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Microsieving in municipal wastewater treatment

Chemically enhanced primary and tertiary treatment

DEPARTMENT OF CHEMICAL ENGINEERING | LUND UNIVERSITY
JANNE VÄÄNÄNEN



Microsieving in municipal wastewater treatment

Chemically enhanced primary and tertiary treatment

Janne Väänänen



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DOCTORAL DISSERTATION

By due permission of the Faculty of Engineering, Lund University, Sweden.
To be publicly defended on Friday 10th of March 2017 at 9:15 am in lecture hall
K:C at the Centre for Chemistry and Chemical Engineering
Getingevägen 60, Lund.

Faculty opponent

Dr.ir. Arjen Frans van Nieuwenhuijzen, Chief Technology Officer Energy Water
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Municipal wastewater treatment plants are constantly forced to make improvements. The main objectives are to reduce energy consumption, to increase the treatment capacity and to improve the effluent water quality. Microsieves in combination with chemical pretreatment can potentially fulfil these objectives. In this work, experiments were mainly conducted at the large pilot scale, and supplementary experiments were conducted at the laboratory scale to establish criteria for chemically enhanced primary and tertiary treatment and microsieving. Full-scale follow-up experiments were also conducted at the first treatment plant in Scandinavia, utilizing coagulation/flocculation and disc filtration in advanced tertiary treatment. Microsieves constructed as disc or drum filters showed removal efficiencies for primary treatment in the range of 30-60% with sieve pore sizes of 30-100 µm without chemical pretreatment. By dosing with cationic polymers, a suspended solids removal > 80% was possible, and the effluent water quality generally contained approximately 20-50 mg SS/L; in addition, most of the particulate phosphorus and COD was also reduced. To further improve the removal to > 95%, dosing of the coagulant is necessary; then, effluent containing < 10 mg SS/L and 0.1-0.2 mg TP/L with mostly dissolved COD remaining was produced. Sieve pore sizes in the range of 30-100 µm had a minor influence on the removal with chemical pretreatment; however, the solids loading capacity differed. For chemically enhanced primary treatment and microsieving, common feedback PI automation with occasional support from the feed forward control can be used together with online turbidity measurements to control the removal of COD. A consistent effluent COD concentration could be maintained independent of the influent COD or flow variations. Phosphorus removal could be controlled by adjusting the coagulant dose in relation to the polymer dose. Pretreatment with chemically enhanced primary treatment and microsieving was also beneficial for the microfiltration of primary wastewater treatment. The effluent water quality from microfiltration was improved if pretreatment with polymer and coagulant prior to microsieving was conducted. Anionic polymers were the most applicable because they generated a high flux. During tertiary treatment, for the highest possible removal, a sieve with a pore size of 10 µm was needed. It is possible to consistently achieve < 0.1 mg/L for the effluent phosphorus concentration, but careful design of the dispersion/coagulation and flocculation stages is important, and control of the operation is necessary. Polymer addition is crucial for chemically enhanced treatment and microsieving. Polyacrylamide based synthetic anionic or cationic polymers with a high molecular weight and low-medium charge were shown to be suitable for both primary and tertiary treatment. A general polymer dose of 1-5 and 0.5-1.5 mg polymer/L can be expected for primary and tertiary treatment, respectively. Alternative starch based biopolymers were also applicable, but the required dose was higher. Both iron and aluminium coagulants were applicable, but aluminium based coagulants were shown to be an overall a better choice. During primary treatment, the coagulant dose was variable, depending on the demand. During tertiary treatment, a molar ratio of 5-7 mol Me^{3+}/mol influent TP was sufficient to fulfil the effluent criteria. This corresponded to a dosing of approximately 1-4 mg Al^{3+}/L for the ordinary secondary effluents. Screening of chemicals and doses was performed in the laboratory with modified jar tests. Comparable treatment results were achieved in the laboratory, at the pilot scale and at the full scale; however, the laboratory experiments overestimated the solids loading capacity.				
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Microsieving in municipal wastewater treatment

Chemically enhanced primary and tertiary treatment

Janne Väänänen



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I would also like to thank Veolia Water Technologies AB/Hydrotech, VINNOVA and Svenskt Vatten for their financial support.

Finally, I would like to thank my family, Ylva, Ella and Nora.

Preface

This work is the result of an industrial PhD project between Veolia Water Technologies AB/ Hydrotech, and the Water and Environmental Engineering, Department of Chemical Engineering, Lund University. The study focused on various aspects of microsieving for primary and tertiary wastewater treatment with and without chemical pretreatment. The work was conducted within the framework of VA-teknik Södra with financial support from Hydrotech, Veolia Water Technologies AB, VINNOVA and Svenskt Vatten.

There was an article published in 1993 by K. Anders Ericsson named “The Role of Deliberate Practice in the Acquisition of Expert Performance”. Its conclusion is as follows: with basic skills, an average of 10 000 h or 6-10 years of full-time, dedicated work is required for a person to acquire expert performance, where motivation is decisive. Science is similar; it takes considerable time and motivation. For example, approximately 9600 h of work has been invested in this thesis.

Abstract

Municipal wastewater treatment plants are constantly forced to make improvements. The main objectives are to reduce energy consumption, to increase the treatment capacity and to improve the effluent water quality. Microsieves in combination with chemical pretreatment can potentially fulfil these objectives. In this work, experiments were mainly conducted at the large pilot scale, and supplementary experiments were conducted at the laboratory scale to establish criteria for chemically enhanced primary and tertiary treatment and microsieving. Full-scale follow-up experiments were also conducted at the first treatment plant in Scandinavia, utilizing coagulation/flocculation and disc filtration in advanced tertiary treatment.

Microsieves constructed as disc or drum filters showed removal efficiencies for primary treatment in the range of 30-60% with sieve pore sizes of 30-100 μm without chemical pretreatment. By dosing with cationic polymers, a suspended solids removal $> 80\%$ was possible, and the effluent water quality generally contained approximately 20-50 mg SS/L; in addition, most of the particulate phosphorus and COD was also reduced. To further improve the removal to $> 95\%$, dosing of the coagulant is necessary; then, effluent containing < 10 mg SS/L and 0.1-0.2 mg TP/L with mostly dissolved COD remaining was produced. Sieve pore sizes in the range of 30-100 μm had a minor influence on the removal with chemical pretreatment; however, the solids loading capacity differed.

For chemically enhanced primary treatment and microsieving, common feedback PI automation with occasional support from the feed forward control can be used together with online turbidity measurements to control the removal of COD. A consistent effluent COD concentration could be maintained independent of the influent COD or flow variations. Phosphorus removal could be controlled by adjusting the coagulant dose in relation to the polymer dose.

Pretreatment with chemically enhanced primary treatment and microsieving was also beneficial for the microfiltration of primary wastewater treatment. The effluent water quality from microfiltration was improved if pretreatment with

polymer and coagulant prior to microsieving was conducted. Anionic polymers were the most applicable because they generated a high flux.

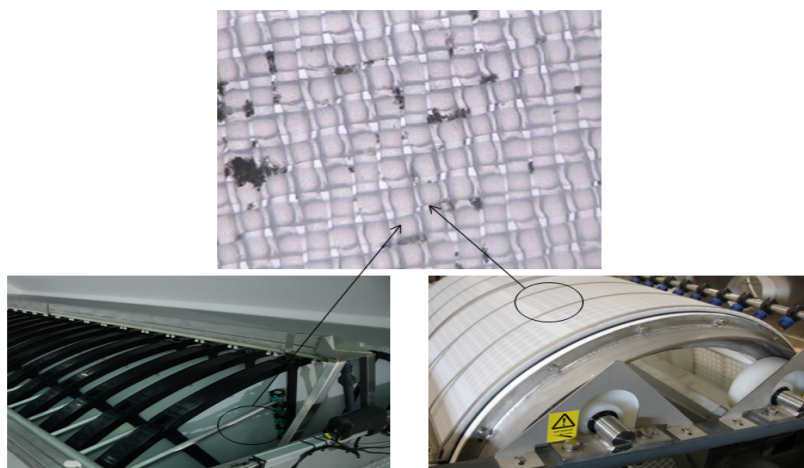
During tertiary treatment, for the highest possible removal, a sieve with a pore size of 10 μm was needed. It is possible to consistently achieve $< 0.1 \text{ mg/L}$ for the effluent phosphorus concentration, but careful design of the dispersion/coagulation and flocculation stages is important, and control of the operation is necessary.

Polymer addition is crucial for chemically enhanced treatment and microsieving. Polyacrylamide based synthetic anionic or cationic polymers with a high molecular weight and low-medium charge were shown to be suitable for both primary and tertiary treatment. A general polymer dose of 1-5 and 0.5-1.5 mg polymer/L can be expected for primary and tertiary treatment, respectively. Alternative starch based biopolymers were also applicable, but the required dose was higher. Both iron and aluminium coagulants were applicable, but aluminium based coagulants were preferred. During primary treatment, the coagulant dose was variable, depending on the demand. During tertiary treatment, a molar ratio of 5-7 mol Me^{3+} / mol influent TP was sufficient to fulfil the effluent criteria. This corresponded to a dosing of approximately 1-4 mg Al^{3+} /L for the ordinary secondary effluents. Screening of chemicals and doses was performed in the laboratory with modified jar tests. Comparable treatment results were achieved in the laboratory, at the pilot scale and at the full scale; however, the laboratory experiments overestimated the solids loading capacity.

