NTNU – Trondheim
Norwegian University of
Science and Technology

Assessment of theoretical and practical aspects of the Salsnes filtration unit

Anders Gåre Søraunet

Civil and Environmental Engineering
Submission date: June 2012
Supervisor: Stein Wold Østerhus, IVM

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

Norwegian University of
Science and Technology
NTNU

Department of Hydraulic and
Environmental Engineering
Faculty of Engineering Science and Technology

Project description

MSc – project

Water and Wastewater Engineering

2012

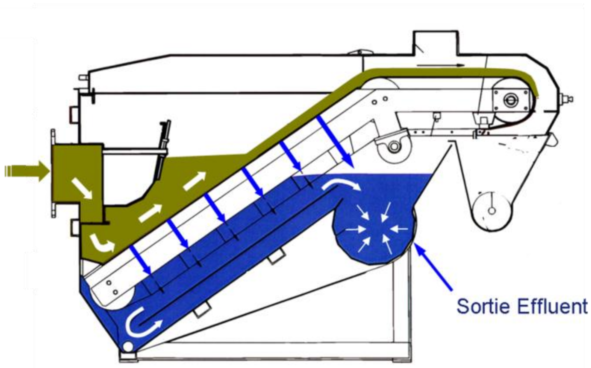
Stud. techn.: Anders Gåre Såraunet

Title: Assessment of theoretical and practical aspects of the Salsnes filtration unit

Background

Salsnes Filter has had large success with their filter technology with applications ranging from municipal wastewater treatment, sludge dewatering, fish farming, cruiselines/ships, slaughter house, pig manure, meat-/fish processing, food-/beverage processing, textile industry, pulp and paper industry, etc. The municipal wastewater treatment includes primary treatment, increased secondary and tertiary treatment and various municipal upgrades.

The filter technology consists of a standardised and patented technology that can be scaled up or down according to the customers' requirements. The mechanical filters are constructed to maintain a high degree of treatment under a varying hydraulic volume. This is achieved solely through using the patented compressed air flushing of the filter mesh cloth. This results in stable capacity and good treatment effect while the very fine mesh cloths is kept clean without using large volumes of hot water or manual cleaning methods. The mechanical treatment appliances filter the wastewater, condense the sludge and are very compact with an integrated sludge-dewatering unit inside the machine. The dewatered sludge has a high content of solids due to the air-cleaning device, which "pre-treats" the sludge before dewatering in the screw.



THE NORWEGIAN EPA's extensive study "SFT Primary treatment", also shows other advantages of the company's filter technology, such as the control of the technology, how fine mesh cloths are held in place in the mesh frame, how necessary the air flushing actually is for fine mesh filtering, and that Salsnes filter is the only proven primary treatment solution in use in Norway today.

The technology of Salsnes Filter is known for being flexible with respect to water volumes and degree of treatment. They are supplied as simple or advanced models for most mechanical treatment requirements. The emphasis is on creating a good working environment for the operator by minimising any contact with pollution by air or water. Fully automated plants require about 1 hour of service per week.

The performance of the Salsnes filter is generally better than what would be expected considering general sieving theory. Without going into details on theory and possible mechanisms, which would be the task of MSc-candidate, one possible and logical explaination would be cake development and cake filtration. However, the theory and treatment mechanisms occurring in Salsnes filter is poorly understood. Although the performance of the Salsnes filter is generally good, there are also examples where the performance is very poor without any obvious explaination (especially during periods of low surface loads, for example at Tiendeholmen). This further confirms that the theory and treatment mechanisms are poorly understood, which makes it difficult to optimize both the design and operation of the unit.

The candidate will look into the theory and mechanisms which can/should be applied to the Salsnes filter. The overall aim of this and later work will be to improve the understanding of the theory and treatment mechanisms applicable to Salsnes filter, and in the long run thereby improve the design and operation of the unit. The aim of the work for <u>this</u> MSc-project is to:

1. Give an overview of the design and operation characteristics of Salsnes filter.

2. The main focus of the work will be on investigating and assessing theory, models, mechanisms, etc relevant to the design and operation of Salsnes filter. This will mainly be a desk study. The work should end up with a theoretical base which can be used for, and developed further, in later work with the Salsnes filter unit.
3. Give a general evaluation of possible implication of the results and findings on practical design and operation of the unit.
4. Propose follow-up work based on the results, which in the long term would increase the understanding of the processes, and improve the design and operational fundamentals of the unit.

2. Specified assignment

The work will mainly be a desk study, with a few simple experiments to possibly confirm hypotheses or findings during the desk study. The specified tasks which should be included in the thesis would include:

2.1 Give an overview of the design and operation characteristics of Salsnes filter.

2.2 Give a state of the art review of the theory which may be relevant for the design and operation of Salsnes filter.

2.3 Suggest and discuss theoretical aspects, mechanisms, models, etc relevant to the Salsnes filter. Assess how the suggestions need to be modified and can be implemented into the process understanding. The overall aim is to develop a theoretical base which can be used for later work to improve process understanding, and design and operational fundamentals.

2.4 Perform some simple experiments (using the cylinder and sieve apparatus from Salsnes filter) to possibly confirm hypotheses and findings from the theoretical work

2.5 The theoretical and experimental results should be thoroughly discussed, and possible practical implication on the recommended design and operation should be included in the discussion.

2.6 The Results should end up with a theoretical base which can be used for, and developed further, in later work with the Salsnes filter unit. Consequently, suggestion for future work should include how to bring this current theoretical base further in order to improve both the process understanding, and the design and operational fundamentals.

3. Supervision and assistance

Prof. Stein W. Østerhus and prof. TorOve Leiknes, Department of Hydraulic and Environmental Engineering, NTNU, will be the supervisors for the candidate. The candidate should also seek advice from Bjørn Aas, Salsnes filter, and from other employees at Salsnes filter.

