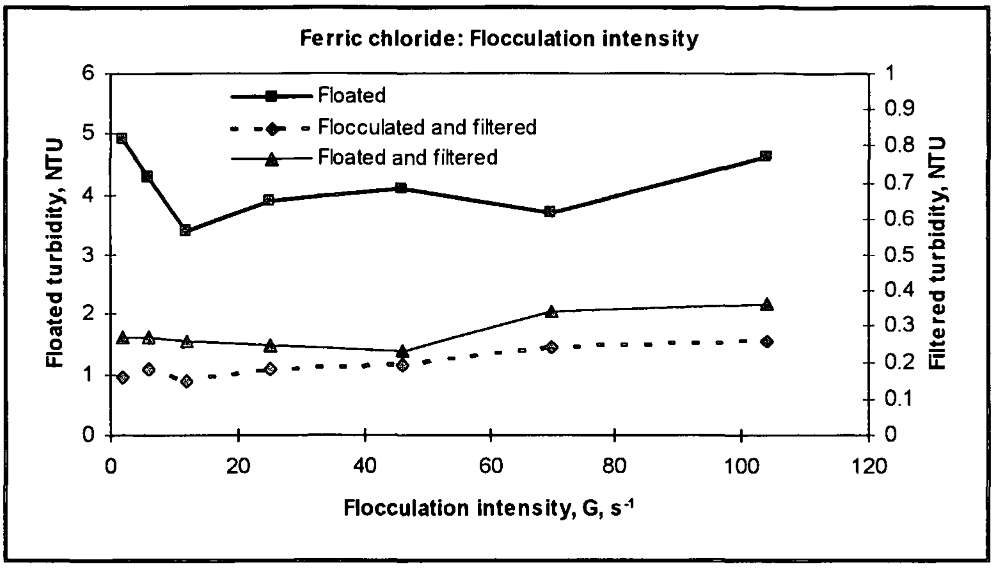


Figure 7.2: Effect of flocculation intensity on DAF treated water turbidity using ferric chloride

7.5.3 Optimisation of air-water recycle

Having established the optimum coagulation and flocculation conditions, the effect of variation in the air-water recycle flow into the contact zone of the flotation vessel was investigated.

Figure 7.3 shows that the best treated water clarity was achieved at a recycle between 6 and 8 %. Both the floated and filtered turbidities follow similar trends with respect to variation in recycle.

These values are in very good agreement with generally accepted values from literature (Haarhoff and van Vuuren, 1993). A 7% recycle was applied to the pilot plant for coagulant evaluation.

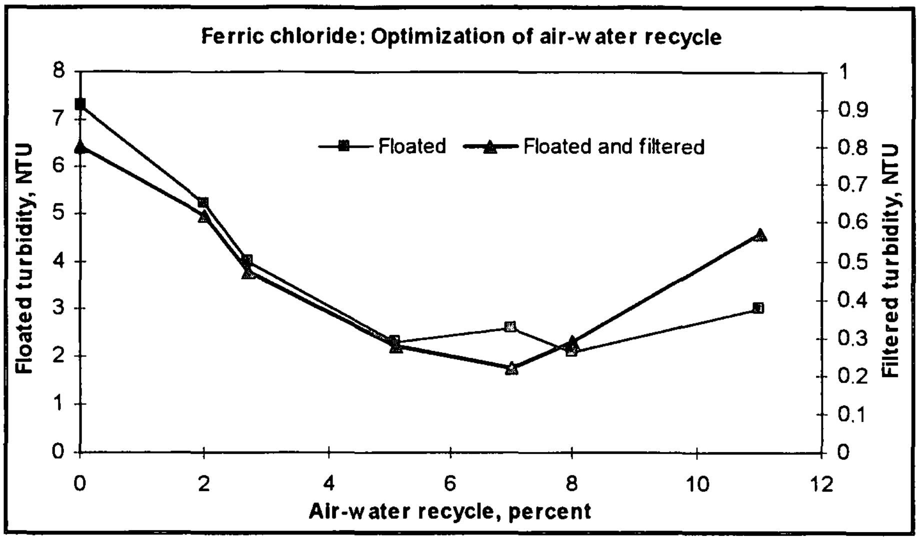


Figure 7.3: Effect of air-water recycle on DAF treated water turbidity using ferric chloride

7.5.4 Coagulant Dose

Having established the flocculation and flotation parameters, the coagulant dose was varied while the other operating parameters were kept constant. The optimum coagulant dose was the minimum ferric chloride concentration, expressed as mg/l Fe, that would be required to produce a treated (filtered) water turbidity less than 0.5 NTU. Figure 7.4 shows the optimum ferric chloride dose corresponded to 4 mg/l for a filtered turbidity of 0.34 NTU. Figure 7.4 also indicates that further increase in ferric chloride dose in excess of 6 mg/l had no significant effect on filtered water turbidity. The floated water turbidity appeared to increase after a dosage of 10 mg/l Fe. Figure 7.5 shows the effect of ferric chloride dose on pH. It can be seen that the pH of the treated water did not drop sufficiently to solubilise the iron and thus be responsible for the deterioration in floated water turbidity. The increase in turbidity was attributed more to the instability of the ferric float layer during the optimisation exercise and the possible inefficiency in the flotation of additional floc formed by the addition of excess coagulant. The fact that there was no change in the turbidity of the (flocculated and filtered) water with increasing ferric chloride dose, indicates that there was no significant restabilization of particles with excess ferric chloride.

Parameter	Units	Setpoint
Coagulant dose	mg/l as Fe	variable
Coagulation time	minutes	1
Coagulation intensity	velocity gradient, G, s^{-1}	350
Flocculation intensity	velocity gradient, G, s^{-1}	40
Flocculation time	minutes	10
Air-water recycle	percent	7
Raw water turbidity	NTU	6 - 9
Raw water pH	pH units	7.1

Table 7.4: Operating conditions for DAF pilot plant

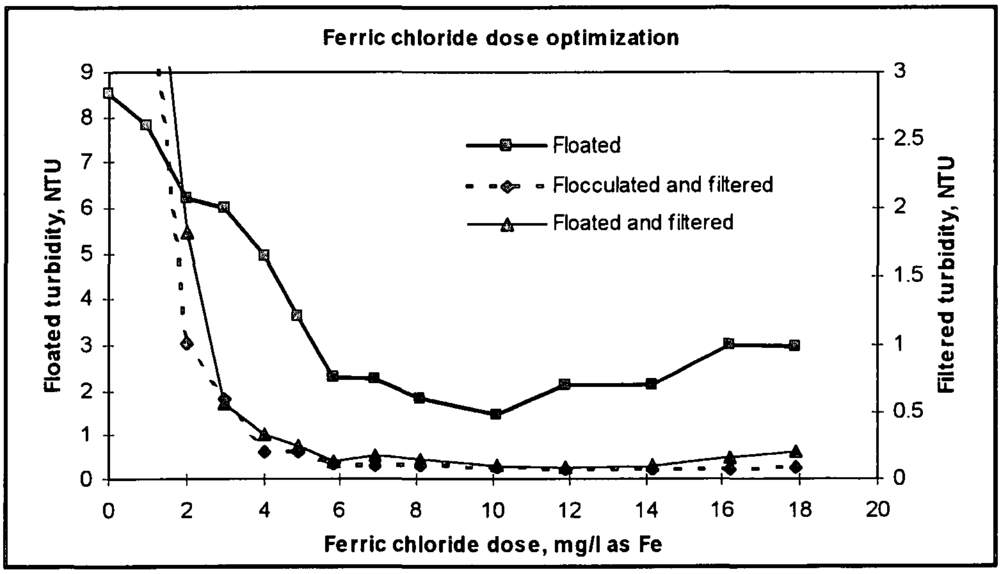


Figure 7.4: Variation of turbidity with ferric chloride dose

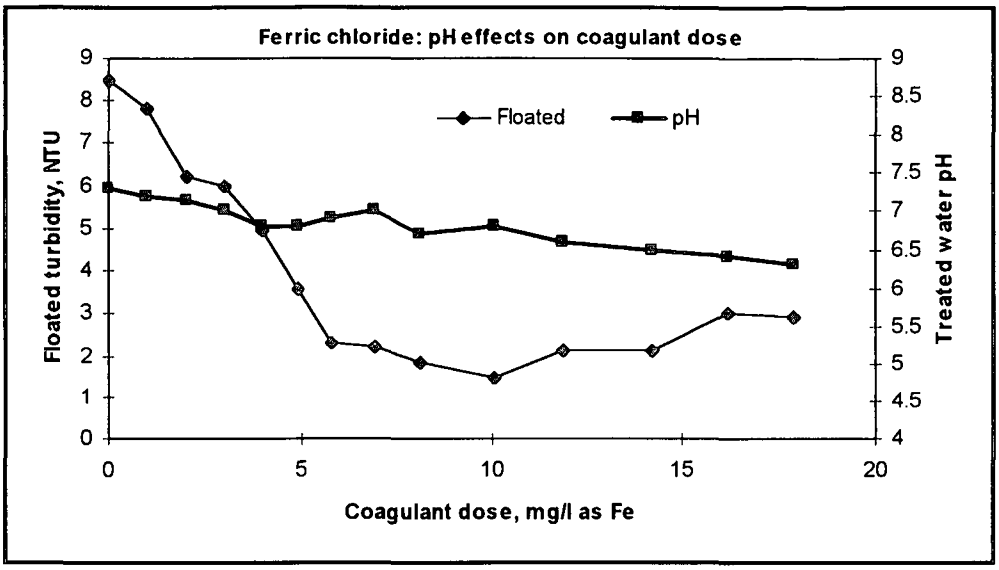


Figure 7.5: Variation of floated turbidity and pH with ferric chloride dose

7.6 Optimisation of DAF operation for polymeric coagulant (Poly A)

7.6.1 Determination of pilot plant consistency and stability using PolyA

The procedure for the determination of pilot plant stability was repeated with Poly A as coagulant. The percent variance in the floated water turbidity and filtered turbidity is shown in Table 7.5 where the percent variance in filtered turbidity was nearly three times as high as the variance in floated turbidity measurements.

PolyA	Flocculated, filtered Turbidity NTU	DAF treated water Floated turbidity NTU	 Filtered turbidity NTU
Average	0.30	3.25	0.57
Standard deviation	0.04	0.14	0.06
Variance for 95% confidence	0.09	0.27	0.13
Range	0.2 to 0.4	3.0 to 3.5	0.4 to 0.7
%Variance for 95 % confidence	30	8	23

Table 7.5: Variation of DAF treated water quality at constant operating conditions using PolyA

7.6.2 Optimisation of coagulation/flocculation and flotation parameters

7.6.2.1 Coagulation intensity

Initial DAF operating conditions, identical to those used for optimisation using ferric chloride were applied for the polymeric organic coagulant, PolyA. The graph of rapid mixing intensity versus turbidity (Figure 7.6) indicates that DAF treated water was not sensitive to coagulation intensity in the range tested. Higher turbidities were consistently recorded for the DAF treated 'floated and filtered' sample than for the 'flocculated and filtered' sample. These may be attributed to floc shear in the flotation vessel, indicating a relatively weak floc. Differences in filtered turbidity before and after flotation appeared to be fairly constant, indicating that changes in coagulation intensity had no significant effect on floc characteristics especially floc strength.

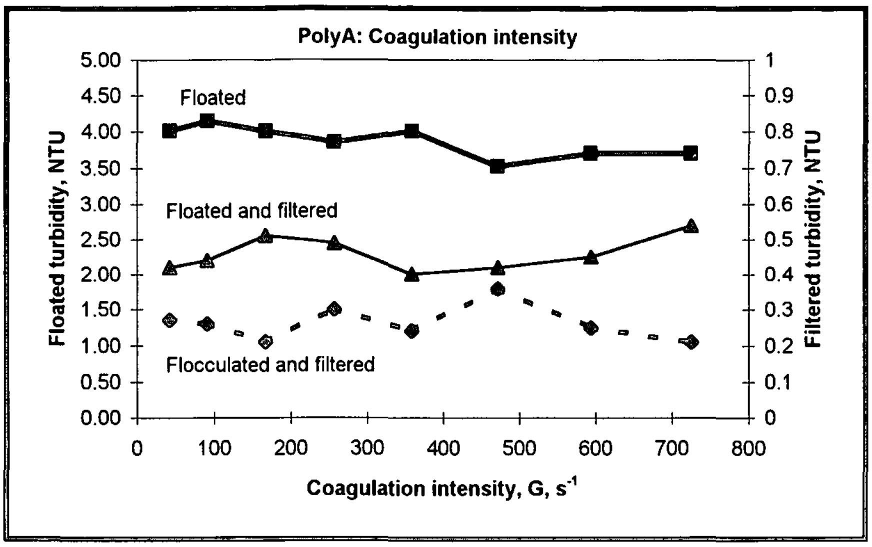


Figure 7.6: Effect of coagulation intensity on DAF treated water turbidity using PolyA

7.6.2.2 Effect of flocculation intensity

Figure 7.7 indicates that a significant reduction in floated turbidity was observed when the flocculation intensity was increased from 2 s^{-1} to 50 s^{-1}. Further increase in flocculation intensity had no significant effect on floated turbidity. The slow rate of change in filtered turbidity with flocculation intensity indicated that filtered turbidity was less sensitive to flocculation intensity. The 'flocculated and filtered' turbidity was more sensitive at the lower mixing intensities but showed no significant change between 50 and 100 s^{-1}. Using 'filtered turbidity' and the floated turbidity as a basis, it was found that the optimum flocculation intensity was 40 s^{-1}.

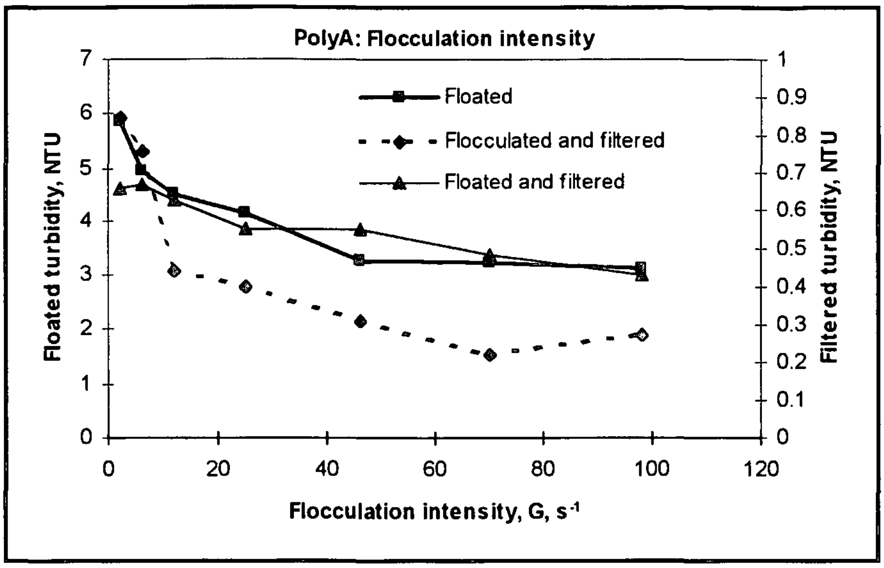


Figure 7.7: Effect of flocculation intensity on DAF treated water turbidity using PolyA

7.6.3 Optimisation of air-water recycle

The effect of air-water recycle on turbidity is shown in Figure 7.8. The lowest filtered water turbidity was achieved with a 6 % recycle. There was no further significant improvement in DAF treated water turbidity for recycle rates in excess of 6%.

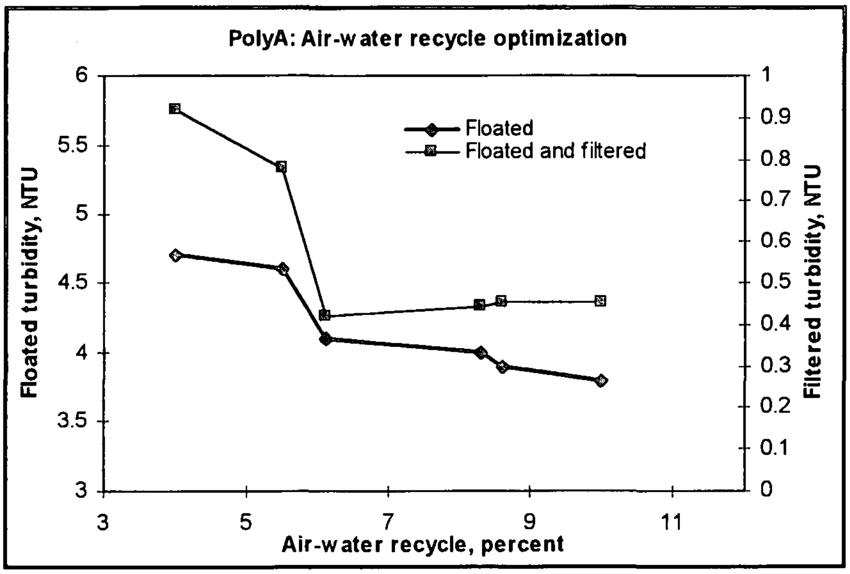


Figure 7.8: Effect of air-water recycle (percent) on DAF turbidity using PolyA

7.6.4 Optimisation of coagulant dose

Table 7.6 shows the flocculation and flotation conditions that were set on the DAF pilot plant for the determination of the minimum coagulant dose required to produce filtered turbidity less than 0.5 NTU.