Populärvetenskaplig sammanfattning

Genom att uppgradera våra avloppsreningsverk med kemisk förbehandling, mikrosilning och ozon kan dagens reningsverk bli producenter av energi och råvaror. Vidare kan utsläppen av fosfor och mikroföroreningar ut i våra sjöar och vattendrag minskas markant och detta till priset av vad en öl på krogen kostar per invånare och år.

Nedan visas en bild av hur föroreningar i form av partiklar silats bort av en mikrosil. Här visas även två vanliga typer av mikrosilar. Silen i sig består oftast av en vävd duk av polyester. Vid tillverkningen av denna väv anpassar man avståndet mellan trådarna för att producera mikrosilar med olika storlek. Hålen kan ses som de ljusa rektangulära områdena i bilden nedan. I dagsläget går det att med denna teknik framställa mikrosilar med hål tre gånger mindre än tjockleken på ett hårstå.



Reningsverken kan förmås att bli energiproducenter istället för som idag energikonsumenter genom att tillvarata så mycket organiskt material som möjligt

så tidigt (i reningsprocessen) som möjligt. Man kan även minska utsläppen av fosfor med upp till 10 gånger, fosfor som annars bidrar till övergödningen av våra vattendrag. Idag börjar vi även tänka på hur människans användande av läkemedel och andra kemiska substanser påverkar vår miljö och då främst våra vattendrag. Avloppsreningsverk står för en stor del av dessa utsläpp och i framtiden är det därför inte otänkbart att vi kommer att behöva rena avloppsvattnet även från dessa så kallade mikroföroreningar.

Det inkommande och utgående avloppsvattnet kan med fördel genomgå en kemisk förbehandling och sedan filtreras i mikrosilar. Med kemisk förbehandling menas tillsats av ämnen till vattnet för att få innehållet i avloppsvattnet att klumpa ihop sig. Man får då ämnena i avloppsvattnet, som till största delen är små partiklar bestående av organiskt kol, kväve och fosfor, att binda sig samman och bilda större aggregat. Detta är viktigt för att det ska vara möjligt att senare kunna avskilja dem i en mikrosil. Man kan likna processen vid osttillverkning där löpe tillsätts till mjölken varvid ostmassa fälls ut. Här är ostmassan istället de aggregat som bildas när man tillsätter ämnen, även kallade fällningskemikalier, till avloppsvattnet. För att dagens avloppsreningsverk ska kunna bli energiproducenter ska merparten av det organiska kolet avskiljas och användas till att producera energi i form av biogas. Den producerade biogasen kan användas för att driva fordon eller för att producera elektricitet och värme. Då man inte behöver rena bort lika mycket som tidigare får avloppsreningsverket som en extra bonus en sänkt energiförbrukning i de efterföljande reningsstegen.

Att tidigt avskilja ämnena ur avloppsvattnet görs redan idag. Men med hjälp av kemisk förbehandling och mikrosilning kan detta göras mer effektivt och kontrollerat. Det är nämligen viktigt att kontrollera avskiljningen för att den efterföljande reningen, som normalt sker med hjälp av bakterier, ska fungera bra och vara ekonomisk.

En automatiserad kontroll är att föredra och vanligtvis används då någon form av återkoppling. Farthållaren på en bil är ett bra exempel på automatiserad kontroll med hjälp av återkoppling. Det fina med återkoppling är att den automatiskt kompenserar för uppförsbackar, nerförsbacke, medvind eller motvind. Utan återkoppling blir det föraren som får gissa lämpligt gaspådrag i relation till backens lutning och aktuella vindstyrka, och hoppas på det bästa.

I detta arbete har en ny metod baserad på just återkoppling för att styra den kemiska förbehandlingen före mikrosilning tagits fram. Detta gör det möjligt att reglera avskiljningen på ett sådant sätt att det går att optimera biogasproduktionen och säkerställa att bakterierna i efterföljande reningssteg ska fungera väl. Det faktum att det är möjligt att använda sig av återkoppling är tack vare mikrosilen. I förhållande till andra metoder är mikrosilning en mycket snabb avskiljningsmetod och detta är en förutsättning för en fungerande återkoppling. Så vad är den stora vinsten? Jo, som i fallet med bilens farthållare, det blir mycket lättare och mer exakt att reglera avskiljningen med hjälp av återkoppling jämfört med att reglera via gissningar.

När det gäller det utgående vattnet från våra kommunala avloppsreningsverk, som står för merparten av den fosfor som når våra vattendrag idag, kan man med hjälp av kemisk förbehandling och mikrosilning minska halterna upp till tio gånger, detta till den i förhållande till andra teknologier lägsta investerings och driftskostnad. Det är dock viktigt att utforma denna kemiska förbehandling korrekt. I denna avhandling finns råd i hur man på bästa sätt kan göra detta.

Det har även visats att kombinationen kemisk förbehandling med mikrosilning och ozon fungerar utmärkt för att både reducera fosforutsläppen men även utsläppen av mikroföroreningar i form av läkemedelsrester. Tekniken är så pass effektiv att det blir svårt att mäta halterna av mikroföroreningar i utgående avloppsvatten från våra reningsverk.

Avloppsreningsverkens framtid är inte bara att vara reningsverk utan även anläggningar som är producenter av energi och förnyelsebara råvaror.

List of publications

This thesis comprises the following original papers, which will be referred to in the text by their Roman numerals I-VI. The papers are re-printed with kind permission from the copyright owners and appended at the end of the thesis.

- Paper I** Väänänen, J., Cimbritz, M., la Cour Jansen, J., 2016. Microsieving in primary treatment: Effect of chemical dosing. *Water Science and Technology*, 74 (2), 438-447.
- Paper II** Väänänen, J., Memet, S., Günther, T., Lilja, M., Cimbritz, M., la Cour Jansen, J., 2016. Chemically enhanced primary treatment with microsieving to control water quality. (*Submitted*)
- Paper III** Langer, M., Väänänen, J., Boulestreau, M., Miehe, U., Bourdon, C., Lesjean, B., 2016. Advanced phosphorus removal via microsieve filtration in tertiary treatment: Performance and operation. (*Submitted*)
- Paper IV** Kängsepp, P., Väänänen, J., Örning, K., Sjölin, M., Olsson, P., Rönnerberg, J., Wallebäck, F., Cimbritz, M., Pellicer-Nàcher, C., 2015. Performance and operating experiences of the first full-scale Discfilter installation for advanced phosphorus removal in tertiary treatment in Scandinavia. *Water Practice and Technology*, 11 (2), 459-465.

- Paper V** Väänänen, J., Nilsson, F., la Cour Jansen, J., Hörsing, M., Hagman, M., Jönsson, K., 2014. Discfiltration and ozonation for reduction of nutrients and organic micro-pollutants from wastewater – a pilot study. *Water Practice and Technology* 9 (3).
- Paper VI** Hey, T., Väänänen, J., Heinen, N., la Cour Jansen, J., Jönsson, K., 2016. Potentials of mechanical and physicochemical pre-treatment of municipal wastewater combined with direct membrane filtration for small and medium sized wastewater treatment plants. *Environmental Technology*, Jun 2:1-8.

Related publications

During this study, two related publications have also been published.

Langer, M., Mieke, U., Väänänen, J., Stueber, J., Bourdon, C., Lesjean, B., 2011. Advanced phosphorus removal with microsieves in tertiary treatment: an alternative to membrane filtration? Conference presentation, *6th Specialist Conference on Membrane Technology for Water and Wastewater Treatment*, 4-7 October Aachen, Germany.

Väänänen, J., Langer, M., Cimbritz, M., 2013. Phosphorus removal with discfilters in tertiary treatment: Dosing Requirements. Conference presentation, *NORDIWA 2013, The Nordic Wastewater Conference*, 8-10 October, Malmö, Sweden.

My contributions to the papers

I contributed to the following papers as described below:

- Paper I** I planned and conducted part of the experiments. I drafted and wrote the manuscript and received comments from my co-authors.
- Paper II** I planned the experiments. Together with my co-authors, Memet, S., Günther, T. and Lilja, M., the programme was developed and tested. I performed the data analysis and wrote the paper.
- Paper III** I assisted in the planning the experiments together with the OXERAM team, helped conducting the experiments, assisted in the laboratory results analysis and assisted in writing the paper.
- Paper IV** I assisted in planning the experiments. I assisted in the data analysis and wrote part of the paper.
- Paper V** I planned the experiments together with my supervisors and co-authors. I conducted the experiments and part of the laboratory work in cooperation with Filip Nilsson. I wrote the major part of the paper. The analysis of pharmaceuticals was performed by the Department of Chemistry of UMU.
- Paper VI** I assisted in planning the experiments. I conducted the microsieving part of the experiments, assisted in the laboratory results analysis and assisted in writing the paper.

Abbreviations

Al^{3+}	Aluminium ion
Anammox	Anaerobic ammonium oxidation
BW	Backwash
C	Carbon
C/N	Carbon to nitrogen ratio
COD	Chemical oxygen demand
Fe^{3+}	Iron ion
FeCl_3	Iron chloride
G	Average velocity gradient
HRT	Hydraulic retention time
IBC	Intermediate bulk container
Me^{3+}	Metal ion
MF	Micro filtration
N	Nitrogen
NO_2^-	Nitrite
NTU	Nephelometric Turbidity Units
O_3	Ozone
PACl	Polyaluminium chloride
pe	Person equivalent
$\text{PO}_4\text{-P}$	Ortho phosphate
R^2	Coefficient of determination
SS	Suspended solids

SUP	Soluble unreactive phosphorus
TP	Total phosphorus

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1 Introduction

Many municipal wastewater treatment plants are old and are operating close their design limits. Many of the treatment plants that were built in the 1960's and 1970's are currently enmeshed by their cities; thus, space for expansion is often scarce. There has also been a development where municipal wastewater treatment tends to be considered as a producer of bio-based renewable chemicals and primary energy rather than a consumer of electricity and resources (Remy et al., 2014, Morgan-Sagastume et al., 2015). Municipal wastewater treatment plants also play an important role in the eutrophication of the receiving water bodies, not to mention the emerging threat from micropollutants.