4. The report

The report shall be written as a research report including summary in English as well as in Norwegian, with a clear conclusion, with list of content and a literature list etc. The report is to be as short, concise and well written as possible. In the evaluation of the report, emphasis will be given to good documentation of the results with the use of clear tables and illustrations. All sources that are used are to be referred to in a correct way.

5. Report submission and dead-line: 18 June, 2012

The MSc thesis should be subitted according to the regulations of the Department of Hydraulic and Environmental engineering, NTNU. To the department shall also be delivered the report on a CD in Word format or equivalent, including summary, appendix, calculations, spreadsheets, etc. Other copies, for instance to Salsnes filter, shall be agreed on between the candidate and Salsnes filter.

Trondheim 15.01.2012

Stein W. Østerhus

Professor

ASSESSMENT OF THE THEORETICAL AND PRACTICAL ASPECTS OF THE SALSNES FILTRATION UNIT

PREFACE

This very thesis constitutes the final work of the master's degree programme Civil and Environmental Engineering at the Norwegian University of Science and Technology in Trondheim, Norway. The programme consists of several specializations, among these Hydraulic and Environmental Engineering.

Within this specialization, I have focused primarily on water and wastewater treatment. My personal interest toward this topic began during an exchange semester at the University of Melbourne. The course *Water and Wastewater Management* should be mentioned, but I would especially emphasize the quality of *Presenting Academic Discourse*, which benefits can hardly be overestimated, where I got to learn how to critically analyse work in my own field as well as present my own work, both written and oral. At the Norwegian University of Science and Technology, I would mention *Water Chemistry*, *Unit Processes in Water and Wastewater Treatment* and *Water and Wastewater Engineering, Advanced Course* as particularly useful courses to me.

The work with this paper has been challenging at times, especially since I chose a quite theoretical approach to it, but it has also been rewarding with respect to the learning outcomes. The assignment has turned out to be highly relevant with regard both to my background and, presumably, future work.

There are a few persons that deserve acknowledgment. I would like to thank Bjørn Aas at Salsnes Filter for taking the initiative to this assignment and for providing necessary information about the Salsnes Filter technology. Igor Ivanovic has offered invaluable assistance to carry out the experiments. Arne Grostad helped out with the experiment setup. My friend Erik Christian Lindbach was kind enough to assist me during the experiments. Gema Raspati helped to find most of the relevant fouling theory that has been applied. Tor Ove Leiknes has contributed with knowledge and ideas that have been highly useful. A special thank is given to Trine Hårberg and Gøril Thorvaldsen for their great assistance in the laboratory, but also for their encouragement and interest in my work. I would like to thank my supervisor Stein Østerhus for several reasons, but perhaps especially for his patience and friendliness whenever I show up at his office unannounced. Finally I want to particularly mention Neomy Storch at the University of Melbourne. A large proportion of my modest knowledge of academic writing I have learnt from her.

Anders Gåre Søraunet

ABSTRACT

Salsnes Filter delivers a technology used for primary treatment of wastewater. The technology could be described as a rotating belt sieve with continuously air cleaning of the sieve cloth. The process is referred to as 'Salsnes filtration' throughout the text.

Salsnes filtration can point out particularly high treatment efficiency, but it is not fully understood how this is obtained. Furthermore it is not clear how the process should be operated to achieve 'optimum performance'. In an attempt to understand this, both a theoretical and an experimental approach have been applied; hence the paper consists of two main parts.

In the theoretical part, different fouling mechanisms are described, and it is explained how these affect the hydraulic resistance of the sieve cloth and the resulting filtrate flux through it. In the experimental part, sieving under different pressure conditions has been explored. It was not succeeded in obtaining data suitable for statistical analyses, but some useful suggestions were given.

Most importantly, it may not be beneficial to establish a particle cake under high pressure conditions since this provides low permeability. It was found that upholding of high pressure was sufficient to counteract this, but that a relatively small decrease in pressure results in a significant decrease in filtrate fluxes.

It is concluded that Salsnes filtration should strive for a minimum decline in the ratio between pressure difference and hydraulic resistance in order to achieve the most uniform flux through the belt sieve, which is thought to ensure the highest treatment efficiency.

SAMMENDRAG

Salsnes Filter har utviklet en teknologi som brukes til primærrensing av avløpsvann. Teknologien kan beskrives som et roterende silbelte med kontinuerlig rengjøring av silduken ved bruk av trykkluft. Begrepet '*Salsnes filtration*' (Salsnes-filtrering) har blitt brukt om prosessen.

Salsnes-filtrering kan vise til en spesielt høy renseeffekt, men det er ikke fullt ut forstått hvordan denne oppnås. Som en følge av dette er det heller ikke klart hvordan prosessen skal driftes for å oppnå 'optimal ytelse'. I et forsøk på å forstå dette har to tilnærminger blitt brukt, en teoretisk og en praktisk, hvilket gjør at denne avhandlingen består av to deler.

I den teoretiske delen betraktes forskjellige fellingsmekanismer, og det gjøres rede for hvordan disse påvirker den hydrauliske motstanden i silduken og følgelig fluksen gjennom den. I den eksperimentelle delen har siling under ulike trykkforhold blitt utforsket. Det lyktes ikke med å skaffe data velegnet til statistisk behandling, men noen kvalitative antydninger er gitt.

Det kan se ut til at etablering av en partikkelkake under stort trykk resulterer i lav permeabilitet. Dersom trykkforholdene opprettholdes, ser dette ut til å motvirke denne effekten, men en relativt liten minkning i trykk vil derimot medføre en betraktelig minkning i fluks.

Det konkluderes med at det under Salsnes-filtrering bør etterstrebes en minimal minkning i forholdet mellom trykkforskjell og hydraulisk motstand oppover duken for å oppnå en mest mulig ensartet fluks gjennom en størst mulig del av denne, hvilket trolig vil resultere i en høy rensegrad.