Parameter	Units	Setpoint
Coagulant dose	mg/l PolyA	variable
Coagulation time	minutes	1
Coagulation intensity	velocity gradient, G, s^{-1}	350
Flocculation intensity	velocity gradient, G, s^{-1}	40
Flocculation time	minutes	10
Air-water recycle	percent	6
Raw water turbidity	NTU	6 to 9
Raw water pH	pH units	7.1

Table 7.6: DAF pilot plant operating parameters for PolyA

Figure 7.9 shows that the floated water and filtered water display similar trends with respect to turbidity variation with coagulant dose. Figure 7.9 also indicates that further increase in coagulant dose in excess of the optimum dose resulted in an initial flat zone followed by a rapid increase in residual turbidity. This observation is in keeping with the phenomenon of restabilization of floc particles due to formation of a charged layer around the floc particle. The excess coagulant coats the particles by adsorption and they all become positively charged. This restabilization results in repulsion between the particles leading to poor agglomeration and flocculation.

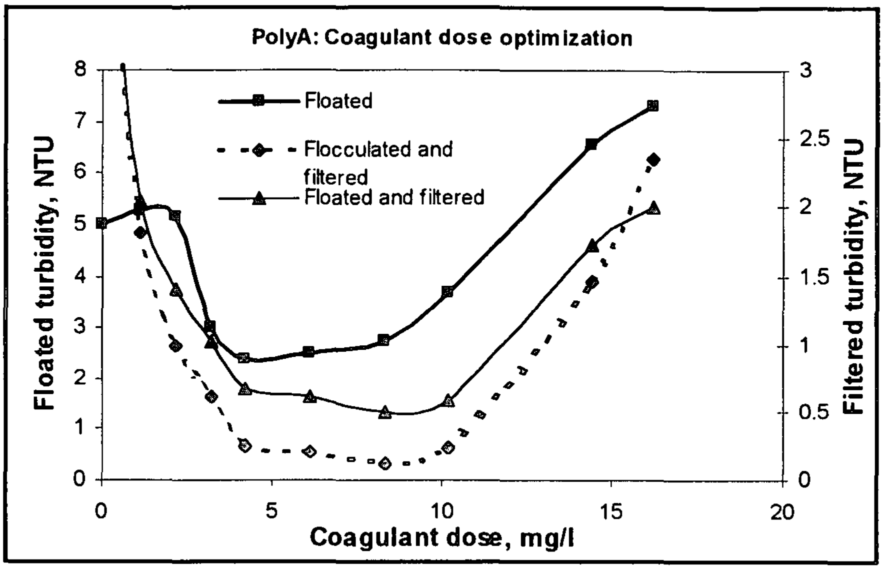


Figure 7.9: Variation of turbidity with PolyA dose

7.7 Optimisation of DAF operation for polymeric coagulant (Poly B)

7.7.1 Determination of pilot plant variability under constant operating conditions for Poly B.

Pilot plant variability at constant operating conditions (Table 7.5) was similar to Poly A, characterised by high variability in filtered turbidities relative to floated turbidity.

PolyB	Flocculated, filtered Turbidity NTU	DAF treated water	
		Floated turbidity NTU	Filtered turbidity NTU
Average	0.17	3.12	0.41
Standard deviation	0.03	0.16	0.08
Variance for 95% confidence	0.05	0.32	0.15
Range	0.1 to 0.2	2.9 to 3.4	0.3 to 0.6
%Variance for 95 % confidence	29	10	37

Table 7.7: Variation of DAF treated water quality at constant operating conditions using PolyB

7.7.2.1 Optimisation of coagulation intensity

Table 7.8 shows the DAF operating conditions used for the optimization of coagulation, flocculation and flotation parameters for PolyB.

Parameter	Units	Setpoint
Coagulant dose	mg/l	3
Coagulation time	minutes	1
Coagulation intensity	velocity gradient, G, s^{-1}	process variable
Flocculation intensity	velocity gradient, G, s^{-1}	40
Flocculation time	minutes	10
Air-water recycle	percent	7
Raw water turbidity	NTU	6 to 9
Raw water pH	PH units	7.1

Table 7.8: Pilot plant operating conditions for PolyB.

PolyB is an organic polymeric coagulant whose physical characteristics are similar to PolyA. Due to the physical similarity of viscosity and specific gravity, between the two polymeric organic coagulants, it may be expected that the optimum coagulation and flocculation conditions for PolyA would also apply to PolyB.

Variation in coagulation intensity, shown in Figure 7.10, had no significant effect on DAF treated turbidity. While the floated turbidity and the 'flocculated and filtered' turbidity were fairly constant, the filtered turbidity of the DAF clarified water showed a relatively wide variation especially for coagulation intensities greater than 200 s^{-1}. However, this variation was still within the limits of the DAF plant variation under constant operating conditions. A coagulation intensity of 200 s^{-1} was considered optimum.

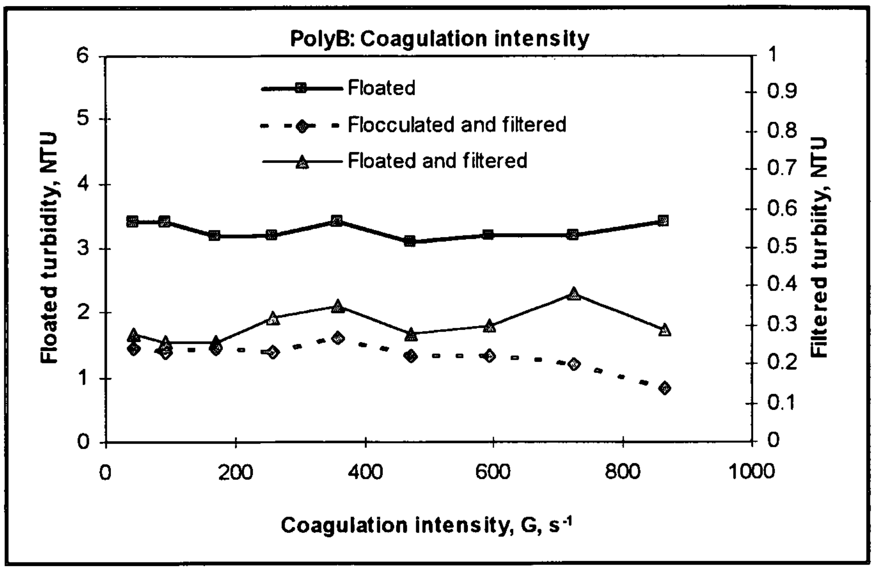


Figure 7.10: Effect of coagulation intensity on DAF treated water turbidity using PolyB

7.7.2.2 Effect of flocculation intensity

Figure 7.11 showed that very good plant performance was achieved at extremely low flocculation mixing intensities (<10 s^{-1}). The response of turbidity removal to G value was almost constant for a 50 fold increase in flocculation mixing intensity. The relatively constant difference between the filtered turbidities before and after flotation also implied that the strength of the flocs formed by Poly B were consistent and were not significantly affected by floc shear due to higher flocculation intensities.

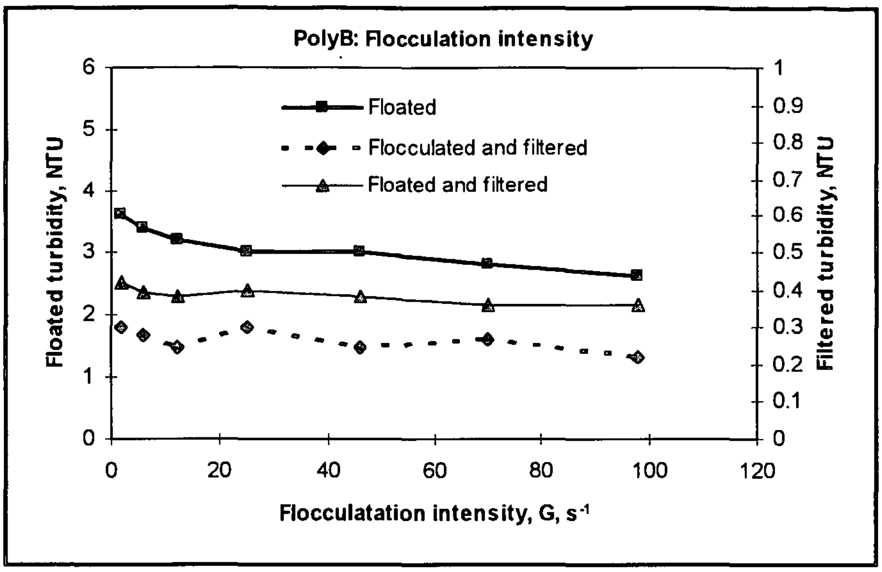


Figure 7.11: Effect of flocculation intensity on treated water turbidity using PolyB

7.7.3 Effect of air-water recycle, percent

The flotation operating conditions were kept constant except for the air-water recycle (percent). Figure 7.12 shows the variation of residual turbidity in the DAF treated water with recycle rate. The optimum air/water recycle was 6%.

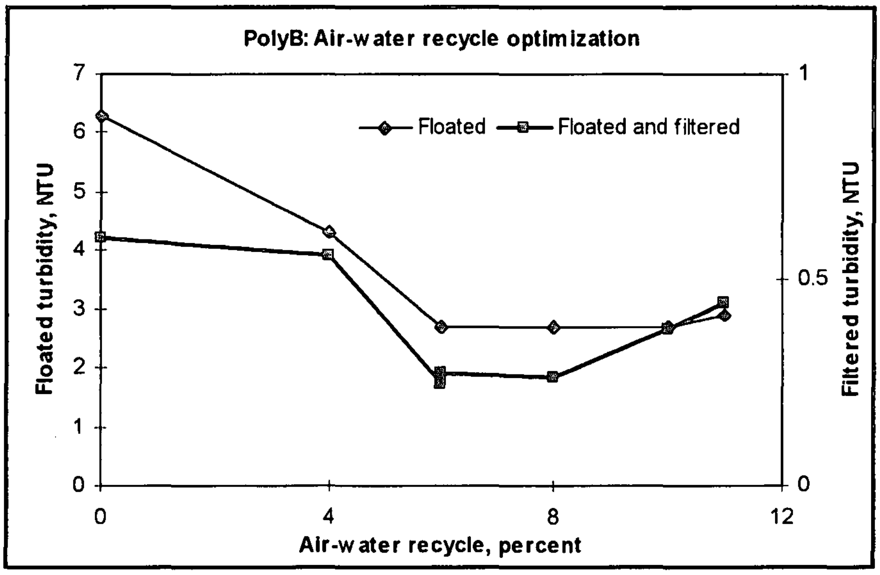


Figure 7.12: Effect of percent recycle on DAF treated water turbidity using PolyB

7.7.4 Optimisation of Poly B dosage

Figure 7.13 clearly shows the initial drop in turbidity with increasing coagulant dose (charge neutralization), the region of relatively insignificant change in turbidity with coagulant dose (optimum coagulant dose) and the region of rapid increase in turbidity (particle restabilization). The closeness of the curve showing 'flocculated and filtered' turbidity, to the 'floated and filtered' turbidity curve, indicates that the flocs formed by PolyB were more resistant to floc shear in the contact zone of the flotation vessel. Floc shear can occur as a result of the turbulence created by the release of the pressurized air-water mixture as a source of air bubbles. The optimum coagulant dose for PolyB was between 2 and 3 mg/l.

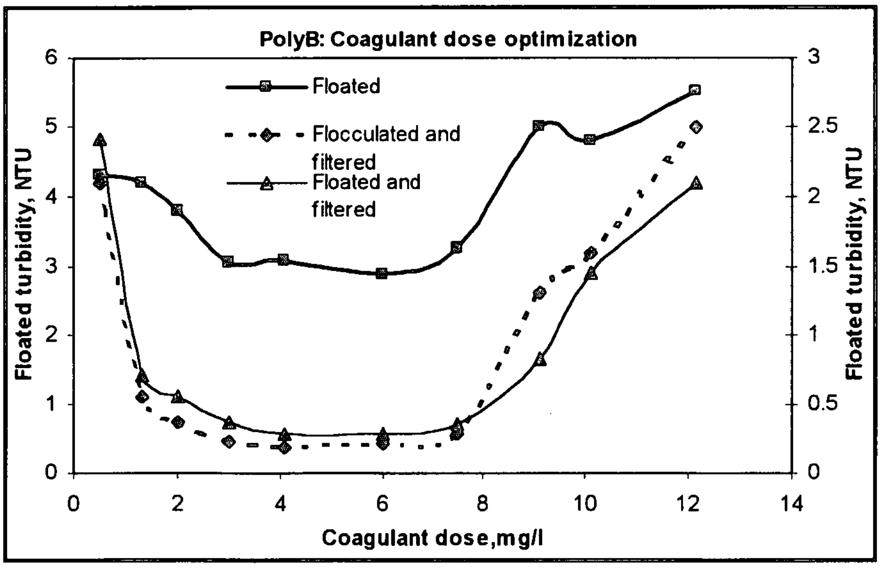


Figure 7.13: Variation of turbidity with PolyB dose

7.8 Discussion of pilot plant optimisation results

The critical parameters investigated were coagulant dose, rapid mixing intensity, flocculation intensity and saturated air-water recycle.

7.8.1 Coagulation and flocculation mixing intensity

The results clearly showed that, under prevailing conditions of raw water quality and range of mixing intensities investigated, coagulation and flocculation were insensitive to mixing intensity, G. These findings are in agreement with similar work done by other workers (Clark *et al*, 1994, Amitharajah and Mills, 1982).

In this study the primary coagulants were ferric chloride and polymeric organic coagulants. The raw water turbidity was low, <10 NTU; pH was 7 and the ferric chloride dosage was 4 mg/l as Fe. Using the Iron (III) coagulation diagram plotted by Johnson *et al* (1983) presented as Figure 7.14, it may be concluded that that the mechanism for ferric chloride coagulation corresponded to sweep coagulation.

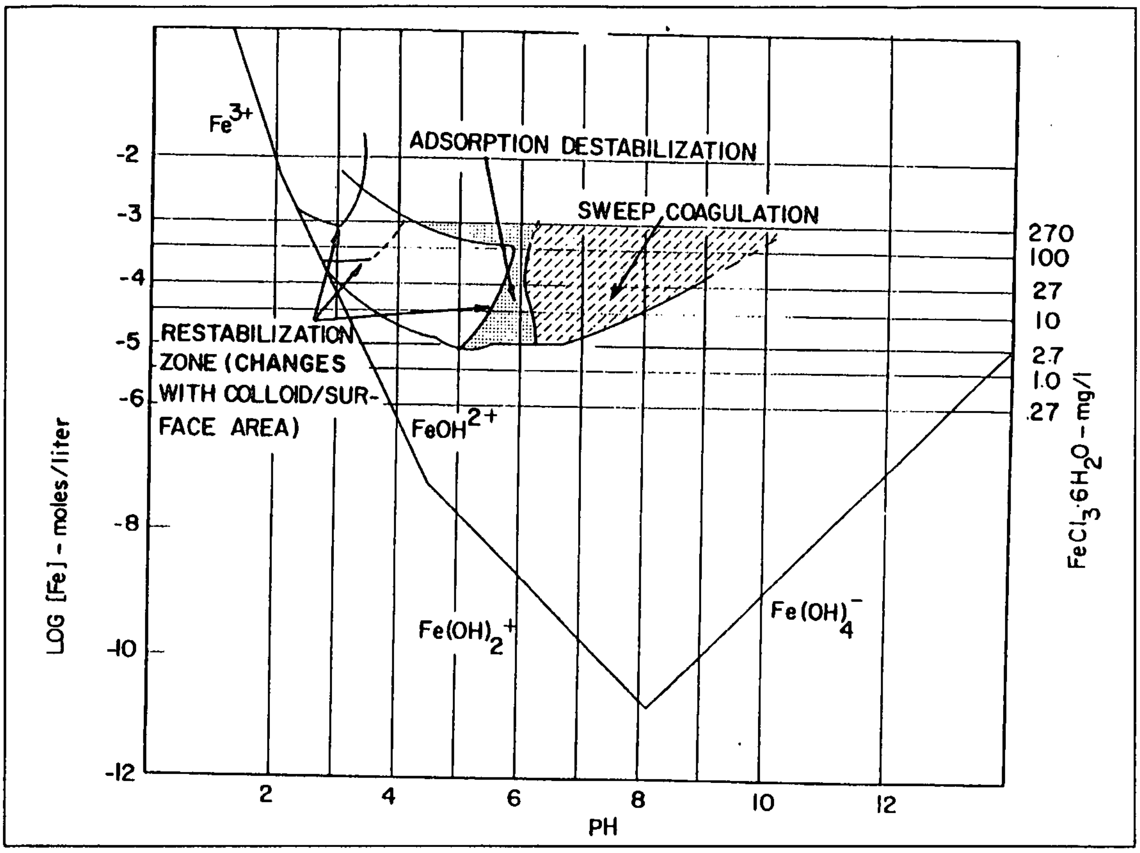


Figure 7.14: Iron (III) coagulation diagram

With low colloidal concentrations and consequent low doses of ferric chloride, coagulation will occur over a charge neutralization region. Thus the polymeric coagulants with charge neutralization as the mechanism of coagulation also showed similar trends to ferric chloride with respect to rapid mixing intensity. The findings were supported by Valade *et al* (1994) and Amitharajah and Mills (1982).