To modernize wastewater treatment and to upgrade wastewater treatment plants to meet new goals is an ongoing process where new processes and technologies are sought for. Preferably, these new processes and technologies will have a minimal footprint and be cost and energy efficient. Microsieving, especially in combination with chemical pretreatment, is a promising candidate that can possibly fulfil many of the requirements.

Many publications on microsieving in wastewater treatment date back to the 1970's and are mainly concerned with applications without chemical pretreatment. More recent publications on the use of microsieves in municipal wastewater treatment are relatively sparse; although, there is an increasing interest for the technology. Research was done over 40 years ago (EPA, 1975, Ljunggren, 2006).

Since then, the technology has developed, and the materials used in their construction have improved. It is therefore of interest to increase the knowledge of how this technology and the pretreatment process can be adapted and optimized to most effectively be implemented in municipal wastewater treatment. In Figure 1 below, a general process scheme of an ordinary activated sludge municipal wastewater treatment process is shown with possible applications for microsieving with chemical pretreatment. There is also a growing interest for physical or chemical-physical treatment with microfiltration. This type of

effluent has gained value for irrigation purposes (Al-Shammiri et al., 2005, Bixio et al., 2005), but pretreatment is necessary to protect the membranes, and here, microsieves alone or in combination with chemical pretreatment can play an important role.

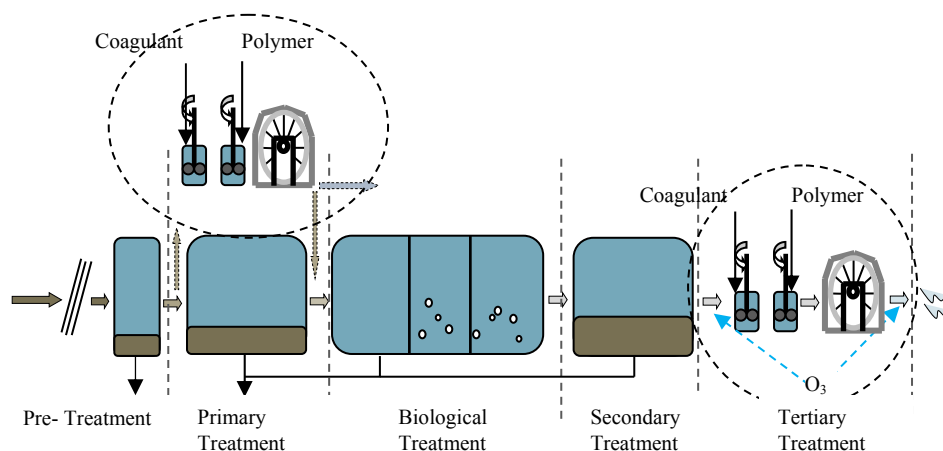


Figure 1 Schematic diagram of a general activated sludge waste water treatment process. The investigated applications for the implementation of microsieve technology are also emphasized.

For this thesis, primary and tertiary treatment were identified to be the most interesting applications in municipal wastewater treatment where the microsieve technology in combination with chemical pretreatment could significantly improve the performance of the existing treatment plants. The technologies could also be combined and possibly improve downstream physical wastewater treatment with microfiltration or ozonation processes for micropollutant reduction. This thesis examines the possibility of implementing microsieving (disc and drum microsieves) in combination with chemical pretreatment in the primary and tertiary treatment of municipal wastewater. The focus was to establish the criteria for suitable pretreatment.

Hypotheses and objectives

The main hypotheses of this thesis are the following:

Chemically enhanced primary treatment and microsieving removal can be automatically controlled to produce a consistent effluent water quality fulfilling the requirements for a) biological nitrogen removal processes, and b) physical membrane separation processes.

It is possible to reliably achieve a total phosphorus level of < 0.1 mg/L in the effluent of wastewater treatment plants with coagulation, flocculation and tertiary disc filtration, and the treatment can be combined with ozone for the reduction of micropollutants.

The following research questions needed to be answered:

- What is the appropriate sieve pore size for primary treatment?
- What are the appropriate chemicals and doses for primary and tertiary treatment?
- Is there an improvement in the membrane microfiltration performance if microsieving is conducted upstream?
- Can advanced tertiary treatment with microsieving for phosphorus removal be combined with ozone for micropollutant reduction?
- Do the hydraulic conditions during chemical pretreatment influence the treatment results?
- How can automation and control be implemented to control organic matter and phosphorus during the primary treatment?
- How are laboratory tests representing the pilot and full scale experience?

The objective of this thesis was to test disc and drum microsieves during primary and tertiary municipal wastewater treatment. For primary treatment, the objective was to study the effect pore size and chemical dosing has on the effluent water quality and filtration capacity. The removal of suspended solids (SS) content, chemical oxygen demand (COD) and total phosphorus (TP) content was of interest, and this information was to be used for automation in order to control the effluent water quality to an appropriate standard for biological processes downstream. Moreover, the applicability of using microsieves in combination with chemical pretreatment to produce an appropriate effluent for a downstream microfiltration process was also of interest.

For tertiary treatment, the objective was to obtain < 0.1 mg TP/L in the effluent. The chemicals used, doses, hydraulic conditions and retention time could impact the performance, and were, therefore, investigated. To obtain the highest possible removal, the sieve pore size was limited to 10 μm . It was also of interest to study the removal of phosphorus with chemically enhanced tertiary treatment and microsieving combined with micropollutant reduction by ozone. This treatment process can potentially be of interest for the new, more stringent effluent requirements that include micropollutant reduction.

Thesis outline

The present work is based on six papers and two conference proceedings for the overall evaluation of the hypothesis. Chapter 2 introduces microsieving in municipal wastewater treatment. Chapter 3 describes the methods used to find answers to the research questions. Chapter 4 presents and discusses the major results and answers to the research questions, and in Chapter 5, the main conclusions are drawn. In Chapter 6, further work within this field of research is suggested.

2 Microsieves in wastewater treatment

Definition of microsieving

Microsieving, microstraining and microscreening are the most common expressions for the process in which particle separation is achieved by physical blocking. In the Environmental Protection Agency (EPA) process design manual for suspended solids removal (EPA, 1975), the following definition for sieving/straining of suspended solids was made:

“Physical straining processes are defined as those processes which remove solids by virtue of physical restriction on media which has no appreciable thickness in the direction of liquid flow.”

Below in Figure 2 an illustration of a physical sieving process can be seen. Here a wastewater particle has been physically restricted by a 10µm polyester sieve. The micrograph is magnified 500 times.

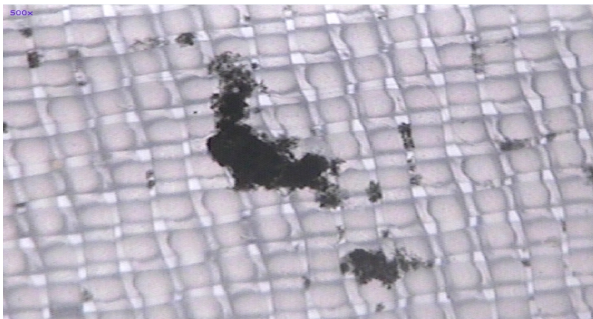


Figure 2 Physical sieving of wastewater particles on a woven microsieve polyester fabric.

Operating principle

Microsieves are generally constructed as drum filters, disc filters or rotating belts; although, other types of constructions exist (EPA, 1975, Bourgeois et al., 2003, Rusten and Ødegaard, 2006). The sieving process for the drum/disc/rotating belt filters is continuous and driven by gravity. A differential pressure of approximately 0.03 bar (0.3 m H₂O) is usually applied. Suspended solids are caught on the filter media, and the solids are backwashed off, generally with the aid of pressurised water (3-8 bar) (Figure 3). Backwash can also be performed either by pressurized air or vacuum (Franchi and Santoro 2015, Bourgeois et al., 2003). The filter media come in pore sizes ranging from 10 to 1000 µm and are made of woven polyester or stainless steel. Non-woven fabrics are also used. These fabrics are usually defined as cloth or pile cloth media, where the cloth media is characterized of a random but flat fabric, and the pile cloth media has fibres extending out from the fabric.