QUOTATION MARKS AND REFERENCING

Two types of quotation marks are used throughout the text. They are used for somewhat different purposes.

> Double glyphs ("…") are generally used for referring to a specific text, typically by direct quotations or particular expressions
>
> Single glyphs ('…') are generally used for common and personal expressions.

To emphasize certain words, text in *italics* is used.

Referencing to sources in the text is done in APA style. However, much of the knowledge that is used in this thesis is acquired from university courses, perhaps especially *Unit Processes in Water and Wastewater Treatment* and *Water and Wastewater Engineering, Advanced Course*. Both courses were held by Stein Østerhus, but it should be clear that possible inaccurate statements throughout the text are *not* caused by misinformation from these lectures.

Wherever statements are taken directly from lecture slides available to students in these classes, this has been credited to Østerhus or Tor Ove Leiknes who made the slides used in *Unit Processes*. The reference years that have been used are 2011 and 2010, respectively, but it should be noted that this may not be entirely correct in all cases.

Table of Contents

INTRODUCTION

The company Salsnes Filter was established in Namsos, Norway in 1991. It is known for its “filter technology” used for primary treatment (or pre-treatment; see appendix A) of wastewater. Three series of filtration units are produced, given in the list below.

- SF models: for wastewater arriving in pipes
- SFK models: for industrial wastewater arriving through channels
- Salsnes Flock models: specifically designed for use together with chemicals that enhances separation through flocculation

The models within each series differ primarily in dimensions, adapted for different hydraulic loadings. The Salsnes Filter technology is perhaps best described as a rotating belt sieve with continuously air cleaning of the sieve cloth. An animation that demonstrates the technology behind the filtration unit can be viewed on Salsnes Filter’s home page (a). The eight defined steps in the process are pictured on the next page, using illustrations from the animation. These are also given below. The animation is based on a SF model, but the technology is essentially the same for all series.

1. Wastewater enters from a pipe
2. The wastewater is filtered through a filter cloth
3. The filtered water flows out of the unit
4. Solids are transported on a rotating filter cloth
5. The solid are collected in the “sludge compartment” by gravity
6. The cloth is cleaned using compressed air
7. Hot water flush for maintenance (regularly, typically twice a day)
8. Dewatering with screw press

This paper is primarily concerned with the steps 1 to 4. These can be seen as one continuous process where the filter cloth is rotating while wastewater is entering the unit, thus removing solids and cleaning the filter cloth. Near the intake, a pressure transmitter register the level of incoming wastewater, and this information is used to regulate the rotating speed of the belt sieve. Paulsrud (2000) mentions that this device is meant to ensure “optimum performance” at different hydraulic loadings, but it could be questioned if this is achieved.