The results show that the role of mixing intensities for coagulation and flocculation may be overstated especially for the treatment of low turbidity raw waters.
This observation concurs with workers, Mooyoung *et al* (1992) who found that the oversimplified rectilinear approach to particle trajectory and particle collisions, that

ignored the effect of a number of important variables, made velocity gradient, G, the principal design parameter. They came up with a new, all encompassing, more mathematically robust curvilinear approach to particle/particle interaction that found G not to be as important. Several pilot studies have determined that optimum G values may be substantially overstated in pilot studies by as much as 100% (Montgomery, 1985).

It may be concluded that rapid mixing intensity is merely a physical requirement for the efficient distribution of coagulant into the water body. The minimum rapid mixing intensity required will be dependent on the physical characteristics of the coagulant like viscosity and concentration at the point of dosing in the rapid mixing vessel.

In general, from evidence in the literature, DAF performance on low turbidity water was relatively insensitive to the flocculation operating parameters studied (Newkirk *et al*, 1991). Flocculation intensity should be just sufficient to keep the flocs in suspension. Small size flocs, typical of low turbidity waters and low coagulant doses may require considerably less intense mixing to keep them in suspension.

7.8.2 Saturated air-water recycle

The optimum air-water recycle was the same for the coagulants tested. This implies that the floc characteristics with respect to floatability may be similar for the coagulants. The experimentally determined air-water recycle was 7% (v/v) for ferric chloride and 6% for PolyA and PolyB. These results were in agreement with reported data (Haarhoff and van Vuuren, 1993).

A consistent occurrence in the relationship between DAF treated turbidity and the air-water recycle for the coagulants was the deterioration in turbidity after the optimum recycle was exceeded. It would be expected that the DAF treated water turbidity will remain constant after the required air-water recycle was applied under constant solids loading and coagulation/flocculation conditions. This deterioration in turbidity at the higher percentage recycles may be attributed to the increased turbulence in the contact zone of the flotation vessel caused by the increased flow rate of the pressurised air-water recycle.

7.8.3 Optimum coagulant dose

For ferric chloride, the DAF treated water (filtered) turbidity initially dropped sharply with increasing ferric chloride dose until the optimum dose was reached. Thereafter the turbidity levelled off and remained constant. The pH of the mixed solution remained within the working range for ferric chloride (pH 4 to 10). The observed trend was in keeping with the generally accepted coagulation mechanism of sweep flocculation applied to an inorganic coagulant like ferric chloride.

For the organic polymeric coagulants, PolyA and PolyB, variation of turbidity with coagulant dose showed the initial drop in turbidity with increasing coagulant dose (charge neutralization), the region of relatively insignificant change in turbidity with coagulant dose (optimum coagulant dose) and the region of rapid increase in turbidity (particle restabilization).

The effect of pH on the performance of the polymeric organic coagulants was considered insignificant due to the small difference in pH between the raw water and the treated water. The pH difference was 0.1 of a pH unit.

7.8 Summary of results

7.9.1 Optimised operating parameters

Due to the insensitivity of coagulation and flocculation to mixing intensity a wide range of rapid mixing and flocculation intensities were applicable. Table 7.9 shows the approximate values and range of values obtained from the optimisation trials.

	Ferric chloride		PolyA		PolyB	
Operating parameters	Flotation	Filtration	Flotation	Filtration	Flotation	Filtration
Coagulant dose, mg/l	6 as Fe	4 as Fe	4	6	3	3
Coagulant intensity, G, s^{-1}	50	100	50 to 200	50	50	50
Flocculation intensity, G, s^{-1}	<20	<20	50	50	25	25
Air-water recycle, percent	7	7	6	6	6	6

Table 7.9: Optimised operating parameters

7.9.2 Coagulant dose optimisation

Table 7.10 shows the results obtained from the coagulant dose optimisation experiments.

Coagulant	$FeCl_3$	PolyA	PolyB
Optimum coagulant dose, mg/l	4 to 5 as Fe	5 to 6	2 to 3
Raw water turbidity, NTU	<10	<10	<10
Raw water pH	7.5	7.5	7.5
Floated water turbidity, NTU	2.0	2.5	3.1
Filtered water turbidity, NTU	0.25	0.52	0.21
Filtered water pH	6.99	7.4	7.4

Table 7.10: Coagulant optimisation

Chapter 8

Pilot Plant Coagulant Evaluation Under Optimised DAF Conditions

8.1 Introduction

The objective was to operate the DAF pilot plant with different coagulants under optimised operating conditions and measure their individual performance over a period of time.

The performance data for each coagulant are presented with respect to a number of performance criteria that were identified and discussed in Chapter 4. These included DAF treated water quality, filterability of the DAF clarified water, DAF float layer stability and chemical treatment costs. Float layer stability and chemical costs will be discussed in chapter 9 where the performance of the polymeric organic coagulants were compared with the performance of the inorganic coagulant, ferric chloride.

8.2 DAF operating conditions

Having determined the effect of critical operating variables, a set of DAF operating parameters were chosen for the evaluation of the coagulants. The optimisation of flocculation and flotation conditions indicated that the same DAF operating conditions were suitable for both ferric chloride and the polymeric organic coagulants. Thus ferric chloride and the polymeric coagulants were run under identical flocculation and flotation conditions.

Table 8.1 shows the optimised DAF operating parameters for the coagulant evaluation trials.

Parameter	**Units**	**Pilot plant Set point**	**Design Guidelines** (Haarhoff & van Vuuren, 1993)
Coagulation and flocculation			
Rapid mixing time	seconds	60	***
Rapid mixing intensity	G, s^{-1}	200	***
Flocculation intensity	G, s^{-1}	40	50 to 120
Flocculation time	minutes	10	4 to 15
Dissolved air flotation			
Contact zone			
Residence time	s	51	60 to 240
Hydraulic loading	m/h	66	40 to 100
Flotation zone			
Crossflow velocity	m/h	75	20 to 100
Hydraulic loading	m/h	5	5 to 11
Side depth	m	1.2	1.5 to 3.0
Residence time	min	8	
Saturator			
Recycle	percent	7	6 to 10
Saturation pressure	kPa	500	300 to 600

*** unspecified for DAF application

Table 8.1: DAF pilot plant operating conditions

8.3 Results

Performance data for the three coagulants is presented in the form of graphs. DAF run time refers to the duration the DAF pilot plant was monitored and may be better described as 'Time elapsed'.

8.3.1 Performance data for ferric chloride

Ferric chloride dose was kept constant at the optimised dose of 4.5 mg/l for the duration of the trials. Raw water turbidity and pH were fairly constant between 6 and 9 NTU and 7.1 and 7.5 respectively.

8.3.1.1 DAF treated water turbidity

Figure 8.1 shows the treated water turbidity results for DAF operation with ferric chloride. The higher turbidity in the first half hour of operation was probably due to plant instability. DAF performance was fairly stable over the remainder of time monitored. The average floated turbidity and filtered turbidity were 2.2 NTU and 0.25 NTU respectively.

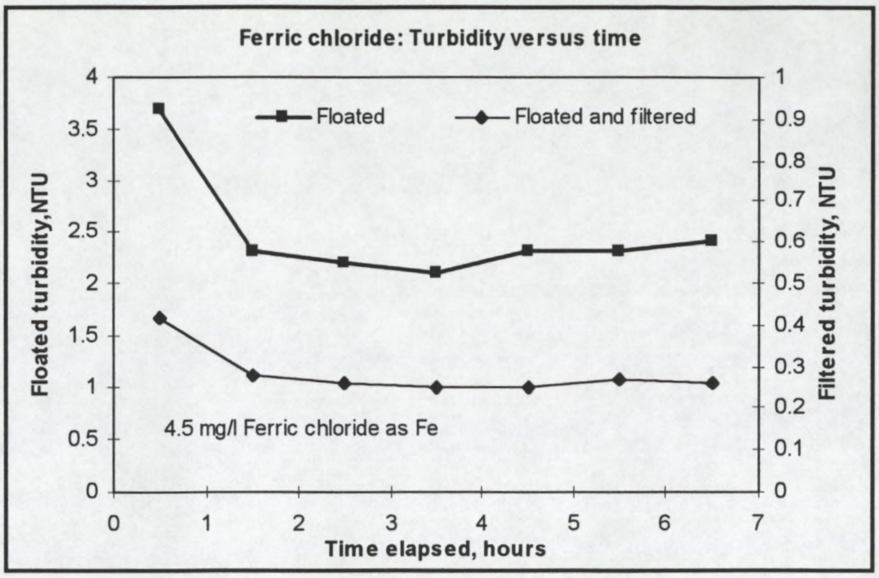


Figure 8.1: Variation of turbidity with time using ferric chloride

Turbidity removal, presented in Figure 8.2, is the difference between the raw water turbidity and the treated water turbidity expressed as a percentage of raw water turbidity. Between 65 and 70% turbidity removal was achieved at the DAF clarification stage, based on floated turbidity and 95% removal was achieved after filtration.

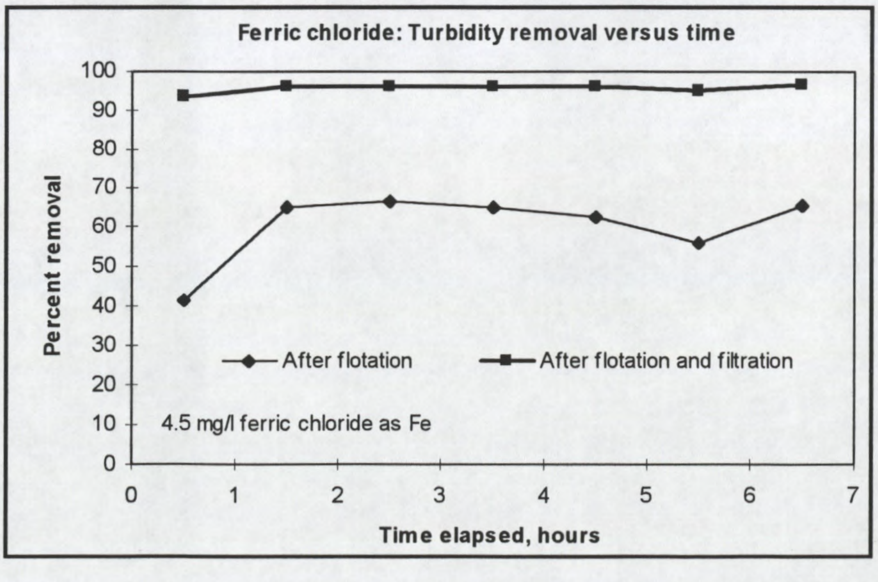


Figure 8.2: Variation of turbidity removal with time using ferric chloride as coagulant

8.3.1.2 UV absorbance (UVA) @ 254 nm

Figure 8.3 shows the variation of UVA @ 254 nm with time. The DAF treated water had a slightly lower UVA than the flocculated and filtered water implying that DAF may be contributing to organic reduction. Further reduction in UV absorbance was evident after filtration.

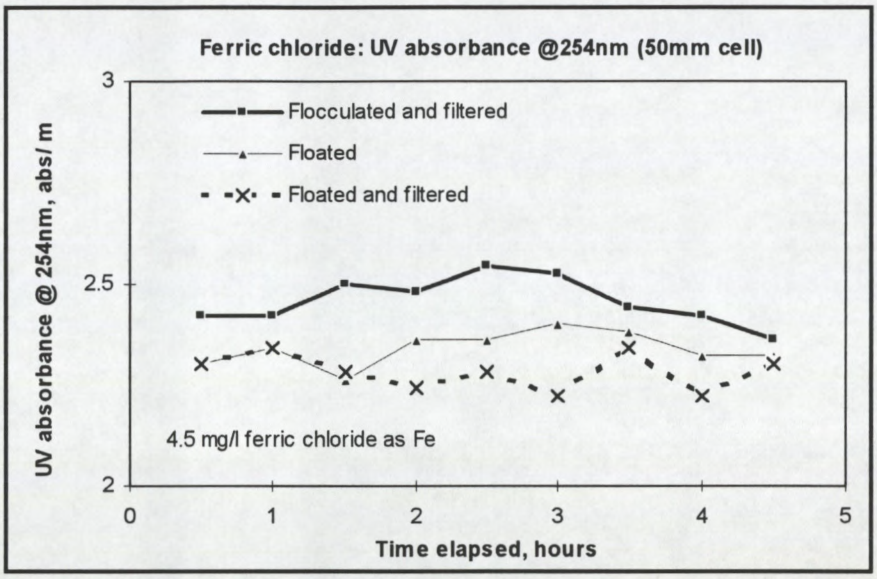


Figure 8.3: Variation of UV absorbance at 254 nm with time using ferric chloride

8.3.1.3 UVA reduction

Percent UVA reduction was calculated as the difference between the UVA of the raw water and the DAF clarified filtered water, expressed as a percentage of the raw water absorbance. Figure 8.4 shows that between 60 and 65% reduction in UV absorbance was achieved with ferric chloride. Reduction in UV absorbance was almost constant with time, indicating that the fluctuations in UV absorbance readings in Figure 8.3 were probably due to systematic errors in UV measurement.

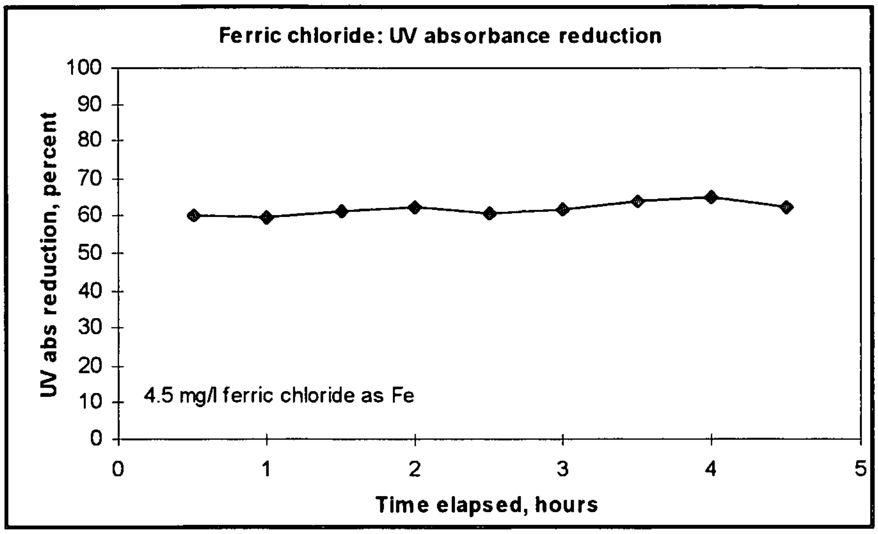


Figure 8.4: Reduction in UV absorbance at 254nm with time using ferric chloride

8.3.1.4 Floc filterability

The tests were run under controlled conditions with respect to media and flowrate. The suspended solids concentration in the DAF clarified water for each of the three coagulants were similar (between 5 and 6 mg/l).

Figure 8.5 shows the headloss and turbidity profile for ferric chloride. The turbidity profile curve clearly shows the three stages, filter ripening, steady state removal and breakthrough, in sand filter operation. From Figure 8.5, the filter ripening stage characterised by an initial drop in filtered turbidity, occurred in the first 19 minutes of the filter run. The duration of steady state filtration, indicated by a period of no significant turbidity change before the onset of turbidity breakthrough, was 61 minutes. Terminal headloss development, at the point of turbidity breakthrough, was 178 mm. The linear relationship between headloss and time indicates that depth filtration was the dominant mode of filtration.