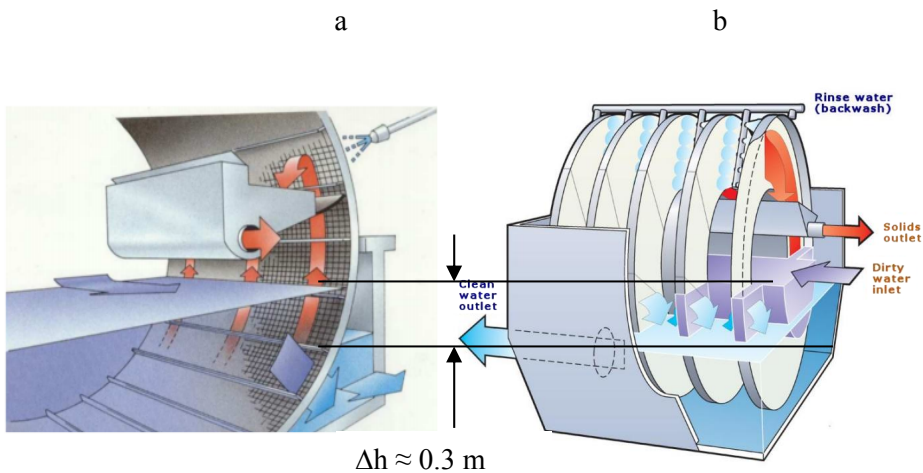


Figure 3 Examples of the microsieves and their operating principle. Drum a), discfilter b) (courtesy Hydrotech AB)

Pile cloth filter media are also used in apparatus similar to the disc and drum filters. Filtration mechanisms for the pile cloth media filter differ slightly compared to the microscreens with woven media. Particle separation in pile cloth media is, to some degree, the result of depth filtration (Bourgeois et al., 2003); thus, the use of the definition stated above for this type of technology can be misinterpreted.

Applications

The first microsieve installation for wastewater treatment was made at Luton sewage works in England in the early 1950's. In 1975, the EPA reported there to be approximately 100 installations in England and in the USA. Today, according to one main manufacturer of microsieves, there are over 8000 of their filters in operation in various applications (Veolia Water Technologies AB, 2015). Another manufacturer states to have approximately 1000 filters installed (Aqua-Aerobic Systems INC., 2016). Thus, the total number of microsieves/cloth media filters in wastewater treatment should be at least in the 10 000 range. Other manufactures of microsieves are Nordic Water Products AB, Salsnes-Filter AS, Huber technology Inc., IN-EKO TEAM s.r.o, and Nova Water Technologies LLC.

Tertiary treatment, or effluent polishing, is and has been the main application of microsieve technology in municipal wastewater treatment (Diaper 1969, EPA 1975, Persson et al., 2006, Matsson et al., 2009, Wilén et al., 2012, Wilén et al., 2016). The replacement of primary settlers with microsieving units has also been tested (Ødegaard 1975, Eriksson and Nielsen 1974, Särner 1976, 1978). This application has also gained increased interest in the past few years (Rusten and Ødegaard, 2006, Razafimanantsoa et al., 2014, Franchi and Santoro, 2015, DeGroot et al., 2015, Caliskaner et al., 2015, Sarathy et al., 2015).

Other applications for microsieve technology, such as storm water treatment and treatment of intake water for drinking water works, can also be found (Diaper and Glovel, 1971, Piontek and Czyżewska, 2012). A new application of interest for tertiary treatment is the combination of microsieves with chemical pretreatment for advanced phosphorus removal. In Europe, a large project investigating the feasibility of implementing disc filtration in combination with chemical pretreatment for extended phosphorus removal was launched in 2010

(OXERAM 2, 2010). In the U.S.A, this application has also gained increased interest (Tooker et al., 2010, 2012, Hart et al., 2012, Reid et al., 2012, Stevens et al., 2012, Hughes et al., 2015). Moreover, for reuse and reclamation and for the removal of Helminth eggs from wastewater, microsieves have proven to be successful (Quinzaños et al., 2008).

Early research combining chemical pretreatment and microsieves has been investigated by several researchers with varying results (Truesdale and Birkbeck 1968, Lynam et al., 1969, Hultman, 1979, Ewing, 1976). In general, it was concluded that the precipitated aluminium or iron flocs were too weak and had to be strengthened, preferably with polymer, in order to be able to withstand the shear forces in the sieving process. Promising results utilizing polymer enhanced flocculation have been published by Ljunggren et al. (2005), Rusten and Ødegaard (2006) and Ødegaard et al. (2010).

3 Methods

The experiments in the present study were mainly conducted at the large pilot scale as the results obtained in this study should be directly implementable at full scale. Tests were also conducted in a minor content in laboratory.

It was considered important to conduct the experiments at the large pilot scale using commercially available equipment in order to avoid scale up effects and to be able to study the effects of long term use. The scale up effects can be related to hydraulic conditions in the filter units possibly causing severe floc breakage that could impact the treatment results. The flock breakage and sieving behaviour could only be evaluated with the commercially available equipment operating within its specified capacity.

In addition, the coagulation and flocculation stage had to be as close to their full-scale installations as possible in order to be able to identify suitable conditions for the chemical pretreatment stage. Continuous operation covering the daily/seasonal variations was also included in the study. It was also necessary to study the effect that debris, such as cotton swab sticks or other larger objects, has on the equipment; thus, operational stability was in focus. Together, these requirements set the standard for conducting this study at the large/full pilot scale.

However, laboratory experiments were used to speed up the screening for suitable chemicals and doses. Therefore, it was important to verify that the laboratory method could give satisfactory results. The method is evaluated in section below. The laboratory method is a modified jar test including a filtration step using specially designed filtration apparatus (Appendix I).

Large/ full scale pilot experiments

In this thesis, the large/full scale pilot experiments were the equivalent of treating municipal wastewater from 100 to 3200 population equivalents (pe) with a specific pe load of $0.3 \text{ m}^3/\text{p}\cdot\text{d}$ (Henze et al., 2002). In Table 1, the test sites for the pilot experiments for primary treatment are shown. The pilot experiments were conducted in Sweden, Denmark and Italy.

Table 1 Large/full scale pilot experiments for primary treatment. The test sites, sieve pore size, pilot plant operational window and related publications are given.

Site	Lund (S)	Knislinge (S)	Klagshamn (S)	Frederikshavn (DK)	Malmö (S)	Helsingborg (S)	Monza (IT)
Name	Källby WWTP	Knislinge WWTP	Klagshamn WWTP	Frederikshavn WWTP	Sjölunda WWTP	Öresundsverket WWTP	WWTP San Rocco
Sieve pore size (μm)	30/40/100	100	40	100	40	100	100
Q_{in} (m^3/h)	1-6 15-45	9.8-11	12-24	10	24	12-39	10-31
Publication	Paper I, II, VI	Paper I	Paper I	Paper I	Paper I	Paper I	Paper I

Large/full scale pilot experiments for tertiary treatment were conducted on three test sites located in Germany and Sweden. In Table 2, the test sites for the pilot experiments for tertiary treatment are shown.

Table 2 Large/full scale pilot experiments for tertiary treatment. The test site, sieve pore size, pilot plant operational window and related publications are given.

Site	Berlin (DE)	Landskrona (S)	Malmö (S)
Name	Ruhleben	Lundåkraverket	Sjölunda
	WWTP	WWTP	WWTP
Sieve pore size (µm)	10	10	10
Q_{in} (m³/h)	10-30	5-20	15-65
Publication	Paper III Langer et al., 2011	Paper V	Väänänen et al., 2013

A large/full scale microsieve pilot plant can be difficult to visualize because we all have different reference marks. In Figure 4, examples of the pilot plants are shown to give an impression of the size of these pilots. The disc- or drum filters were the standard commercially available Hydrotech microsieves of various sizes from the smallest drum filter (HDF 801) to a relatively large disc filter (HSF 2201/4). For coagulation and flocculation, stainless steel or IBC tanks with top mounted stirrers with a variable speed were used. The dosing equipment was comprised of standard products acquired from Grundfos (Grundfos AS, Denmark). Online measurements of turbidity and phosphorus were made with standard equipment from Hack Lange (Hack Lange GmbH, Germany).



Figure 4 Examples of pilot plants used in this study.

Laboratory scale experiments

Performing pilot experiments is costly and time consuming even though the data they obtain are preferred. In this work, a modified jar test including a sieving step was used to screen for appropriate chemicals and doses (**Paper I-III**). During pilot testing, parallel jar tests were conducted to identify the similarities and differences between the removal and filtration rates.

The results show that the effluent water quality was very similar between the modified laboratory jar test method, the pilot plant and a full-scale installation (Figure 5a and b) while applying the same chemical dose and type. During tertiary treatment, the target was set to < 0.1 mg TP/L in the effluent, and if this was obtained in the laboratory experiments, then this was also obtained in the pilot and full scale experiments. The chemical dose and type were of the greatest importance to achieve the targeted effluent TP content independently if the experiments were conducted at the laboratory, pilot or full scale.

A comment on the jar test results during primary treatment (Figure 5a) is therefore necessary. The reason why four out of five results deviate slightly from the pilot experimental results is due to the inappropriate type of polymer.

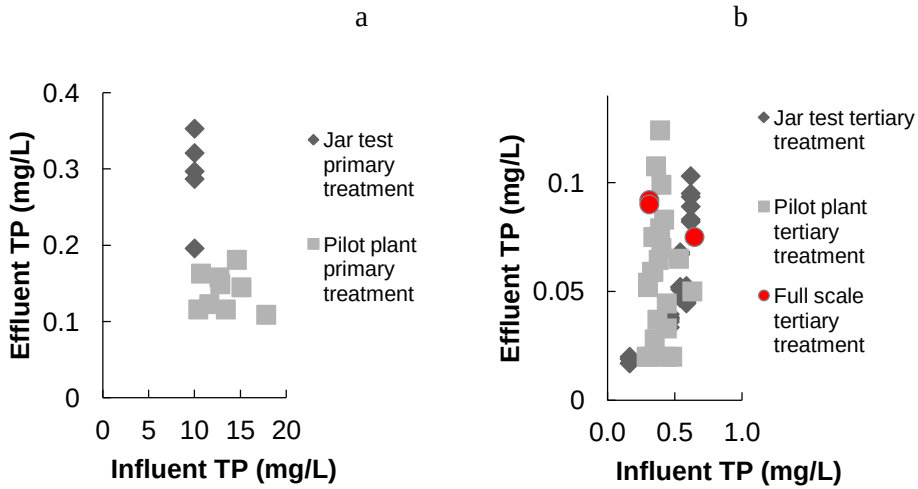


Figure 5 Comparison between jar test and pilot plant performance in primary and tertiary treatment.