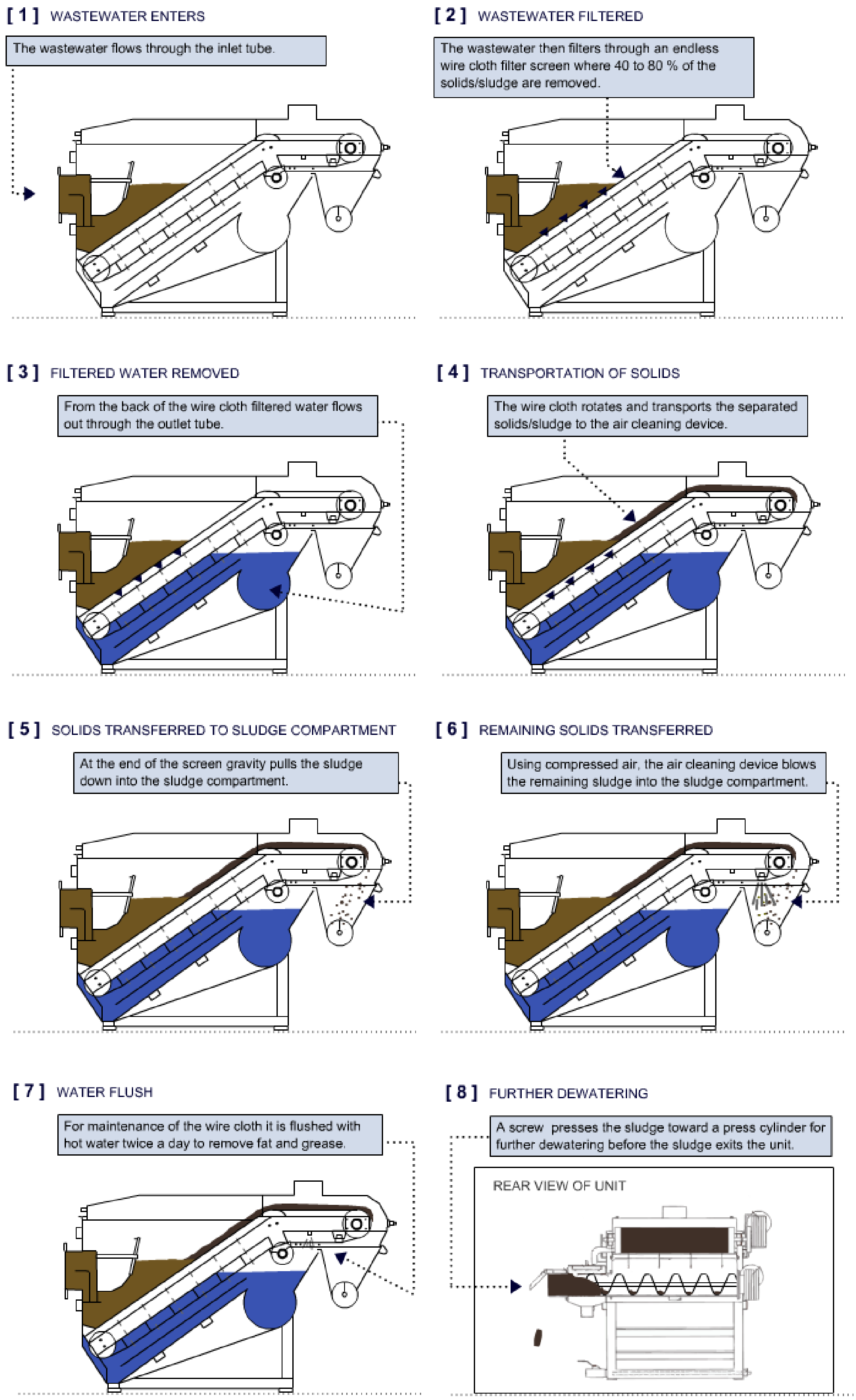


Figure 1. Stepwise explanation of Salsnes filtration.
(Salsnes Filter a)

Paulsrud examined the performance of Salsnes Filter at Tiendeholmen wastewater treatment plant and found average removal efficiencies of 59 % for SS[1], 45 % for COD[2] and 36 % for BOD_5[3]. It is claimed that "the mechanical filters […] maintain a high degree of treatment […] solely through using the patented compressed air flushing of the filter mesh cloth" (Salsnes Filter b), which corresponds to step 6. Moreover, air cleaning gives dry sludge which is beneficial for further treatment, but it seems clear that the adjustable rotating speed of the filter cloth also has a positive effect on the treatment efficiency. This assumption is supported by Rusten and Ødegaard (2006) by their finding that "only rotating belt sieves fulfilled the EU primary treatment requirements" (cf. appendix A) when compared to alternative technology for primary treatment.

At Breivika treatment plant, Rusten and Ødegaard reported average removal efficiencies for SS and BOD_5 as high as 90 % and 80 %, respectively. These results are explained with the use of a "very thick filter mat" at a low sieve rate. It is claimed that the removal efficiencies normally will be lower at higher sieve rates. Bjørn Aas at Salsnes Filter informed that the belt sieve was run at 20 Hz[4] during these tests (personal communication, May 14, 2012).

Yet, Aas has reported that experiments have been carried out at Tiendeholmen wastewater treatment plant, where the belt sieve has been running under frequencies as low as 2 Hz. Surprisingly, this has led to significantly lower removal efficiencies than what was reported by Rusten and Ødegaard.

Hence, Salsnes Filter wants more knowledge on how the treatment efficiency is related to various parameters, including the belt speed. This has led to this thesis, *Assessment of the Theoretical and Practical Aspects of the Salsnes Filtration Unit*. Since the "filter mat" has been found to be of great importance, it is primarily focused on fouling development, cake filtration, filtrate flux, hydraulic resistance and how these parameters are related to the prevailing pressure conditions.

[1] SS: suspended solids
[2] COD: chemical oxygen demand
[3] BOD_5: biochemical oxygen demand (consumption over 5 days)
[4] Corresponds to 3–4 meters/minute, depending on the gear ratio under operation

Brief terminology

In the context of water and wastewater treatment, *filtration* usually describes *depth filtration*. Droste (1997), for instance, treats only the latter in his chapter on filtration. Hence, the Salsnes technology is often referred to as *sieving*, cf. Rusten and Ødegaard.

To theorize fouling in relation to Salsnes technology, the field of membrane technology has been conferred. By Droste this dealt with under the term ‘membrane processes’. Seen this way, ‘Salsnes process’ could have be a suitable term, but it is normally referred to as *Salsnes filtration*. The rotating belt is, however, often referred to as a belt sieve.

While the theoretical part of this paper deals mainly with membrane technology, it is attempted to apply findings in the respective field to sieving and thus Salsnes filtration in the following experimental part.

THEORETICAL PART

PARTICLE FOULING

Particle fouling could be described as accumulation of particles on a surface. The subject has been studied quite extensively in relation to membrane filtration (cf. appendix B), but has apparently not been the main subject of any research conducted on Salsnes filtration previously, although it is known that operation with a "filter mat", as reported by Rusten and Ødegaard, enhances the treatment efficiency during operation. This phenomenon is known as *cake filtration*, which can be regarded both as process and a distinct fouling model.

Fouling models

According to Grenier *et al.* (2008), Grace and Hermia found four models to describe fouling.

- *Complete blocking*: Particles completely cover pore openings, preventing flow through them. (Physical mechanism: *pore blocking*)
- *Standard blocking*: Particles accumulate on pore walls inside membranes, constricting the pores, thus reducing the membrane permeability. (Physical mechanism: *pore constriction*)
- *Cake filtration*: Particles accumulate on the membrane surface, forming a mat (or cake) that capture more particles and increase the hydraulic resistance. (Physical mechanism: *surface deposit*)
- *Intermediate blocking*: Can be regarded as a combination of complete blocking and cake filtration, where the pore openings are covered by a fraction of the particles, while the other accumulate on top of them. (Physical mechanisms: *pore blocking + surface deposit*)

Hwang and Lin (2002) classify the models by use of the accumulating particle size. According to their work, complete blocking is caused by particles that are larger than the membrane pores, standard blocking by particles that are smaller than the membrane pores, and intermediate blocking by particles that are roughly the same size as the membrane pores. Cake filtration is not classified the same way, but it is claimed the "condition is similar to complete blocking", which presumably means that it is primarily caused by relatively large particles, at least initially. The fouling models are illustrated on the next page. Note that the sequence differs from the one given above.