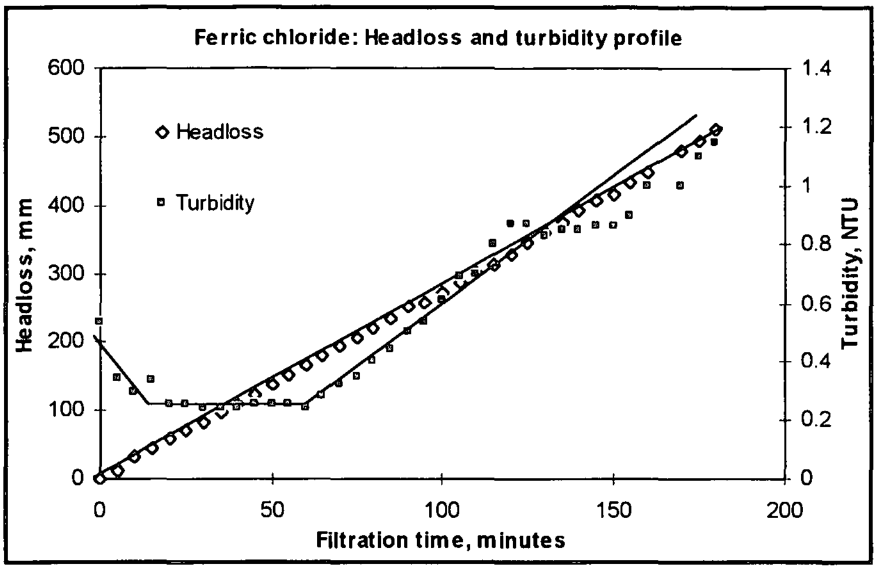


Figure 8.5: Change in headloss and turbidity with filter run time using ferric chloride

8.3.2 Performance data for Poly A

Coagulant dose was set at the optimised dose of 5 mg/l. Raw water conditions were similar to conditions during the DAF optimisation trials.

8.3.2.1 DAF treated water turbidity

Figure 8.6 shows that after an initial drop, floated turbidity remained fairly constant with time. The relatively high floated turbidity at the beginning of the run may be due to plant instability due to initial consolidation of the float layer. There was no significant change in filtered turbidity. The average floated turbidity was 4.2 NTU and the average filtered turbidity was 0.43 NTU.

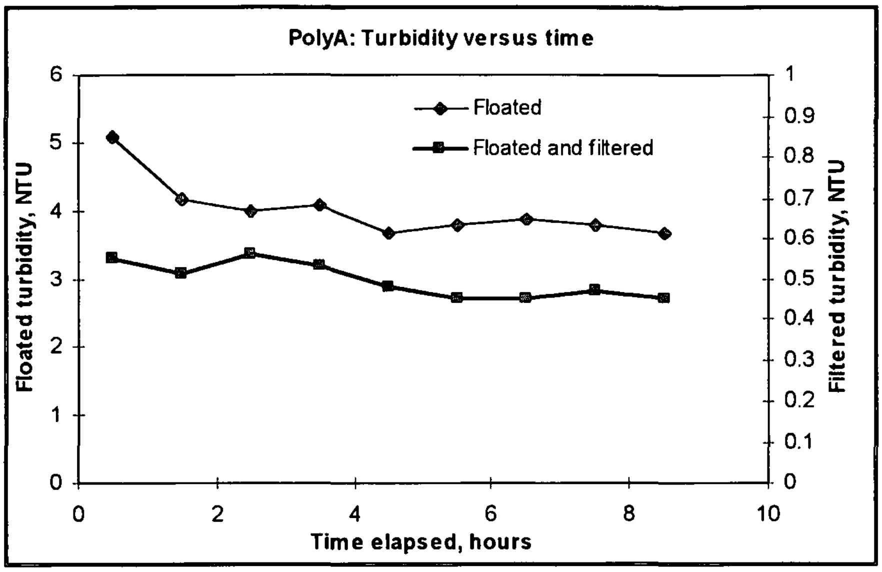


Figure 8.6: Variation of turbidity with time using PolyA

From Figure 8.7, between 35 and 45% turbidity removal was achieved at the DAF clarification stage, based on floated turbidity. Just over 90% turbidity removal was achieved after the filtration stage.

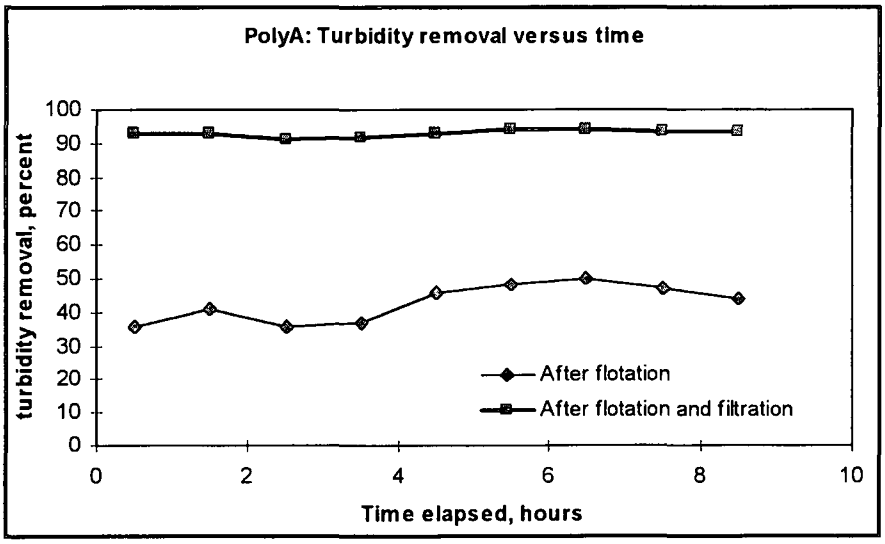


Figure 8.7: Variation of turbidity removal with time using PolyA

8.3.2.2 UV absorbance at 254 nm

Figure 8.8 indicates that UV absorbance of the DAF treated floated water was slightly lower than the absorbance of the flocculated and filtered water. The floated and filtered sample indicated a further drop in UV absorbance.

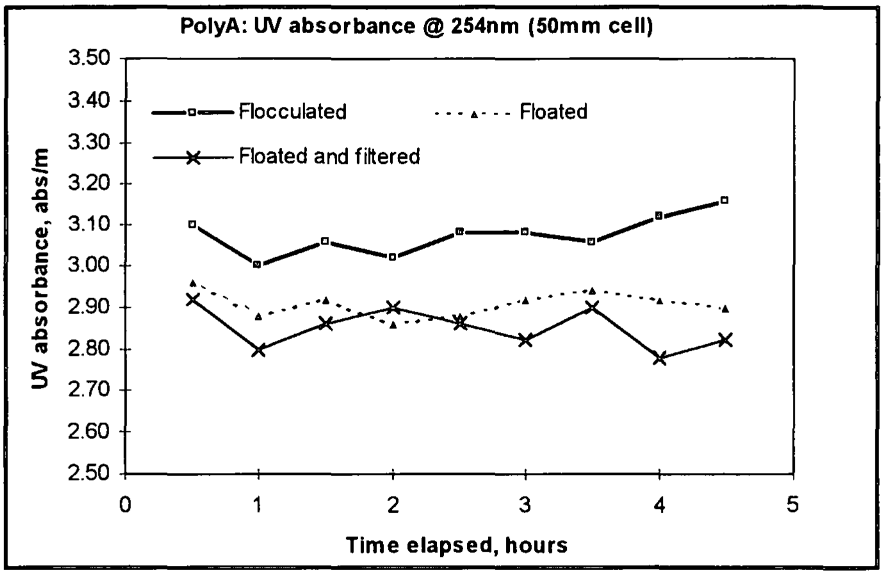


Figure 8.8: Variation of UV absorbance at 254 nm with time using PolyA

From Figure 8.9 UV reduction between 50 and 55% (based on DAF filtered water) was achieved with PolyA as coagulant.

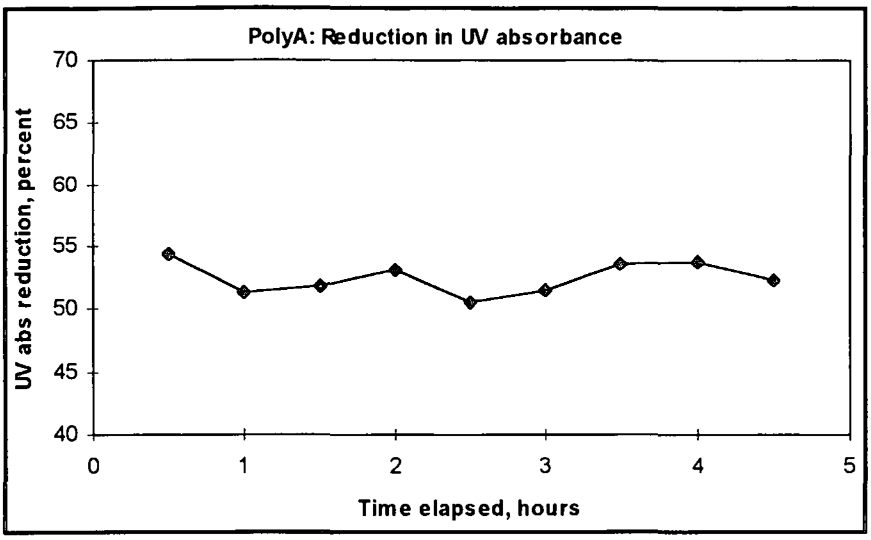


Figure 8.9: Reduction in UV absorbance @ 254nm with time using PolyA

8.3.2.3 Floc filterability

From Figure 8.10, the filter ripening period for PolyA was 28 minutes. The period of steady state filtration was 50 minutes and the headloss at turbidity breakthrough was 125 mm. The headloss versus time curve was concave upwards indicating that some surface filtration may have occurred.

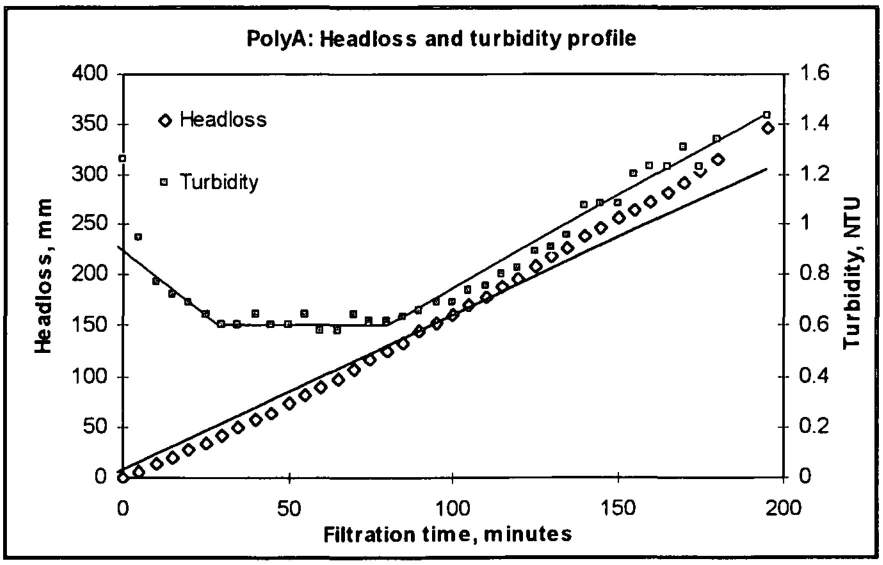


Figure 8.10: Change in headloss and turbidity with filter run time using Poly A

8.3.3 Performance data for polymeric coagulant (Poly B)

PolyB dose was constant at 3 mg/l. Raw water conditions remained unchanged with turbidities less than 10 NTU and pH between 7 and 7.5.

8.3.3.1 DAF treated water turbidity

Figure 8.11 indicates that the floated turbidity varied between 2.5 and 3 NTU. The floated and filtered turbidity was also very consistent for the entire monitoring period at a turbidity close to 0.5 NTU.

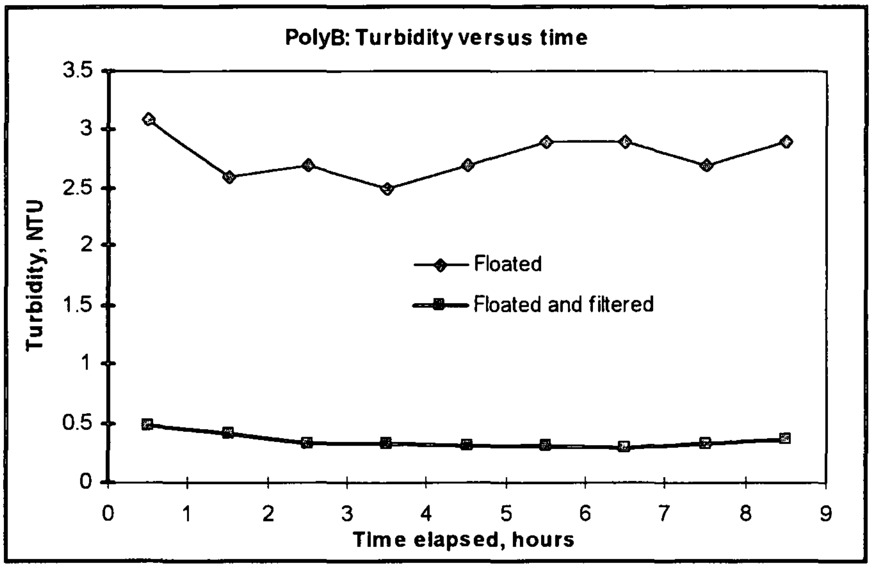


Figure 8.11: Variation of turbidity with time using PolyB

From Figure 8.12, turbidity removal at the flotation stage had a relatively wide variance between 50 and 65%. Turbidity removal after filtration was constantly between 90 and 95%.

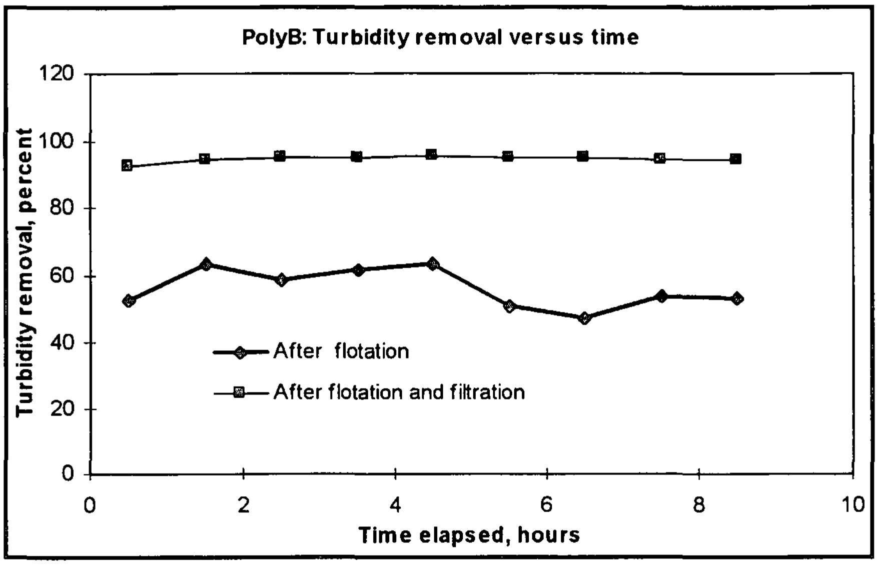


Figure 8.12: Variation of turbidity removal with time using PolyB

8.3.3.2 UV absorbance at 254 nm

The lower absorbance of the DAF clarified water relative to the absorbance of the flocculated water, indicated by Figure 8.13, suggests a further removal of organics by DAF. There was no significant difference in absorbance between floated water and the filtered water.

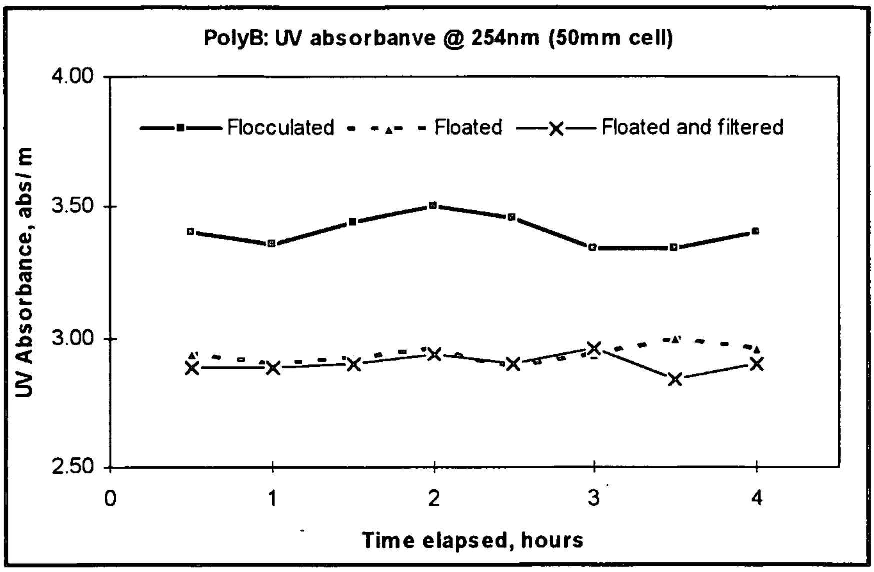


Figure 8.13: Variation of UV absorbance at 254 nm with time using PolyB

Figure 8.14 indicated that between 50 and 55% reduction in UV absorbance was achieved with PolyB.