In regard to one other important design criteria, the filtration rate or solids loading capacity, the scenario was different. The modified jar tests seem to generally overestimate the filtration rates. The hydraulic conditions during the jar test were also shown to influence the filtration rate to a greater extent than in pilot test. In the laboratory, the experimental results showed that increased mixing intensity in the flocculation stage increased the filtration rate by $\approx 80\%$ without a loss in the effluent water quality.

The improvement from 17 to 30 m/h (Figure 6) was shown to more or less linearly correlate when the mixing intensity was increased from $G=50\text{ s}^{-1}$ up to 250 s^{-1} . For the velocity gradient, during the pilot tests, of $G=150\text{ s}^{-1}$ the improvement was not as significant (+ 5% from an average of 10 m/h, unpublished data) as in the laboratory ($\approx + 45\%$).

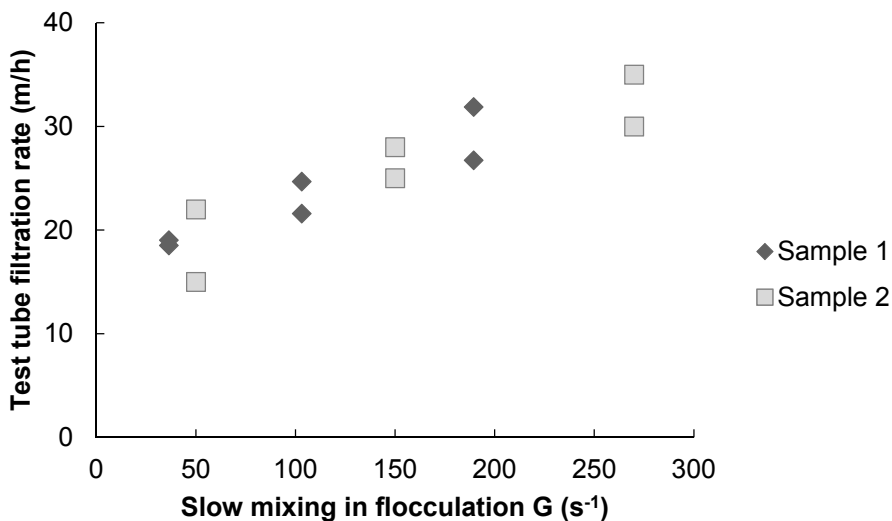


Figure 6 Filtration rate as a function of flocculation mixing intensity from the laboratory test results. Sample 1 effluent TP $0.09\pm0.02\text{ mg/L}$ and Sample 2 effluent TP $0.037\pm0.001\text{ mg/L}$.

The results show that the laboratory test method was applicable for screening for suitable chemicals and doses. Regarding the filtration capacity, the method overestimated the values compared to what was obtainable during pilot experiments.

Analysis

The sample analysis was conducted according to standard methods and procedures. Phosphorus was analysed either with colorimetric methods (Hach Lange, LCK 348/349/350) or with the ICP-OES method in accordance to DIN EN ISO 11885. The COD was analysed with colorimetric methods (Hach Lange LCK 114/314). Aluminium and iron were analysed with the ICP-OES method in accordance to DIN EN ISO 11885. The suspended solids (SS) content was determined according to DIN 38404/DIN EN 872:2005/Standard methods 2005. The turbidity (Nephelometric Turbidity Units (NTU)) was analysed with a Hach 2100P portable turbidity metre or online with Hach Lange Solitax® turbidity probes.

4 Results and discussion

Establishing design criteria for chemical pretreatment and microsieving for municipal primary and tertiary treatment was one of the fundamental questions for this work. Included in this question is the determination of the appropriate chemicals. This is discussed further down in section 4.

One of the hypothesis for this work was to show the possibility to control the effluent water quality to a desired set point for chemically enhanced primary treatment and microsieving to fulfil the organic content for subsequent biological processes. With control, the carbon can be better distributed to biological treatment and biogas production. A lower energy demand for the downstream biological treatment is also expected due to lower loads requiring less aeration. The research question was how to design such a control strategy. The control system should also be simple and reliable to facilitate easy implementation. For primary treatment, a related question was to determine an appropriate sieve pore size. In sections below, the research results related to controlling the effluent water quality and the impact of the sieve pore size are discussed.

Improving the treatment in a previous treatment stage can often be beneficial for microfiltration ($\sim 0.2 \mu\text{m}$) processes (Ravazzini et al., 2005, Fabris et al., 2007). Microfiltration is, for example, gaining emerging interest for irrigation and reuse applications. Experiments combining chemically enhanced primary treatment and microsieving with microfiltration were investigated for their possibilities and potential benefits. These results are presented and discussed.

For tertiary treatment and the second hypothesis emphasizes that it is possible to consistently achieve an effluent containing $< 0.1 \text{ mg TP/L}$ from chemically enhanced tertiary treatment and disc filtration. The research questions in relation to this hypothesis were concerned with finding the appropriate chemicals and doses and appropriate hydraulic conditions. Micropollutants are another high priority topic for municipal wastewater treatment (Hamza et al., 2016). Micropollutant reduction by ozone is an interesting treatment method. Exploring the possibility to combine advanced tertiary treatment and microsieving with

ozone to reduce both phosphorus and micropollutants was included in the second hypothesis. Early in the project a decision was made to only use a 10 µm sieve pore size to optimize the treatment results. Results related to the hypothesis and research questions for tertiary treatment are presented and discussed in the following sections.

Coagulants

Most common coagulants used in municipal wastewater treatment are aluminium or iron based. The experiments showed that poly-aluminium chloride coagulants (PACl) were the best alternative for both applications, but iron chloride coagulants (FeCl_3) were also shown to work well. The treatment results mainly depended on the coagulant dose rather than the type (**Paper I, Paper III**). The effluent water quality was similar when the same molar dosing of the active product ($\text{Al}^{3+}/\text{Fe}^{3+}$) was used; although, the filtration capacity by using FeCl_3 was negatively influenced (**Paper III**).

Polymer

It was evident that the polymer dosing is crucial. Both the anionic and cationic polymers with a high molecular weight and low-medium charge were used with similar treatment results. However, the impact of the polymer charge (positive/negative) on the filterability showed some interesting results. In one of the pilot experiments for tertiary treatment, it was observed that the filtration capacity was reduced when applying the anionic polymer (Langer et al., 2011). Anionic polymers have been used elsewhere (Tooker et al., 2012). The first full-scale coagulation/flocculation disc filter installation at Arvidstorp WWTP in Scandinavia is currently using anionic polymers in combination with aluminium coagulants (**Paper IV**). The lesson learned was that for some occasions, the filtration capacity can be increased by changing from anionic to cationic polymers.

Biopolymer

Another alternative polymer that has become interesting for the future is biopolymers. These polymers can, for example, be manufactured from starch or chitosan. One starch based cationic polymer was identified as promising and therefore further evaluated during tertiary pilot tests.

The results showed that the effluent water quality was comparable with that for the synthetic polymers in terms of the TP, COD, SS and residual aluminium, and the effluent water quality was well below the targeted effluent TP content of < 0.1 mg/L. The filtration capacity was also acceptable. However, the polymer dosing was significantly higher compared to the synthetic alternatives. Biopolymers have also been tested elsewhere in combination with disc filtration in treating urban storm water runoff, with a reported SS removal in the range of 80-90% (Nielsen et al., 2015). Biopolymers can thus be an alternative to synthetic polymers; however, economic constraints exist.

Designing primary treatment

In primary treatment, it is of importance to control the removal of the SS/COD/TP content to have an appropriate effluent for the downstream processes. Different processes have different requirements.

The maximum removal of COD, P, SS is required for direct discharge e.g., storm water. Downstream nitrification without denitrification or anaerobic ammonium oxidation (anammox) requires another type of wastewater quality, and ordinary activated sludge nitrogen removal processes have their own appropriate requirements.

PI feedback control

One of the research questions was how to implement automation and control to control effluent water quality independent of influent load or flow variations. The goal was to be able to produce appropriate wastewater for different downstream requirements. A simple COD measurement was sought, and a method using turbidity as an estimate for the COD has been previously reported to be useful for

wastewater treatment (Mels et al., 2004, Me'tadier et al., 2012, Nguyen et al., 2014). This method was also shown to be applicable in estimating the microsieffluent COD. The results showed that the effluent COD correlated with the effluent turbidity ($R^2=0.92$) with sufficient accuracy and was useful in controlling the effluent COD. The short (in relation to settling) total retention time in the chemically enhanced primary treatment and microsieffluent process was also central to allow for the successful implementation of a common feedback PI control with the support of feed forward control.

The controller automatically adjusts the chemical dosing to control the effluent water quality (**Paper II**). Scheduling of the control parameters of static gain and integration time was implemented to account for the nonlinear behaviour of the chemical dose on the effluent water quality and for flow variations. The control parameters were adjusted in accordance with the set point and influent flow. Supportive feed forward dosing was activated occasionally with the objective to not achieve the desired effluent set point but to stabilize the effluent water quality (**Paper II**); however, the results also indicated that it might be possible to implement pure PI feedback control.