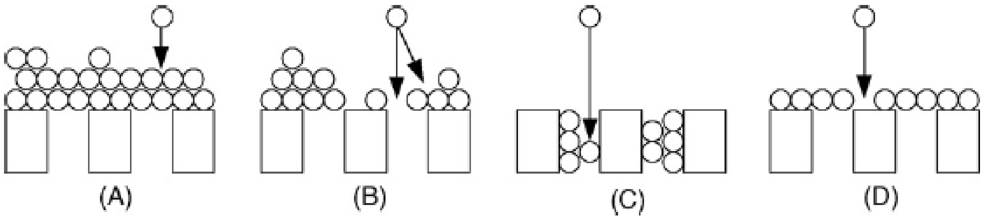


Figure 2. Cake filtration, intermediate blocking, standard blocking, complete blocking.
(Blankert, Betlem & Roffel, 2006)

It should be noted that the particle sizes for the respective models (cf. Hwang and Lin) are not represented in the figure. Moreover, standard blocking (C) apparently *prevents* flow in same manner as complete blocking (D). The pore constriction mechanism that causes standard blocking is usually illustrated differently, as shown in the next figure. From this, it seems clearer how the membrane pores are *constricted*, rather than blocked.

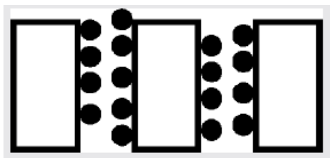


Figure 3. Pore constriction.
(Grenier *et al.*, 2008)

Hermia (1982) summarised the four fouling models for constant pressure in the equation given below, where V denotes the filtrate volume at time t.

$$\frac{d^2t}{dV^2} = k\left(\frac{dt}{dV}\right)^n$$

(1)

The different fouling models are identified by the value of the exponent n, as given in the list below (n is commonly referred to as a 'blocking index'.)

- *Complete blocking*: n = 2
- *Standard blocking*: n = 1.5
- *Cake filtration*: n = 0
- *Intermediate blocking*: n = 1

Hence, the prevailing fouling model at a given time can be found by analysing the relationship between d^2t/dV^2 and dt/dV. The use of a 'finite differences method' to derive a filtration data set into these parameters is recommended. If the value of n does not coincide with any of the four given above, it may indicate a combination of mechanisms, alternatively a non-identified mechanism. However, Grenier *et al.* found that, in their experiments, the assumption of "successive prevailing fouling mechanisms" resulted in a good description of flux decline.

Noteworthy, Grenier *et al.* considered only the three models that are caused by one mechanism each (complete blocking, standard blocking and cake filtration) in their analyses, thus left out intermediate blocking. This consideration seems reasonable since the model has a blocking index value that lies between the corresponding values for the models it can be regarded as a combination of (complete blocking and cake filtration). Moreover, this view may allow for several intermediate models, for instance a combination of pore constriction and surface deposit. At the same time it might also suggest the extent to which each of the mechanism is prevailing.

Combined models

In their study of protein fouling on microfiltration membranes, Ho and Sydney (2000) developed a model that accounts for initial fouling due to pore blocking and subsequent fouling due to cake filtration. A similar result was found by Hwang, Liao and Tung (2006) in their analysis of particle fouling, reporting that "membrane blocking occurs during the initial filtration periods until the condition reaches a critical value; then, the blocking index suddenly drops to zero [thus implying] cake filtration". It is presumed that the authors here distinguish between membrane blocking and cake filtration by including pore blocking and constriction in the former category and surface deposit in the latter. Before this 'critical condition' was reached, the calculated values of the blocking index were found to vary continuously during filtration (cf. figure 4). It is claimed that this finding is not in agreement with the 'four model theory', but it will be argued that this interpretation could be misleading.

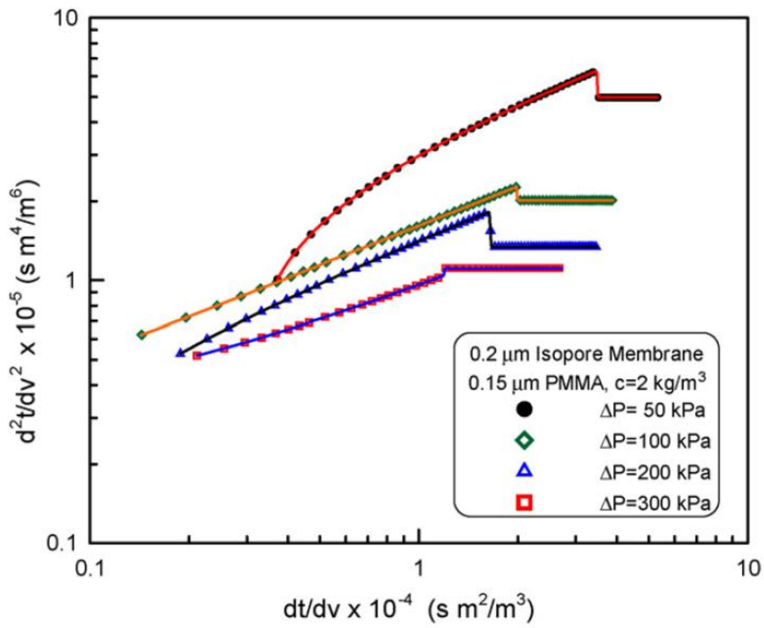


Figure 4. Relation between d^2t/dV^2 and dt/dV under various pressure conditions. (Hwang *et al.*, 2007)

Hwang *et al.* claim that, according to Hermia's equation, "the local tangent slopes of the curve can be considered the blocking index [...] in the models". However, this interpretation seems odd knowing that the blocking index appears as the *exponent* in the relevant equation, so that the local tangent slope should be a product of the blocking index n, the constant k and dt/dV in the power of $(n-1)$.

The nearly straight line for the transmembrane pressure value of 100 kPa actually indicates a value of n close to 1, thus implying intermediate blocking. The line for 200 kPa pressure is slightly concave, but seemingly the value of n is still close to 1, however somewhat lower. This might indicate that surface deposit is more prevalent than for 100 kPa, or perhaps that pore constriction also occurs. The same can be said about the top line (50 kPa transmembrane pressure), but presumably to a greater extent as indicated by a more distinct concavity. The bottom line is concave upward, so under the respective pressure condition (300 kPa), pore blocking is perhaps more prevalent.