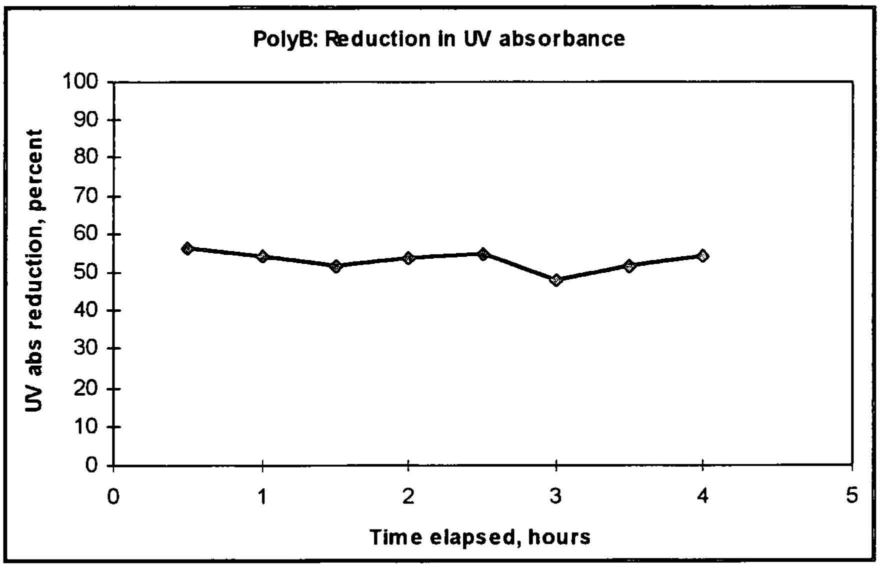


Figure 8.14: Reduction in UV absorbance @ 254nm time using PolyB

8.3.3.3 Floc filterability

From 8.15, the duration of the filter ripening stage was 36 minutes. The period of relative steady state filtration was 99 minutes and the filter headloss at the onset of turbidity breakthrough was 256 mm. Steady state filtration time is longer than the steady state filtration times for both ferric chloride and PolyA.

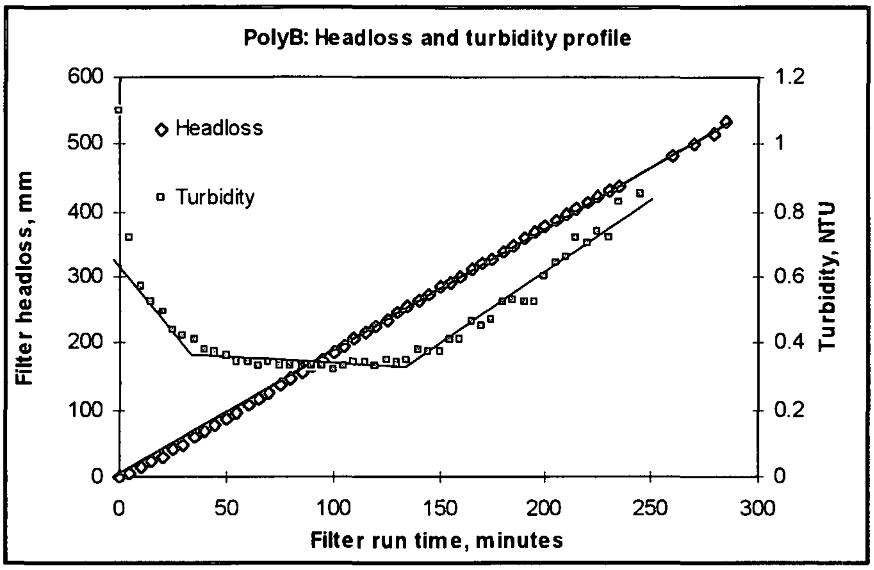


Figure 8.15: Change in headloss and turbidity with filter run time using Poly B

8.4 Summary of results

The performance of the individual coagulants is presented in Table 8.2.

	Ferric chloride	PolyA	PolyB
Coagulant dose, mg/l	4.5 as Fe	5	3
Floated turbidity, NTU	2.2	3.8 to 4.2	2.5 to 3.0
Filtered turbidity, NTU	0.25	0.45 to 0.55	0.4 to 0.5
Turbidity removal, percent			
Flotation stage	50 to 60	35 to 40	50 to 65
Filtration stage	90 to 95	90	90 to 95
UV absorbance @ 254 nm, abs m^{-1}	2.0 to 2.5	2.5 to 3.0	2.5 to 3.0
UV absorbance reduction, percent	60 to 65	50 to 55	50 to 55
Filter ripening time, min	19	28	36
Steady state filtration, min	61	50	99
Terminal headloss, mm	178	125	256

Table 8.2: Summary of results

Chapter 9

Comparison of Coagulant Performance

9.1 Introduction

The objective in Chapter 9 is to use the data presented in Chapter 8 and compare the performance of the polymeric organic coagulants against the control coagulant, ferric chloride.

9.2 Comparison of treated water quality

9.2.1 Floated water turbidity

Figure 9.1 indicates that ferric chloride produced the lowest floated water turbidity (average 2.2 NTU) while PolyA produced floated water with the highest turbidity (average 4 NTU). PolyB produced an average floated water turbidity (2.8 NTU) comparable to ferric chloride. There was a significant improvement in the performance of the polymeric coagulants and ferric chloride after about one and a half hours of operation. This was probably due to plant instability during the formation of the float layer during the initial period of one and half hour.

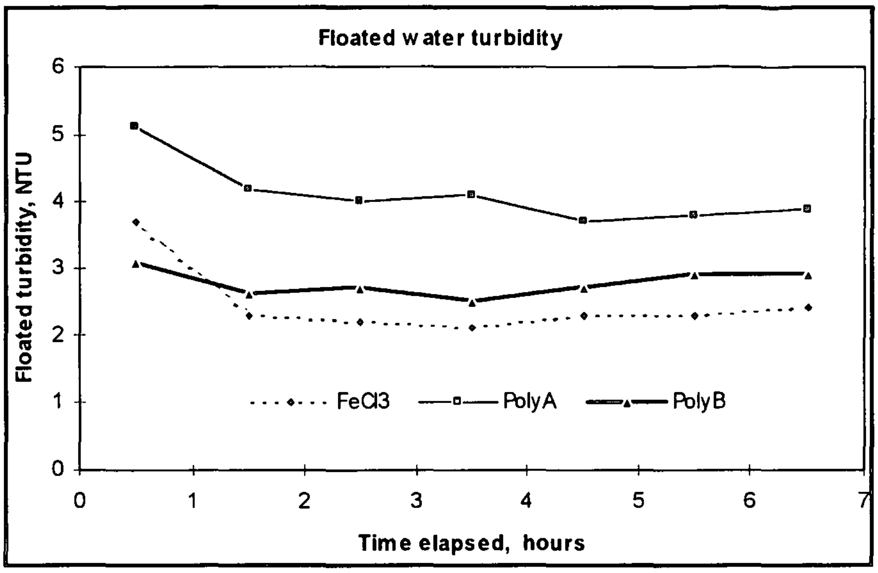


Figure 9.1: Comparison of floated water turbidity

9.2.2 Filtered turbidity

Figure 9.2 shows that ferric chloride and PolyB achieved comparable filtered water turbidities, while Poly A produced significantly higher turbidities.

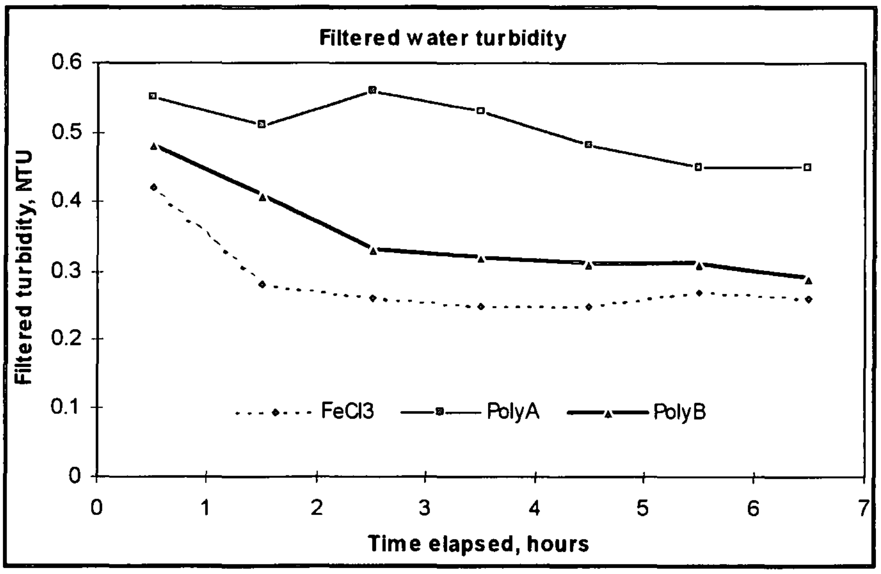


Figure 9.2: Comparison of filtered water turbidity

9.2.3 Turbidity reduction on floated water basis

Turbidity reduction, based on floated water, is calculated as the difference between the turbidity of the raw water and floated water expressed as a percentage of the raw water turbidity. The efficiency of turbidity reduction or removal at the flotation stage will affect solids loading at the sand filtration stage. Table 9.3 shows that PolyB achieved a turbidity reduction similar to that achieved by ferric chloride. Relatively poor results were obtained with PolyA.

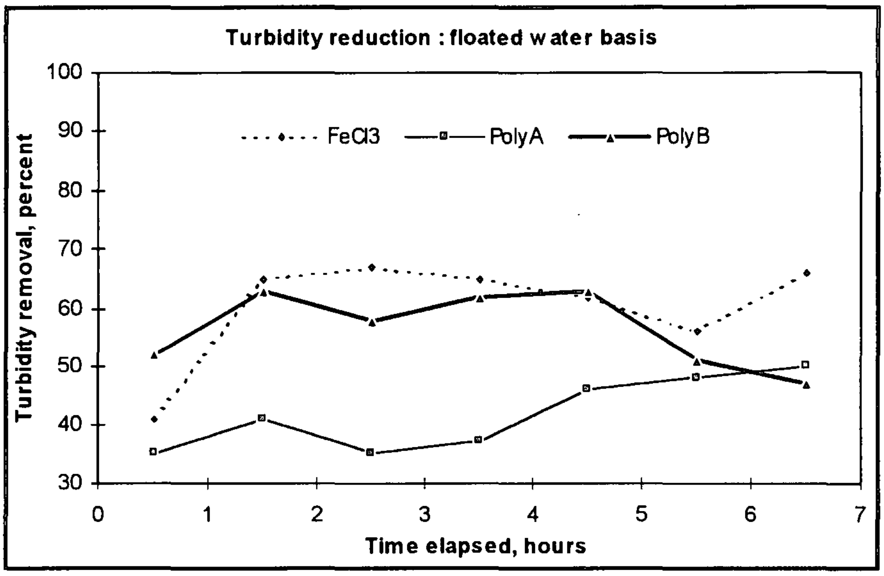


Figure 9.3: Comparison of turbidity reduction on floated water basis

9.2.4 Turbidity reduction based on filtered water turbidity

As indicated in Figure 9.4, PolyB achieved an average final turbidity removal comparable to ferric chloride, (95% and 96% respectively) while PolyA achieved the lowest percentage turbidity reduction (93%). The results show that PolyB achieved turbidity removals comparable to ferric chloride, while the use of PolyA resulted in marginally lower turbidity removals being obtained.

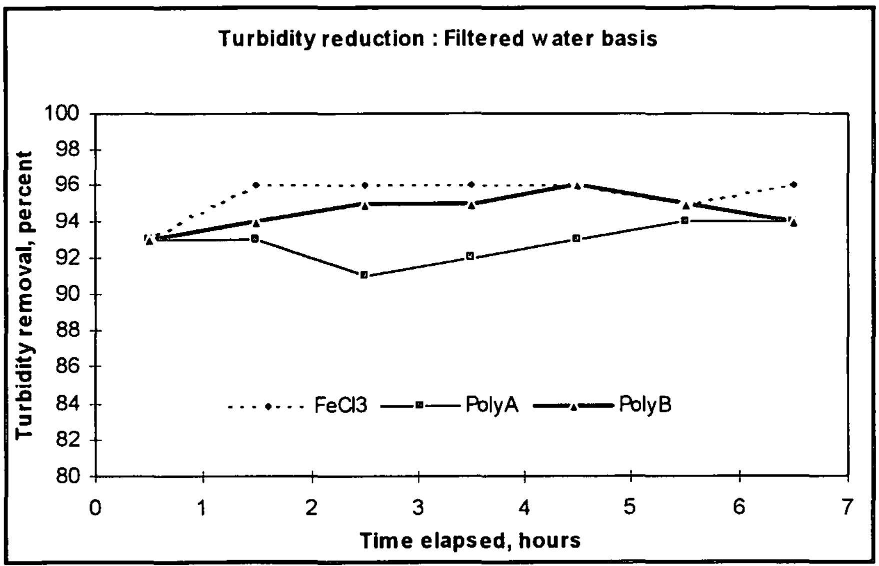


Figure 9.4: Comparison of turbidity removal based on filtered water turbidity

9.2.5 UV absorbance @ 254 nm

UV absorbance @ 254 nm is a pseudo measurement of total organic carbon. Figure 9.5 indicates that both the polymeric coagulants produced DAF treated (filtered) with similar UV absorbances. However, for the ferric chloride treated water low UV absorbances were measured consistently. This indicates that ferric chloride was better than the organic coagulants at organic removal.

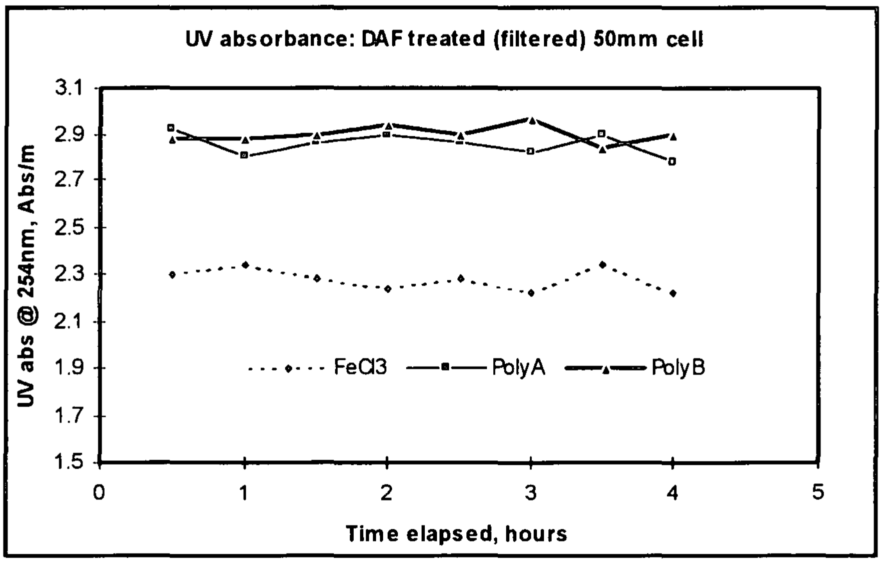


Figure 9.5: Comparison of UV absorbance @254 nm

9.2.6 Reduction in UV absorbance

Figure 9.6 shows that a significantly higher reduction in UV absorbance was obtained with ferric chloride as coagulant (between 60 to 65%). The reductions achieved with PolyA and PolyB were similar (between 50 and 55%).

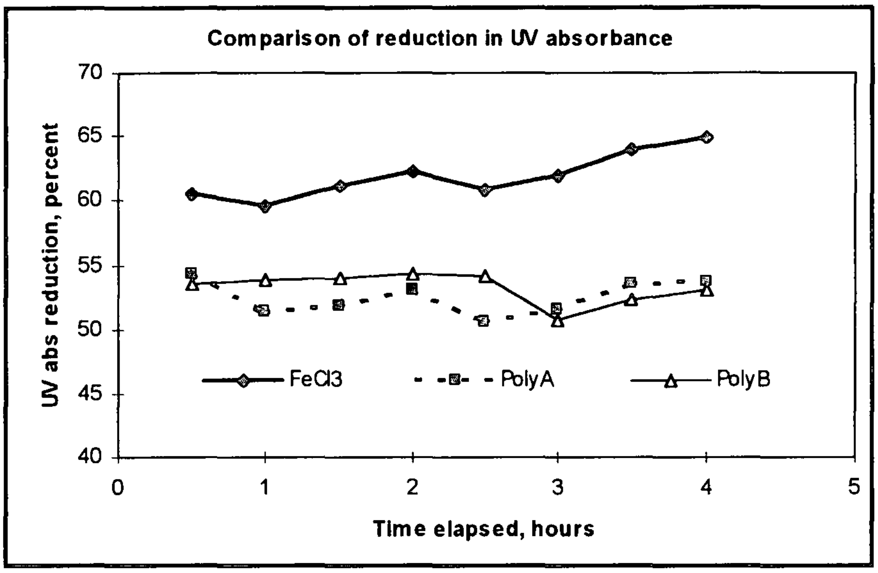


Figure 9.6: Comparison of reduction in UV absorbance @ 254nm

9.2.7 Coagulant dose

Figure 9.7 shows that ferric chloride and PolyB produced similar filtered water turbidities. The optimum PolyB dose was lower than the ferric chloride dose. PolyA produced higher filtered turbidities at a significantly higher dose. Overdosing with polymeric organic coagulants resulted in a drastic deterioration in treated water turbidity. Charge neutralization by adsorption of the coagulant to the colloid is the key mechanism for the removal of water-borne solids from waters. The colloidal charge may not only be reduced to zero but beyond zero. The findings concur with accepted theory that excess coagulant will lead to restabilization and consequent particle to particle repulsion and poor or no flocculation (Penniman, 1981).