The microsieffluent could be controlled in a very broad range (**Paper II**); thus, the effluent could be adapted to different requirements. It was shown that the removal of the SS, COD and TP content was as high as $> 95\%$ (**Paper I**). This type of removal is of interest for storm water treatment or for situations where downstream processes with low organic carbon requirements are used such as for nitrification processes or for the denitrification pathway anaerobic ammonium oxidation (anammox). This process is under development for mainstream nitrogen removal in municipal wastewater treatment plants. The results seem promising with observed nitrogen removal with a very low C/N ratio (Winkler et al., 2012, Lotti et al., 2014 Lauren et al., 2016).

Controlled COD removal

A conventional nitrification/denitrification process requires sufficient COD. A theoretical minimum of 2.9 mg of COD is required to convert 1 mg of N (Henze et al., 2002). Values from 3.5 to 14 mg COD/mg N, depending on the treatment process, have been reported for primary municipal wastewater (Ekama et al., 1984, Henze et al., 2002). For full scale nitrification/denitrification activated sludge treatment plants fulfilling the effluent criteria < 10 mg TN, a C/N ratio of

4.7-8.7 have has been reported (Aspegren et al., 1992, Kristenssen et al., 1992). The carbon requirement for a shortcut nitrification/denitrification process via nitrite (NO_2^-) has been somewhat lowered (Van Loosdrecht and Jetten, 1998, Ruiz et al., 2006, Yang et al., 2007). For pilot scale membrane bioreactors treating other types of wastewaters, similar C/N ranges (4.3-7.2) have been reported (Abegglen et al., 2008, Xia et al., 2008, Bracklow et al., 2007). In this work, influent nitrogen was mostly ammonium nitrogen with a concentration of 20-40 mg/L (**Paper I**), which is common for this type of wastewater (Tchobanoglous et al., 2014). In this work, the effluent COD was controlled in the set point range of approximately 50-300 mg COD/L, which would correspond to a C/N ratio of 1.3-15.

Controlled P removal

Carbon is one requirement for bacterial growth; phosphorus is another and can become a limiting factor. Nordeidet et al. (1994) have reported biofilm reactors that become phosphate limited at influent concentrations below approximately 0.15 mg $\text{PO}_4\text{-P/L}$ during tertiary nitrification. For ordinary nitrification/denitrification processes, phosphorus limitation can occur earlier. A general rule to determine the phosphorus requirement for heterotrophic growth of biomass is $0.005 \cdot \text{COD}_{\text{primary effluent}}$ (ATV, 2000). The phosphorus requirement for heterotrophic biomass growth for effluents containing 50-200 mg COD/L would be approximately 0.25-1 mg phosphorus/L, simplified as $\text{PO}_4\text{-P}$. Thus, phosphorus control can be applicable.

The results show that when only polymer was dosed, effluent phosphorus concentrations were within requirements (**Paper I**). However, if the coagulant was dosed upstream, phosphorus could become limiting if the effluent contained < 0.2 mg TP/L (**Paper I**); therefore, a more careful use of the coagulant has to be considered for these situations. With only polymer dosing, particulate phosphorus was removed to a very high extent ($> 90\%$), and it was demonstrated that additional phosphorus removal can be controlled with the coagulant dose (**Paper I**). In the control program, P removal was controlled by dosing the coagulant in relation to the polymer dose with a specific factor (**Paper II**).

Sieve pore size for primary treatment

The cost of investment in machinery is closely related to the treatment capacity, and for microsieves, the sieve pore size matters. A balance between the treatment capacity and removal has to be considered. The effect of the sieve pore size for primary treatment was investigated to seek answers to the related research question.

Generally, a sieve pore size of 100 μm was shown to be most preferable. Without chemical pretreatment, a slightly improved removal was achievable with smaller pore sizes, such as 30-40 μm , but a loss in the filtration rate or solids loading capacity ($\approx 50\%$) should be considered with the minor improvement in the effluent water quality. With chemical pretreatment, optimal dosing of approximately 0.005-0.007 mg polymer/mg influent SS and with a coagulant dose in the range of 15-40 mg Me^{3+}/L , the effluent water quality was very similar between the pore sizes and contained only small amounts of SS ($< 10 \text{ mg/l}$) (**Paper I**).

Another aspect of the filtration capacity was its dependence on the chemical dosing. It was shown that depending on the chemical dosing, the filtration rate could significantly vary (**Paper I**). This is an important aspect to take into account and can become important at the design stage. If automation and control is introduced, this can even become critical as the microsieve will periodically treat chemically treated wastewater that is suboptimal for facilitating high filtration rates.

In the laboratory, the results showed (non-published data) that a 200 or perhaps 500 μm sieve pore size could be applicable if reduced effluent water quality was accepted. This would result in an increased solids loading capacity, reducing the investment costs. From these data, it can be expected that with chemical pretreatment and a disc or drum microsieve, the effluent SS for a 200 μm pore size would be in the 50-100 mg/L range and 150-200 mg/L for a 500 μm pore size. This is also in agreement with published data that applied chemical pretreatment and microsieving with rotating belt filters. An effluent SS content in the range of 10-110 mg/L with an average of approximately 40-50 mg/L was reported for a sieve pore size of 250 μm (Rusten and Ödegaard, 2006).

Chemically enhanced primary treatment and microsieving prior to microfiltration (MF)

Compared to biological processes, downstream physical separation processes have other demands on the microsieve effluent. Stabilizing the water quality entering the MF unit was the primary concern. In this study pretreatment was both purely mechanical (100 μm) and combined with chemical pretreatment.

It was demonstrated that the MF operation was more consistent (**Paper VI**) if microsieving was used as pretreatment. Without microsieve pretreatment, a vast amount of debris was found in the MF unit causing operational problems and potential breakage of the MF membrane due to abrasive wear.

By applying chemical pretreatment and microsieving either only with polyaluminium chloride (PACl) or in combination with an anionic polymer, the MF flux was increased from a normalised average permeate flux of 87 L bar/m² h to approximately 200 L bar/m²h. The effluent water quality from the MF step was significantly improved if the coagulant and polymer (both anionic and cationic) were dosed upstream from the microsieve. An MF effluent containing < 0.03 mg TP/L was observed if the coagulant and polymer were used in combination. Whilst, if only coagulant was dosed upstream, the effluent TP content was approximately 0.2 mg/L.

The improvement could be explained due to the improved water quality supplied to the MF step. Without polymer addition for the microsieve, the retention of phosphorus was minor for coagulation with inorganic coagulants, such as polyaluminium chlorides or iron chlorides (Chon et al., 2012, Väänänen et al., 2013); thus, most of the precipitated phosphorus was found in the MF unit, and there, the shear forces caused by membrane aeration were thought to break up the floc into smaller particles, allowing them to pass through the MF membrane. Biological activity could also free some of the phosphorus for example in the cake layer (Zhaid et al., 2012).

Anionic polymers were preferable though, as in combination with cationic polymers, the normalised average permeate flux was decreased to 97 L bar/m²h. It was also shown that with chemical pretreatment by the coagulant and polymer, the membrane fouling was reversible. After chemical cleaning, the initial membrane flux was back to normal.

Note: In the pilot experiments, during chemically enhanced primary treatment, similar hydraulic conditions ($HRT > 1\text{-}4$ minute and $G > 100\text{ s}^{-1}$ in the coagulation and flocculation phase) were utilized and found to be optimal for chemically enhanced tertiary treatment, and these conditions should be favoured.

Dosing requirements for tertiary treatment

Naturally, the focus for primary treatment was different than for tertiary treatment. For primary treatment, adapting the removal was the objective, and hence, the effluent water quality was not absolute. After introducing advanced tertiary treatment, the objective was to countervail eutrophication in the receiving water body, and therefore, the focus was on maximized removal. In this work, the target was set to $< 0.1\text{ mg TP/L}$. The focus in this work was to explore the effect of the dosing requirements and hydraulic conditions on the treatment results in order for the long-term stability to meet or be below the targeted effluent TP concentration.

Not surprisingly, the chemical dose was of prime importance. It was shown that the chemical dosing requirements to achieve $< 0.1\text{ mg TP/L}$ were in the range of $1\text{-}5\text{ mg Me}^{3+}/\text{L}$ and approximately $0.6\text{-}2\text{ mg/L}$ ($0.05\text{-}0.12\text{ mg polymer/mg}$ influent SS) cationic synthetic polymer (as the active product) (**Paper III, Paper IV**) for ordinary secondary effluents (Henze et al., 2002) containing $\approx 0.3\text{ mg TP/L}$ and $\approx 10\text{ mg SS/L}$. The coagulant dose was equivalent to a molar ratio dose of approximately $5\text{-}7\text{ mole Me}^{3+}/\text{mole influent TP}$ ($10\text{-}14\text{ mole Me}^{3+}/\text{mole PO}_4\text{-P}$). The coagulant dosing in terms of the molar ratio is in agreement with other literature data for advanced P removal for tertiary treatment targeting $< 0.1\text{ mg TP/L}$. (Zheng et al., 2012, Bratby, 2006, Henze et al., 2002).

In this work, the fraction of the soluble nonreactive phosphorus (SUP) was in the range of $\approx 0.03\text{ mg TP/L}$. This fraction was not significant in this work; however, with a significant amount of SUP, targeting an effluent $< 0.1\text{ mg TP/L}$ can be problematic. Fractionation of the effluent revealed that 23% was particulate P ($> 0.45\text{ }\mu\text{m}$) and 77% was dissolved P (**Paper III**) of which 79% could be classified as SUP and 21% as orthophosphate ($\text{PO}_4\text{-P}$).