Hermia (1982) does not seem to oppose other intermediate fouling models, although the possibility is not mentioned either. Either way, it is clear that all the four curves in figure 4 turn to horizontal straight lines, thus implying cake filtration. This result is in accordance with the findings of Ho and Sydney. In addition, the suggestion that lower transmembrane pressure results in fouling more oriented towards cake filtration, while higher values results in a greater ratio of pore blocking, is noteworthy.

Orsello, Li and Ho (2006) developed a "three mechanism model" where fouling firstly occurs by pore constriction, subsequently by pore blocking and finally by surface deposit. This model was found to be in good agreement with experimental data.

Influence of pore structure

The morphology of the membrane might also promote certain fouling mechanisms. This is suggested by Hwang and Lin (2002), based on a study on fouling on three membranes with the same mean pore size of 0.1 µm, but with different pore structures. The figure on the next page illustrates these structures.

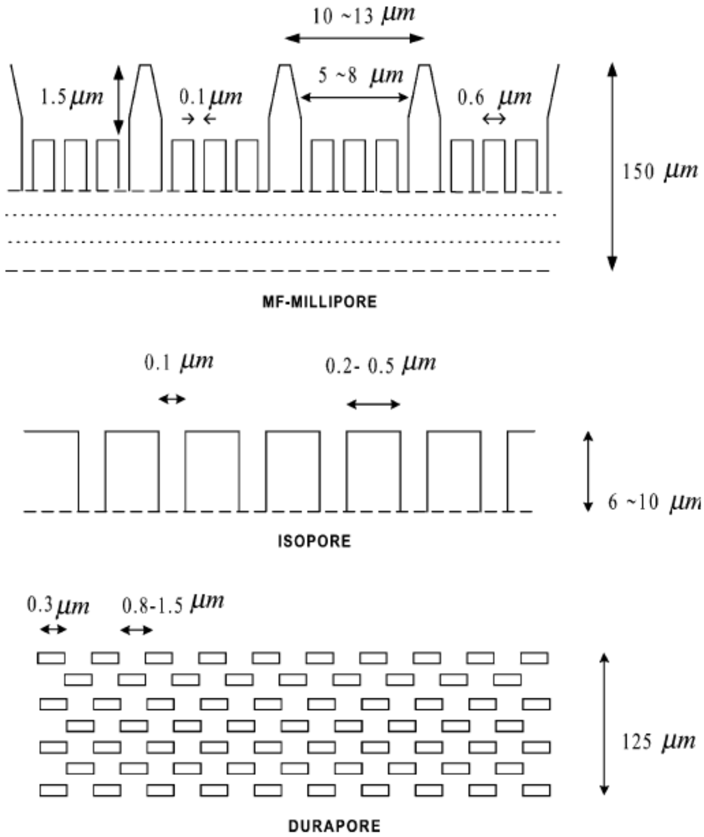


Figure 5. Membrane pore structures.
(Hwang & Lin, 2002)

At early stages of filtration, different models described the fouling on each of the membranes. Standard blocking occurred on the MF-Millipore membrane on top of the figure; complete blocking occurred on the Isopore membrane in the middle; and intermediate blocking occurred on the Durapore membrane at the bottom. After some time, the fouling on the three membranes developed from the respective initial models to cake filtration, a finding that is in agreement with several studies, as discussed previously.

Moreover, Hwang and Lin suggest that the filtration rate through membranes is determined by the level of cake formation. As previously discussed, it is found that cake formation normally succeeds pore blocking or constriction. Hence, a high level of cake formation implies that other fouling mechanisms are present to a significant extent, so the filtration rate might be determined by the *total* level of fouling.

The Isopore membrane was reported to have low levels of cake formation, while the MF Millipore membrane had high levels. This could imply that pore constriction results in higher levels of cake formation than pore blocking. Regardless, this finding indicates utility of an intermediate model for pore constriction and cake filtration.

FLUX, RESISTANCE AND TREATMENT EFFICIENCY

Generally, fouling is an unwanted phenomenon in membrane filtration. This is because fouling leads to pressure drop, reduced flux through the membrane and need for maintenance, possibly also other problems.

The flux trough a membrane is called filtrate flux and is often denoted J. It equals flow rate per surface area of a membrane. The surface area A_0 is regarded as constant, so that a change in filtrate flux is due to a change in flow rate.

$$J = \frac{1}{A_0} \cdot \frac{dV}{dt}$$

(2)

Darcy's law

In several analyses, e.g. Grenier *et al*. (2008), the following version of Darcy's law is used to model the membrane flux.

$$J = \frac{\Delta P}{\mu R}$$

(3a)

The filtrate flux is here given as a function of transmembrane pressure ΔP, the solution viscosity μ and the resistance R of the membrane, including possible resistance from accumulations. The equation can be rewritten by dividing the resistance R into two components, the clean membrane resistance R_m and the resistance of accumulated particles R_a.

$$J = \frac{\Delta P}{\mu(R_m + R_a)}$$

(3b)

It should be noted that (2b) may not be directly comparable to corresponding equations in other papers. Some authors choose to distinguish cake resistance from blocking resistance and include the blocking resistance in the membrane resistance. Moreover, different subscripts are also used. It seems, however, that splitting up the resistance into these two components seems favourable when analysing the flux. The membrane resistance can be approximated to be constant for a particular membrane, so that variations in flux are given as a result of transmembrane pressure and resistance from fouling. This leads to the following differential.

$$dJ = \frac{d(\Delta P) \cdot R - \Delta P \cdot dR_a}{\mu R^2}$$

(4)

Here, R again denotes the *total* resistance of the membrane and the accumulated particles. The delta in the expression for transmembrane pressure denotes the difference across the membrane, i.e. from one side to the other, but this difference may still vary in time or along different parts of the surface area of a membrane.