Increasing the ferric chloride dose beyond the optimum, had no detrimental effect on treated water turbidity. The ferric hydroxide flocs formed were easily removed by flotation and filtration. Deterioration in turbidity from overdosing with ferric chloride will only occur if the solution pH drops below the limit at which ferric hydroxide solubilizes in water.

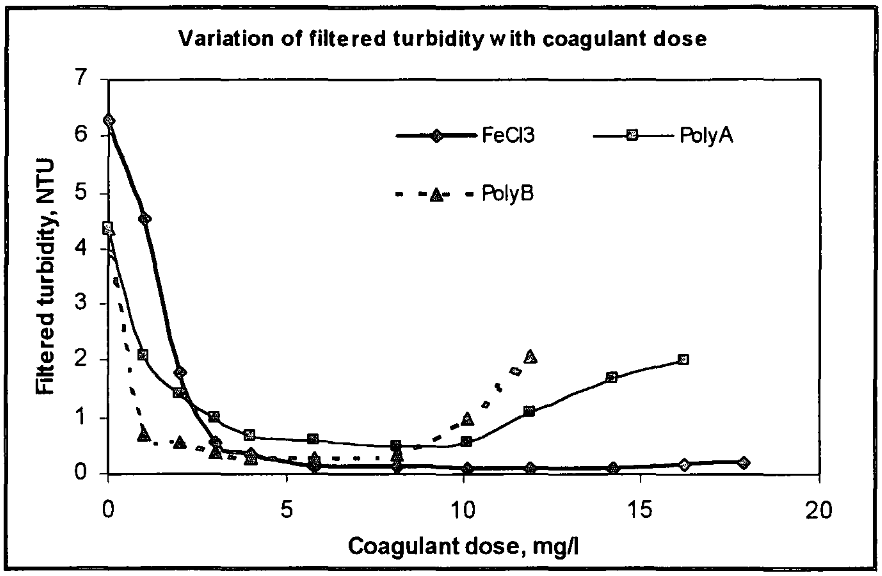


Figure 9.7: Comparison of coagulant dose versus filtered water turbidity

9.2.8 pH

It is evident from Figure 9.8 that ferric chloride consumed a significant amount of alkalinity resulting in a reduction in pH, with increasing dose. Polymeric coagulants had no significant effect on final water pH.

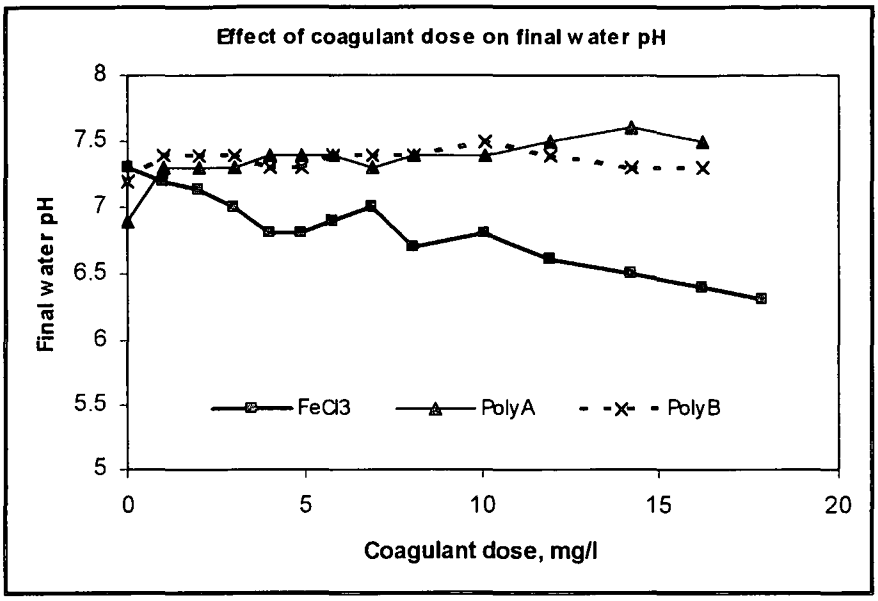


Figure 9.8: Effect of coagulant dose on pH

9.2.9 Comparison of final water quality

The more critical chemical determinands that affect water quality were measured on the DAF treated (filtered) water. Comparison with the Umgeni Water standard indicated that all the coagulants evaluated, produced final water that met Umgeni Water's minimum standards for potable water (Table 9.1). Although the generic Umgeni Water standard for final water turbidity was 1 NTU, the Waterworks in the Urban areas under the jusidiction of Umgeni Water, are optimised to produce final water turbidities less than 0.5 NTU.

	Colour Hazens	pH	Al µg/l	Fe mg/l	Mn mg/l	Turbidity NTU	TOC mg/l
DAF raw	20	7.0 to 7.5	494	0.37	0.01	10	3.8
Poly A final	4	7.0 to 7.4	52	0.02	<0.01	0.5	3.6
Poly B final	3	7.0 to 7.4	51	<0.02	<0.01	0.3	3.2
$FeCl_3$ final	3	6.5 to 6.8	37	<0.02	0.01	0.2	2.6
UW Std	20	6.0 to 9.0	150	0.2	0.05	1.0	10

Table 9.1: Some determinands affecting water quality

9.3 Sludge/float layer characteristics

The physical and chemical characteristics of the sludge float that accumulates on the surface of the flotation vessel during flotation is important because it impacts on the operation and performance of the DAF treatment process. A weak float layer may be easily disturbed by the relatively high upflow velocity in the contact zone, that drives the bubble/particle conglomerate on to the surface of the flotation vessel. The shearing action of the crossflow velocity acting at the interface of the contact zone and the flotation zone can also be disruptive to a weak float layer. The stability of the float affects the DAF run time which may be defined as the duration of the flotation process before it is necessary to desludge the float layer. The stability of the float layer can be expressed as the time taken for the float to start disintegrating and causing an increase in floated water turbidity, during normal operation and stable plant conditions.

9.3.1 Float layer stability

Ferric chloride formed a voluminous float layer. As the thickness of the float increased, sludge at the water / float interface became increasingly unstable and caused the floc particles to be dislodged from the float layer. The settling particles resulted in a deterioration in floated water turbidity. Figure 9.9 represents the variation of floated water turbidity with time, for the three coagulants run under optimised flocculation and flotation conditions. A significant deterioration in turbidity of the ferric treated water was noted after about 14 hours of continuous operation without desludging. The float layer formed by the polymeric coagulants was 'drier' and more compact. This resulted in stable conditions in the flotation vessel for longer periods relative to similar conditions when ferric chloride was used as coagulant. DAF run time exceeded 72 hours before desludging for the polymeric organic coagulants.

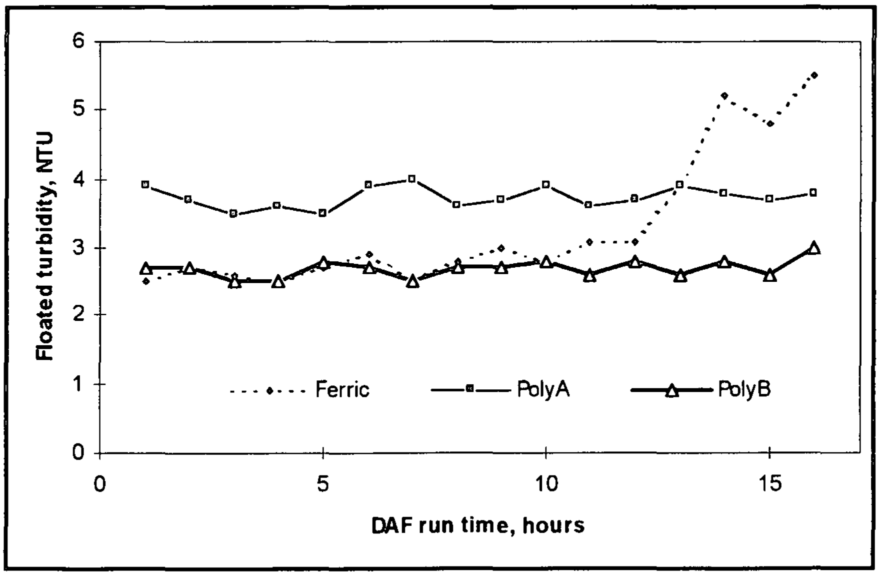


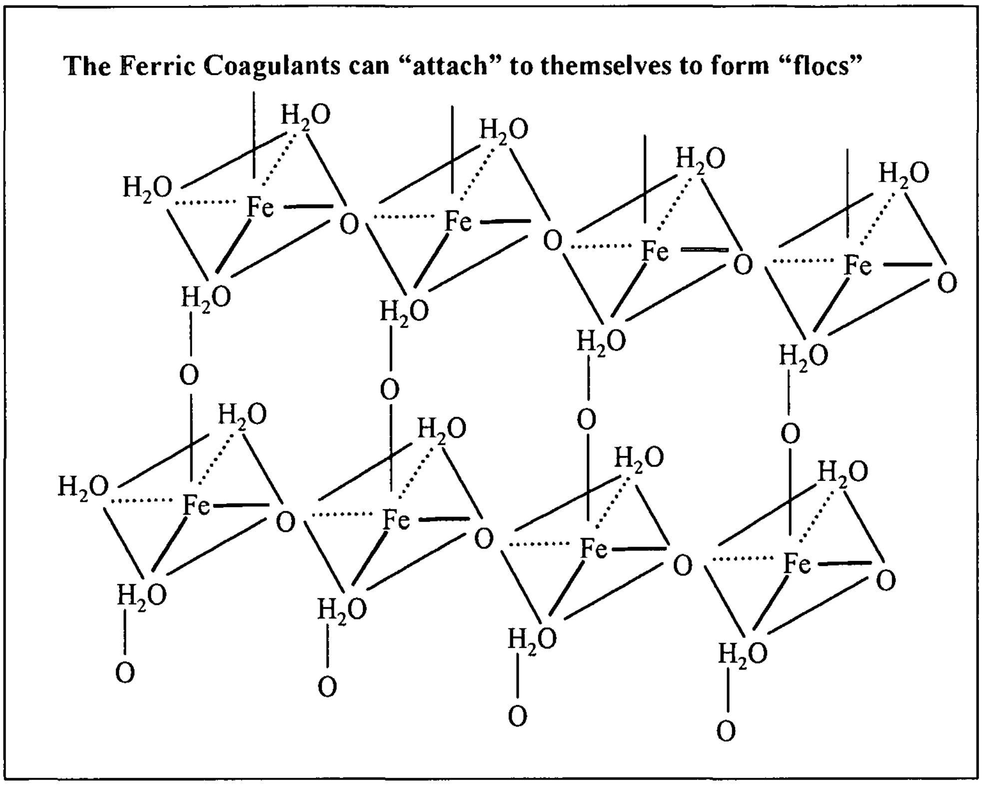
Figure 9.9: Float layer stability

Table 9.1 indicates that the dry solids content of the sludge produced by the polymeric coagulants was at least twice as high as the solids content in the ferric sludge.

Coagulant	**Dry solids concentration of float layer, percent (m/m)**
Ferric chloride	6.6
PolyA	14.6
PolyB	13.6

Table 9.2: Float layer dry solids

The difference in sludge characteristics is due in part to the mechanism of coagulation. Ferric chloride hydrolysis in water, produces iron hydroxide precipitates that combine with particles in the water by enmeshment and sweep flocculation. Figure 9.10 shows the ferric 'floc' matrix in water (Gonzalez, 1992). The matrix is three dimensional and voluminous, providing for entrapment of solids. As the ferric floc contracts (freeing the solvent molecules) and settles, the suspended solids remain enmeshed in the settling floc.



The Ferric Coagulants can "attach" to themselves to form "flocs"

Figure 9.10: Ferric floc matrix in water

This destabilization mechanism results in the generation of large amounts of wet iron sludge which are difficult and costly to dewater.

The mechanism of coagulation with polymeric coagulants is charge neutralization and possibly particle to particle bridging in the case of relatively large molecular weight coagulants. The flocs formed are very small and tend to form a more compact sludge.

9.4 Floc filterability

9.4.1 Turbidity profile

For comparison purposes, the period of steady state operation of the filter was taken as the effective filter run time. Turbidity profile during filtration (Figure 9.12) shows that the ferric suspension (ferric chloride treated DAF clarified) water had the shortest filter run time (40 minutes) compared to PolyB (90 minutes). Filter run time for the PolyA treated water was about 30% longer than the ferric chloride suspension but significantly shorter than filtration time for the PolyB treated water.

Filter ripening also followed the same trend as filter run time. The ripening period was the shortest for the ferric treated water and longest for the PolyB treated water.

Turbidity breakthrough may be defined as the initial increase in filtered water turbidity at the end of a filter run. Turbidity breakthrough is usually an indication of irreversible deterioration in filter performance after a period of constantly good filtered water quality. Again, turbidity breakthrough occurred sooner for the ferric suspension, relative to the polymeric organic coagulants.

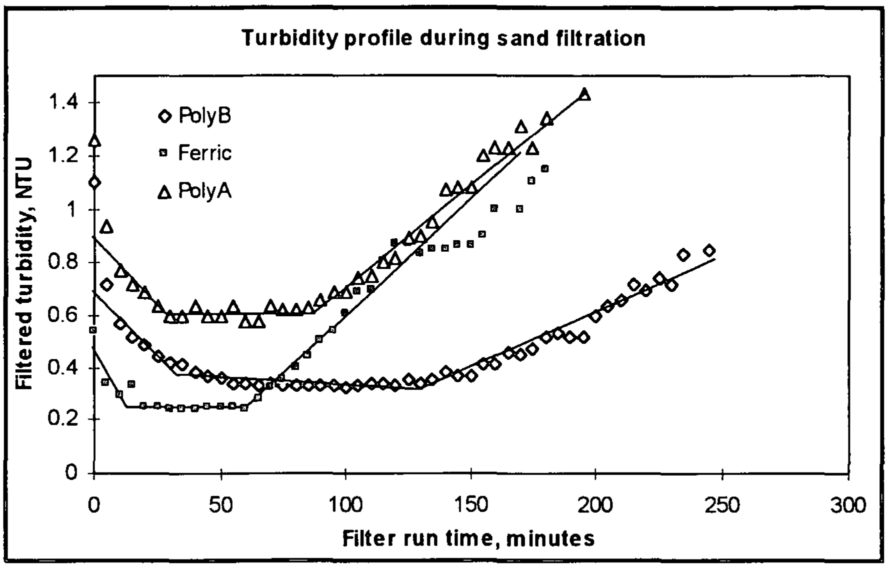


Figure 9.11: Turbidity versus time profile during filtration

9.4.2 Headloss development

Figure 9.13 shows a linear relationship between headloss and time, suggesting that depth filtration was occurring (Cleasby, 1990). A higher rate of headloss occurred for the ferric chloride treated water in comparison with headloss produced by the filtration of water treated with organic coagulant. This is evident from the gradient of the headloss versus time plot, where the gradient of the ferric plot was nearly twice that of the polymeric coagulants (Figure 9.13). This concurs with the conclusions drawn from the turbidity profile analysis that the polymeric organic coagulants produced flocs that achieved longer filter runs compared to the ferric flocs.

Ferric chloride formed large flocs, Poly B formed a relatively smaller size floc and Poly A formed flocs that were barely visible to the naked eye. Results of the filterability tests are summarised in Table 9.3.