Impact of hydraulic conditions in the dispersion, coagulation and flocculation phase

Hydraulic conditions during dispersion of the chemicals and in the coagulation and flocculation stage play important roles for the final result (Dharmappa et al., 1993, Rossini et al., 1999, Bache and Gregory 2007, Gregory and Barany 2011). A mean velocity gradient in the range of $500\text{--}1000\text{ s}^{-1}$ has been recommended (Bratby 2006; DVGW W217-218). In these studies, the mean velocity gradient (G) was calculated to be approximately $400\text{--}1000\text{ s}^{-1}$ for the dispersion of the coagulant and the polymer. In pilot experiments conducted for tertiary treatment, the rapid dispersion of the coagulant was increased to approximately 2000 s^{-1} by mounting an orifice plate in front of the coagulant dosing point and static mixer, but the effluent water quality was similar. The rapid dispersion of the chemicals should also be conducted within a few seconds.

In the optimized pilot plant (**Paper III**), the lowest possible retention time was approximately 1 minute during coagulation and 4 minutes during flocculation, and this was enough to maintain the effluent water quality (**Paper III**). The full-scale installation at the Arvidstorp WWTP has a design with approximately these retention times. Therefore, with appropriate hydraulic conditions, this would be approximately the minimum hydraulic retention time. Similar retention times were also reported by Remy et al. (2014) for microsieves for chemically enhanced primary treatment.

Moreover, the results showed that if the mixing intensity was increased in the coagulation and flocculation stage from approximately 80 s^{-1} to $150\text{--}250\text{ s}^{-1}$ and $120\text{--}170\text{ s}^{-1}$, respectively (Appendix II), the effluent residual aluminium and polymer usage was lowered. No significant difference in the TP content was observed, and a lower SS content in the effluent was observed (**Paper III**); thus, a trade-off between the mixing, effluent quality and polymer usage prevailed.

The reason for this trade-off is not clear, but it was speculated that due to the increased mixing, the particle collision rate and possible floc formation increased (Thomas et al., 1999). Increasing the rate of floc formation reduces the time for polymer adsorption on the particle surface as adsorption sites are simultaneously trapped within the formed flocs (Tanaka et al., 1990, Durand–Piana et al., 1986). Flocks are developed with less but sufficient amounts of polymer that are strong enough to be equally and effectively separated in the microsieve. The lower SS content in the effluent also indicates that the particles are more efficiently

flocculated despite a lower polymer dosing; thus, the polymer is more evenly distributed on the incoming particles surfaces. The true explanation is hidden for now, however. To consistently obtain $TP < 0.1 \text{ mg/L}$ in the effluent with minimal chemical consumption, a careful design of the coagulation and flocculation stage has to be considered. During this work, the sieve pore size was not the focus, all experiments were conducted with $10 \text{ }\mu\text{m}$. Recent publications have shown that a sieve pore size of $20 \text{ }\mu\text{m}$ is applicable and can meet the effluent demand of $< 0.1 \text{ mg TP/L}$ (Rossi, 2014) with the advantage of a general increased filtration rate or solids loading capacity.

Chemically enhanced tertiary treatment and ozonation

Chemically enhanced tertiary treatment and microsieving was combined with ozone for reduction of organic micropollutants. It was of interest to investigate the possibility of combining these two technologies to reduce the phosphorus and micropollutant content in our receiving water bodies. The experiment was performed as a pilot study.

The results showed that it was more beneficial to apply ozone after advanced tertiary treatment and microsieving. An observed overall higher degree of micropollutant reduction was achieved. For the pharmaceuticals carbamazepine ($1500 \pm 180 \text{ ng/L}$) and oxazepam ($1200 \pm 150 \text{ ng/L}$) and the antibiotics sulfamethoxazole and trimethoprim ($280 \pm 30 \text{ ng/L}$, $2 \text{ gO}_3/\text{L}$, respectively) the incoming concentrations were relatively high and constant throughout the experiments. The results showed that for carbamazepine the reduction was 97/98/99% if the ozone was applied after advanced treatment and 79/96/96% if the ozone was applied prior. For oxazepam, the reduction was 52/71/91% and 34/47/84%, respectively, and for the antibiotics sulfamethoxazole and trimethoprim the reduction was 88% if ozone was applied after microsieving and 75% if ozone was applied prior (**Paper V**).

In both cases, the TP and SS content was unaffected and independent of the onset or dose of ozonation. The effluent TP and SS contents were consistently at approximately 0.03 mg TP/L and $< 2 \text{ mg SS/L}$.

Today, the general trend is that ozone is to be combined with biological treatment downstream for the treatment of transformation products. Research has shown that a retention time of approximately 20-30 minutes is sufficient

(Stapf et al., 2014, Li et al., 2015), and this equivalent volume has to be placed prior to or after advanced tertiary treatment with microsieving and ozone.

Operational experiences

The acceptance of new or improved existing technologies can be successful if the reliability is adequate and if the operation is similar when compared to common standards. In the following section, the operational experiences during the pilot test and the first year of operation at the full scale for the coagulation/flocculation disc filter installation at the Arvidstorp WWTP are discussed. This was not included as one of the main hypotheses or research questions, but this type of information is of importance for the overall successful performance of this type of process and should be highlighted.

Disc or drum filters in municipal wastewater treatment

For the experiments for primary treatment, both disc and drum filters were used. The treatment results were shown to be similar, independent of the filter type (**Paper I**). The intended use of the disc filter was originally developed for effluent polishing and therefore designed accordingly. Due to the existence of large debris in the pretreated waste water, the drum filter was regarded to be more suitable for primary treatment; however, with adaptation of the disc filter design, this filter type can probably be made more suitable for primary treatment. For tertiary treatment, the disc filter is regarded to be more superior due to its low footprint (Wilén et al., 2012) and therefore a better solution.

Coagulation and flocculation tank design

From time to time flocs were displaying floating properties during the flocculation stage. It is therefore important to have a design that facilitates the removal of floating sludge from the flocculation stage. In the pilot plant this was accomplished by having the effluent exit the flocculation stage via surface flow. A similar arrangement was also applied at the first full scale installation in Scandinavia at the Arvidstorp WWTP in Trollhättan, Sweden. Here, the

flocculated wastewater is transported in open channels to the disc filter installation.

Cleaning of the filter media

Applying chemical cleaning to the filter media at appropriate intervals was necessary in order to maintain a high filtration rate to reduce operational costs. The frequency of the chemical cleaning varied depended on the process conditions and application.

A chemical cleaning interval of approximately 6-9 weeks was applied during tertiary pilot trials and at the full scale at the Arvidstorp WWTP. This interval was shown to maintain a sufficient treatment capacity throughout the year during the first year of operation at Arvidstorp WWTP. The amount bypassing the disc filter stage was 2.6% of the total flow to the treatment plant (**Paper IV**), which is considered to be low.

During pilot testing for tertiary treatment, a capacity decrease by approximately 30-40% was observed prior to cleaning; however, the capacity did not decrease linearly but was more pronounced during the first days and the last week and was more constant in-between. This is similar to what was observed for microfiltration but with different timescales (**Paper VI**) (Ravazinni et al., 2011).

During the pilot experiments for primary treatment with chemical pretreatment, there was no need for chemical cleaning of the filter panels during the longest duration of interrupted operation of approximately one month. In one of the experiments using 30 μm media for primary treatment without chemical pretreatment, there was no significant decrease in the treatment capacity during a two month period. For chemically enhanced primary treatment and microsieving, Remy et al. (2014) reported a 6 month interval between chemical cleanings. However, the capacity was not the focus of this study; therefore, a low filtration capacity could probably be accepted. In general, chemical cleaning of the filter panels for primary treatment is to be expected as necessary every 2-3 month and every 4-6 weeks for tertiary treatment. Moreover, in general the trend during pilot testing was that clogging was lower if the operation was continuous and chemical dosing was held within the identified optimum dosing interval (Väänänen et al., 2013).

Sludge production and quality

The suspended solids accumulated on the filter media during filtration was backwashed with pressurized water, generating the sludge. This sludge was collected in a backwash gutter and then withdrawn. After primary treatment, the sludge production was 1-5% of the treated flow (**Paper I**). After tertiary treatment, the sludge production was on average 1-3% of the treated flow during the 2 year pilot test at the Ruhleben WWTP (**Paper III**) and 1.1-3.6% for the full-scale installation at the Arvidstorp WWTP (**Paper IV**). In comparison, the backwash water after primary treatment for pile cloth media was < 10% of the treated flow (Caliskaner et al., 2016), and for dual media filters in tertiary treatment, 4% has been reported (Remy, 2013). The solids content in the produced sludge after primary treatment was 0.5-2% (**Paper I**) and 0.1-0.75% after tertiary treatment (**Paper III**, **Paper IV**).

Maintenance work for the operation of disc filter installations

During pilot testing no filter panels had to be replaced due to operation fatigue. At full scale, the breakage of filter panels was also very scarce. At the full-scale installation in the Arvidstorp WWTP, 12 out of ~ 3000 filter panels (0.4%) had to be replaced during the first year of operation (**Paper IV**). Nunes et al. (2013) have reported the necessity of a few panel replacements within the first three years of operation at the disc filter installation in the Rya WWTP. From the full-scale experience, the maintenance was mostly related to the non-automated chemical cleaning of the filter panels (40%) and inspection of the backwash nozzles (40%). The total maintenance work load was approximately 38 min/m² year (**Paper IV**). For reference, Nunes et al. (2013) have reported 22 min/m² year, of which 24% were for automated chemical cleaning and 40% for the inspection of backwash nozzles for a full scale disc filter installation without chemical pretreatment.