Hydraulic resistance due to fouling

The hydraulic resistance in a membrane can be analysed using Darcy's equation (2a). Tracey and Davis (1994) found that the development over time due to fouling distinguishes pore blocking and constriction from surface deposit. Standard and complete blocking result in a plot of the resistance versus time that is concave upward, while intermediate blocking and cake formation result in a plot that is concave downward. Hence, the resistance growth rate is increasing for pore blocking and constriction and decreasing for surface deposit.

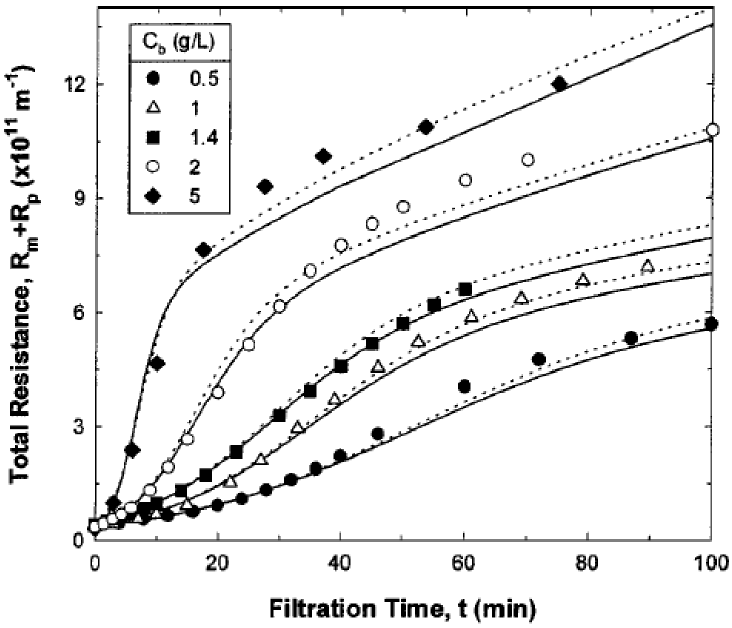


Figure 6. Hydraulic resistance vs. filtration time.
(Ho & Sydney, 2000)

Cake filtration

In relation to membrane technology, cake filtration is usually seen as a part of the 'fouling problem', but Tien (2002) recognize the possibilities for utilizing the phenomenon, stating that "cake filtration, as a solid–liquid separation process, is widely used in the chemical and process industry". Thus, it could be argued that 'cake filtration' is a more suitable term for the treatment process, while the fouling model perhaps should be named 'surface deposit' after the underlying mechanism, this to avoid confusion.

Tien suggests that determination of certain cake properties, namely the porosity, ε, and permeability, k, is of importance for cake filtration. Since this is mentioned in relation to utilization of the phenomenon, it seems likely that these properties can be associated with the resulting treatment efficiency of the process. This view on cake filtration presumably makes the process comparable to depth filtration, where corresponding properties are used to characterize a filter. Tien also mentions cake thickness as a central parameter, partly due to its relation to cake resistance. It seems likely that the resistance is also affected by the cake permeability. Hence, if the permeability is defined as a material parameter, the suggested relation on next page might hold.

$$R_c = \kappa \frac{L}{k}$$

(5)

The cake thickness is denoted L, while k and R still denote permeability and resistance, respectively. The subscript c is used to indicate cake filtration. κ is a constant, probably dependent on other cake properties. It was argued that cake filtration could be compared to depth filtration; hence, an exploration of the mentioned properties could have its basis in the five "filtration mechanisms" mentioned by Leiknes (2010a): hydrodynamic retention, diffusion, sedimentation, inertia and interception.

In this context it seems sufficient to appreciate that the treatment efficiency of a filtration process can be regarded as the ability of to retain particles while letting water through. This is presumably analogous to cake filtration, with the cake acting as a filter. Hence, there are certain cake characteristics that also promote the treatment efficiency. The porosity and permeability have been mentioned, but the thickness is quite likely also of importance; a thicker cake should have the ability to retain more particles.

It seems that the influence of porosity and permeability is more complex. The parameters are closely related; no porosity undoubtedly leading to no permeability. Therefore, it seems reasonable to focus on permeability. If a cake is non-permeable, then no treatment is offered since the wastewater cannot filtrate through. On the other hand, if a cake is very permeable due to great porosity, it is likely that particles are not retained to a satisfactory extent.

To simplify this, it could be assumed, probably quite inaccurately, that the treatment efficiency is proportional to the experienced resistance. Consequently, by Darcy's equation (2a), high treatment efficiency is implied by a large pressure drop.

EXPERIMENTAL PART: SALSNES FILTRATION

INITIAL CONSIDERATIONS

The fouling theory in the theoretical part had its basis in membrane filtration. Therefore, before it is applied on Salsnes filtration, some considerations are made. It is seen that these will lead up to a basic assumption regarding Salsnes filtration.

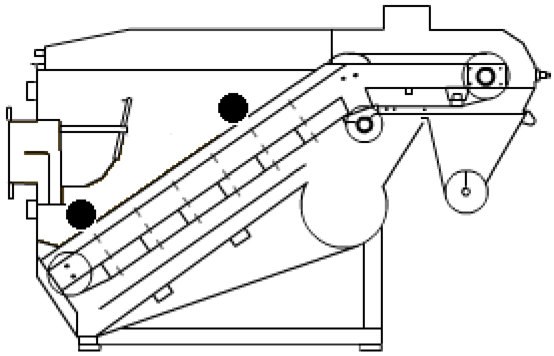


Figure 7. Salsnes filtration unit.
(Salsnes Filter a; modified)

Differences

Clearly, there are several differences between membrane filtration and Salsnes filtration.