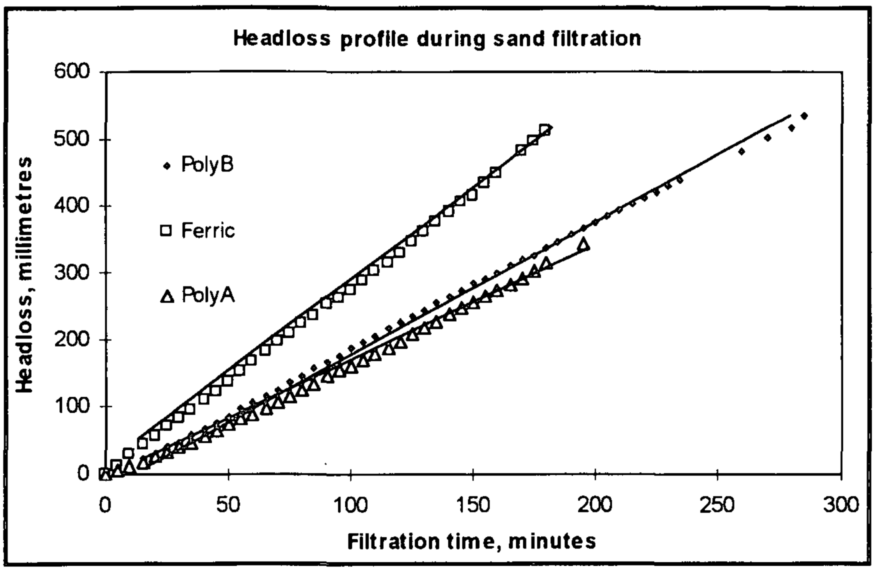


Figure 9.12: Headloss versus time during filtration

Coagulant	Filtration flowrate l/h	Filtration rate m/h	Terminal Headloss mm	Filter run Time min	Turbidity at break through NTU
Ferric chloride	0.3	10	160	40	0.3
Poly A	0.3	10	150	60	0.7
Poly B	0.3	10	240	90	0.4

Table 9.3: Filtration parameters

9.5 Cost comparison

The cost comparison presented is relative to prevailing raw water conditions and budget price of coagulants during the coagulant evaluation period. For a more reliable and accurate costing, evaluation during times of higher inflow turbidities may be required. Thus the cost comparison is simplistic and not rigorous.

9.5.1 Coagulant cost comparison

Table 9.4 shows a coagulant cost estimate, based on average dosages and budget prices. For calculation purposes, ferric chloride dose was converted from mg/l as iron to mg/l 43% ferric chloride. The cost comparison indicates that treatment with ferric chloride costs more than twice as much as the polymeric coagulants. PolyB was the most cost effective coagulant.

Chemical	Dosage mg/l	Chemical cost cents/kg	Chemical usage g/kl	Chemical cost Cents/kl
PolyA	5	466	5	22
Poly B	3	466	3	14
Ferric Chloride	17 (as 43% $FeCl_3$)	110 (as 43% $FeCl_3$)	39.5	45

Table 9.4: Coagulant cost

9.5.2 pH correction chemicals

The polymeric organic coagulants had no significant effect on the final treated water. The higher acidity imparted by ferric chloride resulted in a relatively large drop in treated water pH. The need for higher quantities of pH correction chemicals will further push chemical costs in favour of organic coagulants.

9.5.3 Sludge treatment and disposal

Depending on the mode of sludge disposal, lower volume and 'drier' sludge generated by the organic coagulants may be more cost effectively treated and disposed than the voluminous ferric sludge. The on-site treatment of the ferric sludge may require an intermediate sludge thickening stage before final dewatering. The solids concentration of sludge produced by the organic coagulants is high enough for direct dewatering by centrifuge, belt press or other means.

9.5.4 Coagulant storage requirements

As a result of the lower activity of the ferric chloride solution (normally 43% ferric chloride solution as delivered) compared to the polymeric organic coagulants, more chemical storage space will be required. From the dosage ratio of polymeric coagulant (PolyB) to ferric chloride (1:4), it may be simplistically deduced that four times more storage space may be required for ferric chloride than for the polymeric organic coagulants.

9.6 Summary

A summary of the results obtained from the evaluation of polymeric organic coagulants, relative to a control inorganic coagulant, ferric chloride, is presented in Table 9.5.

- PolyB produced DAF treated water with turbidities comparable to turbidities obtained from the ferric chloride treated water. PolyA produced relatively higher treated water turbidities.
- PolyB compared favourably with ferric chloride with respect to turbidity removal at the DAF clarification stage. Both the organic coagulants produced turbidity removal efficiencies in the final filtration stage, which were similar to that of ferric chloride.
- Lower organic removal was achieved with the polymeric organic coagulants compared to ferric chloride.
- Poly B achieved similar treated water quality to ferric chloride at the lowest coagulant dose. Significantly higher doses of PolyA, (compared with PolyB) were required to produce acceptable final water quality.
- The organic coagulants had no significant effect on the pH of the final filtered water. For the ferric treated water a significant pH reduction was evident.
- The polymeric coagulants produced a 'drier' and more consolidated float layer. The sludge float layer was stable for more than 72 hours compared to the ferric float that became unstable after 13 hours of operation.

- Flocs formed by PolyB showed better filterability characteristics than those formed by ferric chloride. This is evident from the significantly longer filter run time. The higher headloss at turbidity breakthrough for the filtration of flocs formed by PolyB implies that a higher solids loading on the filter may be possible, compared to ferric chloride and PolyA flocs. The low rate of headloss development for PolyB (1.8 mm/min), indicated by the slope of headloss versus time graph, compared to the rate of development for the ferric floc (2.8 mm/min), is further evidence that the filterability characteristics of PolyB are better than ferric chloride and PolyA.

	Units	**Ferric chloride**	**PolyA**	**PolyB**
Treated turbidity,				
Floated	NTU	2.5	4.1	2.8
Filtered		0.28	0.50	0.35
Removal (floated)	%	60	42	57
Removal (filtered)	%	95	93	95
UV absorbance @ 254nm (50mm cell) of final filtered water	Abs/ m	23	29	29
Reduction	percent	62	53	53
Coagulant dose	mg/l	4 as Fe	5	3
Treated water pH	pH units	6.8	7.4	7.3
Float stability	hrs	9 to 13	>72	>72
Filterability				
Filter ripening	min	20	30	50
Steady state	min	40	60	90
Turbidity Breakthrough	min	60	90	140
Headloss at turbidity breakthrough	mm	160	150	240
Slope of headloss versus time graph	mm/min	2.8	1.9	1.8

Table 9.5: Summary of results

Chapter 10

Conclusion

10.1 Introduction

The aim of this work was to investigate the application of polymeric organic coagulants for DAF treatment of potable water on a continuous pilot plant scale. The objective of the research was to compare the performance of polymeric organic coagulants against a control inorganic coagulant (ferric chloride) with respect to coagulant dose, water quality, filterability, sludge characteristics and chemical treatment costs.

The raw water was relatively clean, characterised by low turbidity and organic loading. Raw water quality was consistent for the duration of the coagulant evaluation trials and there was no significant change in coagulant demand.

The coagulant trials were run under optimized flocculation and DAF conditions using ferric chloride as coagulant. The trial was then repeated under identical conditions using polymeric coagulants.

10.2 Optimization of coagulation and flocculation parameters

Coagulation and flocculation with both ferric chloride and the polymeric coagulants were insensitive to physical conditions of mixing. Both the jar test and pilot plant optimization trials indicated that coagulation and flocculation was dependent on chemical changes (coagulant type, dosage and pH) and was insensitive to physical conditions of mixing time and intensity. Jar tests showed that treated water quality was not compromised even when the rapid mixing stage was excluded from the process. Pilot plant optimization results showed that low flocculation intensities (<20 s^{-1}) and short detention time were adequate for the production of good quality water. The performance of the coagulants, ferric chloride and the polymeric coagulants, PolyA and PolyB did not appear to be affected by or sensitive to any particular mixing matrix. This implied that one set of operating conditions could be used for both the inorganic coagulant (ferric chloride) and the organic polymeric coagulants (PolyA and PolyB).

10.3 Comparison of coagulant performance under optimised operating conditions

The performance of two polymeric organic coagulants, PolyA and PolyB were compared with the performance of ferric chloride under identical coagulation, flocculation and flotation operating conditions.

PolyB produced similar quality DAF treated water in terms of turbidity, to that produced by ferric chloride. In contrast, PolyA, produced DAF treated water with relatively higher residual turbidities and lower turbidity removals. Generally all the coagulants, both the inorganic and organic coagulants, produced DAF treated water (floated) turbidities that were acceptable as clarified water feed for sand filters.

From the measurements of UV absorbance @ 254 nm on the treated water and the reduction in absorbance relative to raw water, it was concluded that ferric chloride achieved better organic removal than the polymeric organic coagulants. The higher organic removal efficiency of ferric chloride over the polymeric coagulants may be attributed to the mechanism of sweep flocculation, where the precipitated ferric hydroxide species provide a larger surface or adsorption sites for organic removal.

Comparison of the optimum coagulant doses indicated that lower doses of polymeric organic coagulants were used (relative to ferric chloride) to produce final water turbidities comparable to turbidities of the ferric treated water. Overdosing with ferric chloride was more forgiving than (overdosing with) polymeric organic coagulants.

Ferric chloride imparted more acidity into the water, relative to the polymeric coagulants. Depending on the buffering capacity of the raw water, the ferric treated water may have a significantly higher demand for pH correction chemicals.

Although ferric chloride produced marginally better quality DAF treated (filtered) water, all the coagulants (both organic and inorganic coagulants) produced final water that met Umgeni Water's minimum standards for potable water.

Ferric chloride produced a voluminous float that appeared to be less dense and occupied a larger volume compared to the more compact and 'drier' float produced by the polymeric organic coagulants. The stability of the float layer strongly impacted on the DAF run time. Stability tests based on DAF run times indicated that the DAF could be operated continuously for three days before desludging, when polymeric organic coagulants were used. The ferric float started to became unstable after ten hours of continuous operation, resulting in rapid deterioration of DAF clarified water.

Dry solids concentration of sludge generated by the polymeric organic coagulants was twice as high as the concentration of the ferric sludge. Depending on the mode of sludge treatment and disposal, the large volume of relatively 'thin' sludge generated by ferric chloride, may have significant cost implications.

Filterability tests showed that PolyB, produced DAF treated water with the best filtration characteristics. Significantly longer filter run times were achieved for sand filtration of floated water pre-treated with PolyB relative to the ferric chloride treated water. Significantly longer filter run times were achieved for sand filtration of floated water pre-treated with PolyB relative to the ferric chloride treated water. The lower terminal headloss at turbidity breakthrough and steeper gradient of the headloss versus time relationship for the ferric chloride treated water, was further evidence that ferric chloride produced flocs that had less favourable filterability characteristics compared to flocs generated by PolyB. The filterability characteristics of PolyA were marginally better than those of ferric chloride.

A chemical cost comparison based on average coagulant doses and budget chemical costs indicated that the polymeric organic coagulants were more cost effective than ferric chloride.

10.4 Comparison of optimization results between DAF jar test and DAF pilot plant

There was very good agreement in the optimum coagulant dose determined using the jar test and the pilot plant for both ferric chloride and the polymeric organic coagulant. Similar DAF treated water turbidities were achieved on the jar test and pilot plant.

There was no significant correlation in mixing conditions with respect to mixing intensity, between the jar test and the pilot plant. It was evident from batch scale jar tests and the DAF pilot plant trials that mixing conditions on a jar test may not be directly applicable to fullscale environments.

10.5 Concluding remarks

For DAF treatment of raw water with low turbidity and organic loading, polymeric organic coagulants will produce treated water of the same quality as that produced by ferric chloride, more cost effectively.

10.6 Recommendations

The following recommendations were made for the DAF treatment of raw waters with low turbidity (<10 NTU) and organic loading (Total organic carbon concentration, < 5 mg/l).

- DAF pilot plant trials be conducted for the evaluation of suitable organic polymeric coagulants for DAF treatment of potable water.

- The application of lower mixing intensities and detention times for floc conditioning before flotation should be investigated as this would impact significantly on operating costs.
- Inorganic coagulants be replaced with suitable organic polymeric coagulants as pre-treatment chemicals for DAF treatment of potable water.

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Appendix 1

Raw water data

Appendix 1.1: Raw water data for DAF trial period

Day	Turbidity NTU	pH	UV abs @254 nm (50 mm cell)	UV abs @254 nm (50 mm cell) Abs m^{-1}
1	4	7.3	0.301	6.02
2	4.9	7.2	0.295	5.90
3	5.5	7.2	0.286	5.72
4	7.2	7.5	0.331	6.62
5	7.0	7.2	0.311	6.22
6	5.9	7.5	0.295	5.90
7	5.5	7.5	0.260	5.20
8	6.3	7.6	0.288	5.76
9	7.1	7.3	0.306	6.12
10	4.5	7.3	0.331	6.62
11	4.0	7.2	0.321	6.42
12	5.5	7.1	0.265	5.30
13	6.2	7.2	0.399	7.98
14	6.1	7.1	0.329	6.58
15	7.1	7.3	0.435	8.70
16	7.3	7.2	0.401	8.02
17	5.3	7.3	0.325	6.50
18	5.1	7.3	0.295	5.90
19	4.5	7.2	0.355	7.10
20	3.9	7.3	0.395	7.90
21	5.6	7.3	0.411	8.22
22	6.5	7.0	0.299	5.98
23	7.1	7.4	0.265	5.30

Appendix 1.2: Other raw water quality indicators during the DAF trial period

Determinand	Units	Concentration range
Total organic carbon	mg/l	3.2 to 4.2
Colour	Hazen units	4 to 20
Algae counts	Counts/ml	<1000
Suspended solids	mg/l	5 to 15

Appendix 2

DAF jar test trials

Appendix 2.1: Standard jar test conditions

DAF jar test parameter	units	setting
Rapid mixing time	min	1
Rapid mixing intensity	rpm	300
Slow mixing time	min	15
Slow mixing speed	rpm	40
Flotation time	min	10
Air-water recycle	percent	10

Appendix 2.2: Optimization of coagulant dose

Coagulant dose mg/l	Floated turbidity, NTU		Floated and filtered turbidity, NTU	
	$FeCl_3$	PolyA	$FeCl_3$	PolyA
1	9.2	7.7	5	3.4
1.5	7.7	7.1	3	3.4
2	6.3	7.1	1.6	2.8
2.5	4	6.3	1.1	2.1
3	2.3	6.5	0.61	1.6
3.5	1.6	5.7	0.55	1.3
4	0.9	5.2	0.3	0.88
4.5	0.6	3.8	0.17	0.65
5	0.5	3.4	0.15	0.51
5.5	0.5	2.7	0.15	0.43
6.5	0.5	2.8	0.15	0.41
7	0.6	2.8	0.13	0.38
7.5	0.6	3.3	0.1	0.34
8	0.5	3.9	0.1	0.42
8.5	0.5	4.4	0.1	0.72
9	0.5	5.7	0.1	1.60
9.5	0.5	6.10	0.1	2.20
10	0.4	6.6	0.1	2.80

Appendix 2.3: Effect of rapid mixing time

Time	Floated turbidity, NTU		Floated and filtered turbidity NTU	
	$FeCl_3$	PolyA	$FeCl_3$	PolyA
0	1.9	4.3	0.3	0.4
0.5	1.8	3.7	0.3	0.4
1	1.8	3.8	0.3	0.4
2	2	3.6	0.4	0.4
4	2.2	3.7	0.4	0.4

Appendix 2.4: Effect of rapid mixing intensity

Mixing Intensity G, s^{-1}	Floated turbidity, NTU		Floated and filtered turbidity NTU	
	$FeCl_3$	PolyA	$FeCl_3$	PolyA
20	1.7	4.0	0.4	0.4
85	1.9	3.3	0.4	0.4
240	1.5	3.0	0.3	0.5

Appendix 2.5: Effect of slow mixing time

Time minutes	Floated turbidity NTU		Floated and filtered turbidity NTU	
	$FeCl_3$	PolyA	$FeCl_3$	PolyA
2.5	2.1	5.3	0.5	0.6
5	1.5	4.1	0.4	0.6
10	1.6	3.9	0.3	0.4
15	1.6	3.9	0.4	0.4
20	1.5	4.1	0.5	0.3

Appendix 2.6: Effect of slow mixing intensity

Slow mixing intensity, G, s^{-1}	Floated turbidity, NTU		Floated and filtered turbidity NTU	
	$FeCl_3$	PolyA	$FeCl_3$	PolyA
5	2.1	5.3	0.5	0.6
10	1.5	4.1	0.4	0.6
20	1.6	3.9	0.3	0.4
85	1.6	3.9	0.4	0.4
240	1.5	4.1	0.5	0.3