5 Conclusions

Chemicals

The most applicable chemicals for both primary and tertiary treatment were polyaluminium chloride coagulants (PACl) and low-medium charged anionic or cationic high molecular weight synthetic polymers. However, biopolymers can be used as an alternative.

Sieve pore size in primary treatment

The effluent water quality with disc and drum filter microsieving technology without chemical pretreatment was comparable to well-functioning primary settling and removed approximately 30-60% of the SS content. In primary treatment, the preferred pore size was 100 μm . With this sieve pore size, a balanced trade-off between the capacity and removal was observed. By introducing chemical pretreatment and microsieving and applying the optimal type and dose of coagulant and polymer, the removal of SS increased to 98-99%. Furthermore, the removal of the COD was 80-85%, and that of TP was 95-97%.

Controlling the primary effluent

In addition, with microsieving, it is possible to apply a common feedback PI control with support from feed forward control to adjust the polymer or polymer and coagulant dosing to control the effluent water quality. Scheduling the control parameters of static gain and integration time was shown to be an appropriate method to account for the nonlinear behaviour of the chemical dose on the effluent water quality and for flow variations. The turbidity corresponded well with the effluent COD; therefore, the carbon removal was controllable.

Phosphorus removal was controlled by adjusting the coagulant dose in accordance to the polymer dose.

Microsieves for pretreatment prior to microfiltration

If microsieves are used for pretreatment prior to microfiltration, then it is most beneficial to conduct chemical pretreatment with anionic polymers in combination with the coagulant. The chemical dose should be selected to maximize the removal of the SS and TP content. This results in a high flux and the best MF effluent water quality.

Microsieving with an effluent < 0.1 mg TP/L in tertiary treatment

An appropriate design of the dispersion, coagulation and flocculation stages is very important for treatment applications. The shear forces in the dispersion phase of the coagulant and flocculant should be conducted under turbulent conditions ($G > 400 \text{ s}^{-1}$) during a few seconds. The shear forces during coagulation and flocculation should be higher than $G=150 \text{ s}^{-1}$, and a minimum hydraulic retention times between 1-4 minutes should be used. Flow through the tanks should facilitate transporting the floating sludge to the microsieve. Moreover, careful control of the chemical dose is critical.

Microsieves with chemical pretreatment and ozone

If microsieves are used in an advanced tertiary treatment stage for increased P removal and are combined with ozone to reduce micropollutants, it is wise to conduct ozonation after the chemically enhanced tertiary treatment and microsieving.

6 Future studies

Periodically, during primary treatment, the effluent water quality was controllable using only feedback control. By eliminating the feed forward control, a simpler system is generated that will ease operation even further. Thus, the possibility to control contaminant removal with pure PI feedback control within the whole operational window must be investigated further.

With the aid of ammonia nitrogen sensors, control of the carbon to nitrogen ratio can be achieved more precisely. It would be interesting to incorporate this type of monitoring and control. However, it might be necessary to limit the periodicity of the set point adjustment to be within the step response settling time of approximately 15-20 minutes to avoid instability.

To further lower the chemical usage in tertiary treatment and to meet effluent demands that are less strict, it would be interesting to investigate the possibility of implementing feedback control and use online TP measurements as a feedback signal. One consideration is that the TP measurement method is colorimetric and semi continuous (15 minutes delay). In this case, signal reconstruction of the measurement is probably needed.

Other applications of interest would be to combine powdered activated carbon (PAC) with chemically enhanced tertiary treatment and disc filtration for organic micropollutant removal or to further investigate the possibility of using disc filtration as a pretreatment method prior to ozonation. More work is also needed to optimize pretreatment with microsieves prior to microfiltration.

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Appendix I

Laboratory jar test and test tube filtration methodology

In wastewater treatment, jar tests are usually used for screening appropriate chemicals (Bratby, 2006). The jar test methodology describes working procedures related to the injection/dispersion of chemicals, mixing conditions and retention time (ASTM, 1995). In this work, a standard methodology was applied with an additional filtration step to simulate a filtration cycle with the microsieves. The filtration test equipment consisted of a transparent plastic cylinder marked at a distance of 200 mm from one end of the pipe, a measuring cylinder, a glass beaker with a variable speed flocculator and test tube filter plates (1 a and b). The filter plates had an effective net area of 0.0035 m^2 and were mounted to the test tube with a flexible pipe coupling.

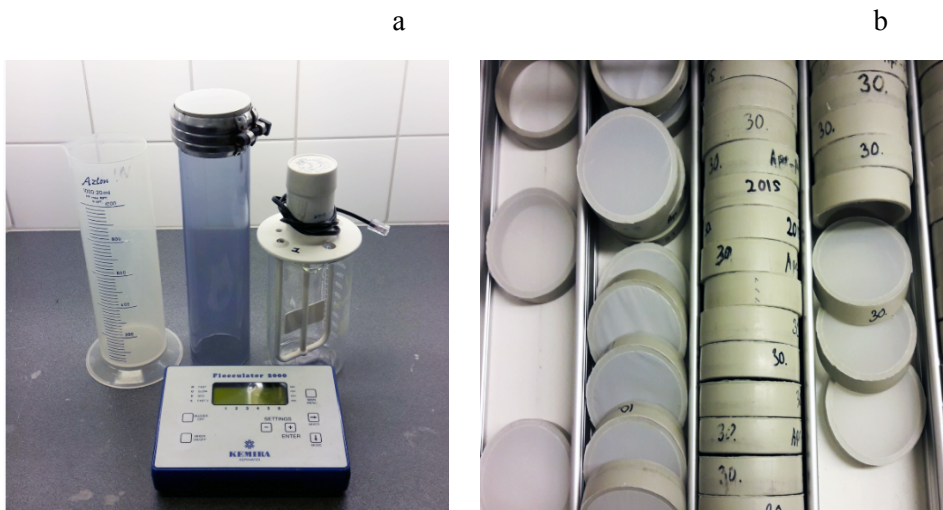


Figure 1 a) Jar test and test tube equipment; Transparent plastic cylinder with a filter element installed, 1000 ml measuring cylinder, and variable speed flocculator with 1L glass beaker and b) Filter elements.

The modified jar test is conducted as follows:

1. A glass beaker is filled with water, and the stirring device is put into the beaker.
2. The mixer is set to a stirring speed of 400 rpm, creating a mixing intensity of about $G=800 \text{ s}^{-1}$ (Cornwell et al., 1983), and the coagulant is thereafter injected into the water with the aid of a pipette close to the impeller for rapid dispersion.
3. Rapid mixing is conducted for 10 seconds and thereafter slow mixing for 1-4 minutes.
4. After slow mixing of the coagulant, the stirring speed is increased to 400 rpm, and the polymer is injected close to the impeller for rapid dispersion.
5. Rapid mixing is conducted for 10 seconds followed by slow mixing for 2-4 minutes.
6. A 1000 ml measuring cylinder is used and placed under the test tube to collect the filtrate.
7. The flocculated water is poured into the test tube up to the 200 mm mark, and by adding more water, the differential pressure is maintained at this constant level ($\pm 2 \text{ cm}$) during 10 seconds, and thereafter, the filtration is terminated by removing the test tube from the measuring cylinder (or vice versa if the test tube is fixed to a test rig).

Note: Flocs accumulated on the walls of the beaker are gently brought into the suspension prior to the filtration step by tapping the walls.

8. The volume of the filtrate is recorded, and additional analyses can thereafter be performed.

The stirring speed during the slow mixing stage of coagulation and flocculation are adjusted depending on the type of tests performed. In this study, a 50-100 rpm rate was used throughout the jar tests when studying mixing conditions, and a 50 rpm rate was used when screening for appropriate chemicals.

Appendix II

Pilot plant coagulation and flocculation mixing intensity measurements

During the pilot tests, the mixing intensity in the coagulation and flocculation stage was determined. The mixer motor was fixed on a friction free support bearing allowing the motor to rotate (Figure 1).



Figure 1 Torque measurement device for determining the mixing intensity in the coagulation and flocculation tanks.

The mixer power consumption was determined according to methods described by Leentvaar and Ywema, (1980). The power (P) was determined by measuring the torque with a Lutron FG 5005 torque metre. The power input was determined as the torque multiplied by the angular displacement according to the following equations:

$$P = Fl_a\omega \text{ (Nm/s)}$$

$P = \text{mixer power consumption (Nm/s)}$

$F = \text{Force (N)}$

$l_a = \text{Length of lever arm (m)}$

$\omega = 2\pi n_m$

$n_m = \text{Impeller rotational speed (rad/s)}$

The applied mixing intensity (G) and impeller power numbers (θ) were calculated according to the equation below (Bratby, 2006):

$$G = \sqrt{\frac{\theta \rho n^3 D^5}{V \mu}}$$

$\theta = \text{dimensionless powernumber related to impeller geometry}$

$\rho = \text{liquid density (kg/m}^3\text{)}$

$n = \text{mixer rotational speed (rps)}$

$D = \text{diameter of mixer impeller (m)}$

$V = \text{volume of coagulation/flocculation tank (m}^3\text{)}$

$\mu = \text{absolute viscosity (10}^{-3} \text{Ns/m}^2 \text{ for water at 20}^\circ\text{C}^\circ\text{)}$

where

$$P = \theta \rho n^3 D^5 = F l_a \omega.$$