Appendix 3

DAF pilot plant optimization data : Ferric chloride

Appendix 3.1: Ferric chloride dose optimization

		Turbidity, NTU				
Ferric Dose mg/l Fe	Raw pH	Raw	Flocculated and filtered	Floated	Floated and Filtered	Filtered pH
0	7.3	8.5	4.6	8.5	6.3	7.3
1	7.3	8.3	3.9	7.8	4.6	7.2
2	7.3	6.0	1.0	6.2	1.8	7.1
3	7.2	6.0	0.61	6.0	0.57	7.0
4	7.2	6.2	0.20	5.0	0.34	6.8
4.9	7.3	6.4	0.20	3.6	0.25	6.8
5.8	7.2	5.7	0.12	2.3	0.13	6.9
6.9	7.2	5.7	0.11	2.2	0.18	7.0
8.1	7.2	5.0	0.10	1.8	0.15	6.7
10.1	7.1	5.0	0.09	1.5	0.11	6.8
11.9	7.2	5.3	0.08	2.1	0.09	6.6
14.2	7.1	5.2	0.08	2.1	0.11	6.5
16.2	7.2	5.4	0.08	3.0	0.16	6.4
17.9	7.2	5.2	0.09	2.9	0.20	6.3

Appendix 3.2: Effect of rapid mixing intensity

Rapid Mixing Intensity G, s^{-1}	Turbidity, NTU		
	Flocculated and filtered	Floated	Floated and filtered
42	0.24	2.9	0.42
91	0.26	2.9	0.26
167	0.24	2.9	0.27
257	0.20	2.8	0.28
359	0.12	2.5	0.23
472	0.18	3.1	0.26
594	0.13	2.8	0.23
726	0.16	3.4	0.23
866	0.28	3.2	0.26

Appendix 3.3: Effect of flocculation intensity

Flocculation Intensity, G, s^{-1}	Turbidity, NTU		
	Flocculated and filtered	Floated	Floated and filtered
2	0.16	4.9	0.27
6	0.18	4.3	0.27
12	0.15	3.4	0.26
25	0.18	3.9	0.25
46	0.19	4.1	0.23
70	0.24	3.7	0.34
104	0.26	4.6	0.36

Appendix 3.4: Effect of percent recycle

Percent recycle	Turbidity, NTU	
	Floated	Floated and filtered
0	7.3	0.80
2	5.2	0.62
2.7	4	0.47
5.1	2.3	0.28
7	2.6	0.22
8	2.1	0.29
11	3	0.57

Appendix 4

DAF pilot plant optimization data: PolyA

Appendix 4.1: PolyA dose optimization

PolyA Dose mg/l	Raw pH	Turbidity, NTU				
		Raw	Flocculated and filtered	Floated	Floated and Filtered	Filtered pH
0	6.9	5.2	4.5	5.0	4.4	7.2
1.1	7.3	5.2	1.8	5.3	2.1	7.5
2.13	7.3	5.2	1.0	5.2	1.4	7.4
3.2	7.3	5.0	0.61	3.0	1.0	7.3
4.2	7.5	4.9	0.25	2.4	0.68	7.4
6.1	7.3	5.0	0.21	2.5	0.61	7.4
8.3	7.3	5.1	0.12	2.7	0.50	7.4
10.2	6.8	5.1	0.24	3.7	0.60	7.4
14.4	7.4	5.1	1.5	6.5	1.8	7.6
16.2	7.3	5.2	2.4	7.3	2.0	7.5

Appendix 4.2: Effect of coagulation intensity

Coagulation Intensity G,s^{-1}	Turbidity, NTU		
	Flocculated and filtered	Floated	Floated and filtered
42	0.27	4.0	0.42
91	0.26	4.2	0.44
167	0.21	4.0	0.51
257	0.30	3.9	0.49
359	0.24	4.0	0.40
472	0.36	3.5	0.42
594	0.25	3.7	0.45
726	0.21	3.7	0.54
866	0.24	3.8	0.54

Appendix 4.3: Effect of flocculation intensity

Flocculation Intensity, G, s^{-1}	Turbidity, NTU		
	Flocculated and filtered	Floated	Floated And Filtered
2	0.85	5.9	0.66
6	0.76	4.9	0.67
12	0.44	4.5	0.63
25	0.40	4.2	0.55
46	0.31	3.3	0.55
70	0.22	3.2	0.48
98	0.27	3.1	0.43

Appendix 4.4: Effect of percent recycle :PolyA

Percent recycle	Turbidity, NTU	
	Floated	Floated and filtered
4	4.7	0.92
6	4.6	0.78
8.3	4.0	0.44
8.6	3.9	0.45
10	3.8	0.45

Appendix 5

DAF pilot plant optimization data for PolyB

Appendix 5.1: PolyB dose optimization

PolyB Dose mg/l	Raw pH	Turbidity, NTU				
		Raw	Flocculated and filtered	Floated	Floated and Filtered	Filtered pH
0.5	7.2	5.2	2.1	4.3	2.4	7.2
1.3	7.2	5.2	0.56	4.2	0.72	7.5
2.0	7.2	5.2	0.37	3.8	0.56	7.4
3.0	7.3	5.0	0.22	3.0	0.38	7.4
4.1	7.4	5.1	0.18	3.1	0.28	7.3
6.0	7.4	5.1	0.22	2.9	0.29	7.4
7.5	7.3	5.1	0.29	3.2	0.36	7.4
9.1	7.3	5.1	1.3	5.0	0.83	7.4
10.1	7.3	5.0	1.6	4.8	1.45	7.5
12.1	7.4	4.9	2.5	5.5	2.1	7.4

Appendix 5.2: Effect of rapid mixing intensity

Rapid mixing intensity G,s^{-1}	Turbidity, NTU		
	Flocculated and filtered	Floated	Floated and filtered
42	0.24	3.4	0.28
91	0.23	3.4	0.26
167	0.24	3.2	0.26
257	0.23	3.2	0.32
359	0.27	3.4	0.35
472	0.22	3.1	0.28
594	0.22	3.2	0.30
726	0.20	3.2	0.38
866	0.14	3.4	0.29

Appendix 5.3: Effect of flocculation intensity

Flocculation Intensity, G, s^{-1}	Turbidity, NTU		
	Flocculated and filtered	Floated	Floated And Filtered
2	0.30	3.6	0.42
6	0.28	3.4	0.39
12	0.25	3.2	0.38
25	0.30	3.0	0.40
46	0.25	3.0	0.38
70	0.27	2.8	0.36
98	0.22	2.6	0.36

Appendix 5.4: Effect of percent recycle

Percent recycle	Turbidity, NTU	
	Floated	Floated and filtered
0	6.3	0.60
4	4.3	0.56
6	2.7	0.25
8	2.7	0.27
10	2.7	0.26
11	2.9	0.38

Appendix 6

Ferric chloride performance data - optimized DAF conditions

Appendix 6.1: Turbidity and pH

	pH	Turbidity, NTU				pH	Turbidity removal percent	
Time elapsed hours	Raw	Raw	Flocculated and filtered	Floated	Floated and filtered	Floated and filtered	After flotation	After filtration
0.5	7.1	6.3	0.27	3.7	0.42	6.7	41	93
1.5	7.1	6.6	0.25	2.3	0.28	6.7	65	96
2.5	7.2	6.6	0.25	2.2	0.26	6.8	67	96
3.5	7.1	6.0	0.26	2.1	0.25	6.8	65	96
4.5	7.1	6.1	0.21	2.3	0.25	6.6	62	96
5.5	7.1	5.2	0.21	2.3	0.27	6.7	56	95
6.5	7.2	7.0	0.23	2.4	0.26	6.7	66	96

Appendix 6.2: UV absorbance @ 254nm (50mm flow cell)

Time Elapsed hours	UV absorbance @ 254nm (50mm cell)				Percent reduction in UV absorbance
	Raw	Flocculated and filtered	Floated	Floated and filtered	
0.5	0.291	0.121	0.115	0.115	60
1.0	0.289	0.121	0.117	0.117	60
1.5	0.293	0.125	0.113	0.114	61
2.0	0.297	0.124	0.118	0.112	62
2.5	0.291	0.127	0.118	0.114	61
3.0	0.292	0.126	0.120	0.111	62
3.5	0.325	0.122	0.119	0.117	64
4.0	0.316	0.121	0.116	0.111	65
4.5	0.306	0.118	0.116	0.115	62

Appendix 7

PolyA performance data - optimized DAF conditions

Appendix 7.1: Turbidity and pH

	pH	Turbidity, NTU				pH	Turbidity removal percent	
Time elapsed hours	Raw	Raw	Flocculated and filtered	Floated	Floated and filtered	Floated and filtered	After flotation	After filtration
0.5	6.9	7.9	0.73	5.1	0.55	6.9	35	93
1.5	7.1	7.1	0.55	4.2	0.51	7.0	41	93
2.5	7.2	6.2	0.51	4.0	0.56	7.1	35	91
3.5	6.8	6.5	0.52	4.1	0.53	6.7	37	92
4.5	7.2	6.8	0.45	3.7	0.48	7.0	46	93
5.5	7.1	7.3	0.49	3.8	0.45	7.1	48	94
6.5	7.2	7.8	0.45	3.9	0.45	7.7	50	94
7.5	7.3	7.2	0.49	3.8	0.47	7.1	47	93
8.5	7.0	6.6	0.53	3.7	0.45	6.6	44	93

Appendix 7.2: UV absorbance @ 254nm (50mm flow cell)

	UV absorbance @ 254nm (50mm cell)				Percent reduction in UV absorbance
Time Elapsed hours	Raw	Flocculated and filtered	Floated	Floated and filtered	
0.5	0.320	0.155	0.148	0.146	54
1.0	0.288	0.150	0.144	0.140	51
1.5	0.297	0.153	0.146	0.143	52
2.0	0.309	0.151	0.143	0.145	53
2.5	0.289	0.154	0.144	0.143	51
3.0	0.291	0.154	0.146	0.141	52
3.5	0.312	0.153	0.147	0.145	54
4.0	0.300	0.156	0.146	0.139	54
4.5	0.296	0.158	0.145	0.141	54

Appendix 8

PolyB performance data - optimized DAF conditions

Appendix 8.1: Turbidity and pH

Time elapsed hours	pH	Turbidity, NTU				pH	Turbidity removal percent	
	Raw	Raw	Flocculated and filtered	Floated	Floated and filtered	Floated and filtered	After flotation	After filtration
0.5	7.1	6.5	0.45	3.1	0.48	7.1	52	93
1.5	6.8	7.1	0.33	2.6	0.41	6.7	63	94
2.5	6.9	6.5	0.26	2.7	0.33	6.9	58	95
3.5	6.9	6.5	0.21	2.5	0.32	6.8	62	95
4.5	7.2	7.3	0.26	2.7	0.31	7.0	63	96
5.5	7.1	5.9	0.22	2.9	0.31	7.1	51	95
6.5	7.0	5.5	0.23	2.9	0.29	7.0	47	95
7.5	6.9	5.8	0.25	2.7	0.33	6.8	53	94
8.5	6.8	6.2	0.29	2.9	0.35	6.8	53	94

Appendix 8.2: UV absorbance @ 254nm (50mm flow cell)

Time Elapsed hours	UV absorbance @ 254nm (50mm cell)				Percent reduction in UV absorbance
	Raw	Flocculated and filtered	Floated	Floated and filtered	
0.5	0.310	0.170	0.147	0.144	56
1.0	0.312	0.168	0.145	0.144	54
1.5	0.315	0.172	0.146	0.145	51
2.0	0.322	0.175	0.148	0.147	54
2.5	0.316	0.173	0.144	0.145	55
3.0	0.290	0.167	0.147	0.148	48
3.5	0.298	0.167	0.150	0.142	51
4.0	0.309	0.170	0.148	0.145	54

Appendix 9

Float layer characteristics

Appendix 9.1: Float solids concentration

Sample number	Dry solids (percent, (m/m)		
	Ferric chloride float	PolyA float	PolyB float
1	7.8	12.9	13.1
2	6.4	14.1	13.9
3	6.9	13.6	14.6
4	5.9	14.7	14.2
Average	6.8	14	14

Appendix 9.2: Measurement of float layer stability

DAF Run Time hours	Floated turbidity, NTU		
	Ferric chloride	PolyA	PolyB
1	2.5	3.9	2.7
2	2.7	3.7	2.7
3	2.6	3.5	2.5
4	2.5	3.6	2.5
5	2.7	3.5	2.8
6	2.9	3.9	2.5
7	2.5	4.0	2.7
8	2.8	3.6	2.5
9	3.0	3.7	2.7
10	2.8	3.9	2.7
11	3.1	3.6	2.8
12	3.1	3.7	2.6
13	3.9	3.9	2.6
14	5.2	3.8	2.8
15	4.8	3.7	2.6
16	5.5	3.8	3.0

Appendix 10

Floc filterability tests

Headloss development and turbidity profile during

Filtration through a sand filtration apparatus

Appendix 10.1 : Sand filtration conditions

Column diameter	mm, ID	43
Sand size	D_{10}, mm	0.5
Sand dry mass	g	150
Sand height in column	mm	50
Filtration rate	ml/min	300

Appendix 10.2: Headloss and turbidity profile during sand filtration

Filter run time min	Headloss development, mm			Turbidity, mm		
	Ferric chloride	PolyA	PolyB	Ferric chloride	PolyA	Poly B
0	0	0	0	0.54	1.26	1.1
10	31	13	14	0.29	0.77	0.57
20	57	27	31	0.25	0.69	0.49
30	82	41	49	0.24	0.60	0.42
40	109	57	69	0.24	0.64	0.38
50	136	73	87	0.25	0.60	0.36
60	166	90	107	0.24	0.58	0.34
70	196	107	126	0.32	0.64	0.34
80	222	124	146	0.40	0.62	0.33
90	252	145	166	0.50	0.66	0.33
100	274	160	186	0.61	0.69	0.32
110	303	179	206	0.70	0.75	0.34
120	330	197	226	0.87	0.82	0.33
130	361	217	245	0.83	0.90	0.34
140	392	237	264	0.85	1.07	0.38
150	417	256	284	0.86	1.08	0.37
160	450	272	301	1.0	1.23	0.41
170	480	292	320	1.0	1.31	0.45
180	512	314	338	1.15	1.34	0.52
190			359			0.52
200			377			0.60
210			395			0.66
220			414			0.70
230			431			0.72
240						0.77
250						0.82
260			482			0.88
270			501			1.01
280			517			1.11

Appendix 11: Calibration of Rapid Mix and Flocculator Stirrers

Rapid mix Stirrer

D, mm	160		μ, Pa.s	0.001
ρ, kg/m^3	1000		V, m^3	0.0177

N, rpm	Re	P_0	P, KW	G, s^{-1}
0			0	0
50	21338	0.3	0.018221316	32
100	42675	0.3	0.145770528	91
150	64013	0.3	0.491975533	167
200	85350	0.3	1.166164226	257
250	106688	0.3	2.277664504	359
300	128026	0.3	3.935804263	472
350	149363	0.3	6.249911399	594
400	170701	0.3	9.329313809	726
450	192038	0.3	13.28333939	866
500	213376	0.3	18.22131603	1015

Flocculator Compartment 1

D, mm	160		μ, Pa.s	0.001
ρ, kg/m^3	1000		V, m^3	0.08887

N, rpm	Re	P_0	P, KW	G, s^{-1}
0			0	0
10	4268	0.3	0.000291541	2
20	8535	0.3	0.002332328	5
30	12803	0.3	0.007871609	9
40	17070	0.3	0.018658628	14
50	21338	0.3	0.036442632	20
60	25605	0.3	0.062972868	27
70	29873	0.3	0.099998582	34
80	34140	0.3	0.149269021	41
90	38408	0.3	0.21253343	49
100	42675	0.3	0.291541057	57
110	46943	0.3	0.388041146	66
120	51210	0.3	0.503782946	75
130	55478	0.3	0.640515701	85

Flocculator Compartment 2

D, mm	160		μ, Pa.s	0.001
ρ, kg/m^3	1000		V, m^3	0.0787

N, rpm	Re	P_0	P, KW	G, s^{-1}
10	4268	0.3	0.000291541	2
20	8535	0.3	0.002332328	5
30	12803	0.3	0.007871609	10
40	17070	0.3	0.018658628	15
50	21338	0.3	0.036442632	22
60	25605	0.3	0.062972868	28
70	29873	0.3	0.099998582	36
80	34140	0.3	0.149269021	44
90	38408	0.3	0.21253343	52
100	42675	0.3	0.291541057	61
110	46943	0.3	0.388041146	70
120	51210	0.3	0.503782946	80
130	55478	0.3	0.640515701	90

Flocculator Compartment 3

D, mm	160		μ, Pa.s	0.001
ρ, kg/m^3	1000		V, m^3	0.0789

N, rpm	Re	P_0	P, KW	G, s^{-1}
10	4268	0.3	0.000291541	2
20	8535	0.3	0.002332328	5
30	12803	0.3	0.007871609	10
40	17070	0.3	0.018658628	15
50	21338	0.3	0.036442632	21
60	25605	0.3	0.062972868	28
70	29873	0.3	0.099998582	36
80	34140	0.3	0.149269021	43
90	38408	0.3	0.21253343	52
100	42675	0.3	0.291541057	61
110	46943	0.3	0.388041146	70
120	51210	0.3	0.503782946	80
130	55478	0.3	0.640515701	90