1. *Pore size*. Most of the research mentioned in the theoretical part is conducted on microfiltration membranes, which should imply a pore size between 0.1 and 5 µm (The Membranes Research Environment), Salsnes filtration is normally operated with a *mesh size* roughly between 200 and 800 µm.
2. *Transmembrane pressure*. It is assumed that the initial pressure during membrane filtration, i.e. before any fouling occurs, is equal across the membrane surface. This is not the case for Salsnes filtration. Consider the above figure. It is clear the two indicated parts at the feed side of the belt sieve experience different hydraulic pressure at a given water level. For a constant hydraulic pressure on the filtrate side, this would result in a linearly increasing *pressure difference* (proposed Salsnes analogue to transmembrane pressure) up along the belt sieve. This is not strictly the case, however, due to the way the filtrate is led out of the unit, but the pressure difference still varies, which is the point to be made.

3. Rotation. While there is an important difference between cross-flow and dead-end filtration, it seems that a specific part of a membrane would have certain properties that does not change much over time. For Salsnes filtration this assumption does not apply due to rotation. A part that experiences a certain filtrate flux and level of particle accumulation at a given time will at a later time be at a place where mainly different pressure conditions, presumably, lead to changes in these. Moreover, the filtrate flux J is used for a constant surface area, A_0. Due to rotation, there is *no* 'constant surface area' during Salsnes filtration, but it is assumed that the wetted area of the belt sieve can be regarded as constant for a given water level on the feed side, hence could be used for A_0.

There are obviously other differences between membrane filtration and Salsnes filtration, but the three above are in this context considered to be of special significance.

Enhanced removal due to fouling

The listed differences lead to an interesting consideration regarding membrane filtration and Salsnes filtration: While fouling generally is an unwanted phenomenon on membranes, this is most likely not the case for Salsnes filtration.

Rusten and Ødegaard concluded that operation with a filter cake was necessary for sieves in order to reach the EU treatment objectives. Consider the following figure, showing the particle size distribution in raw wastewater at two different wastewater plants.

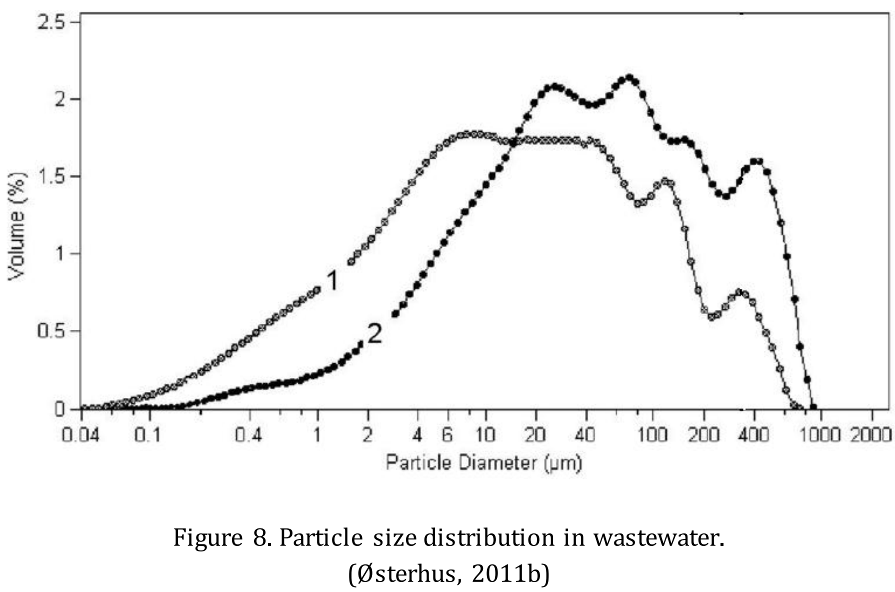


Figure 8. Particle size distribution in wastewater.
(Østerhus, 2011b)

The Salsnes units are normally used with a belt sieve mesh size in the range from 210 µm to 850 µm for municipal wastewater, 350 µm is most commonly used. Presumed that the graphs in the figure above are representative for municipal wastewater, a 350 µm sieve ensures directly removal of only a small proportion of particles, as illustrated in the figure below. It should be noted, however, that the particle diameter is represented *stepwise* linearly along the horizontal axis, but it is still conceivable that the major part of the particles has a diameter below 350 µm.

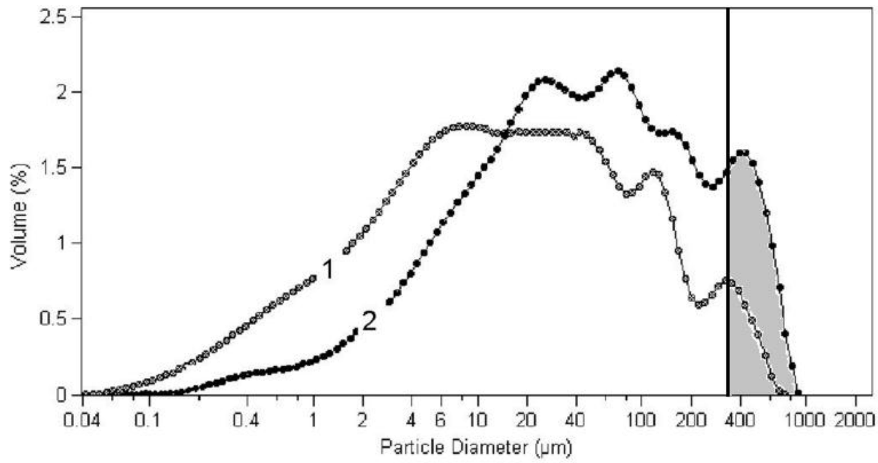


Figure 9. Particles with a diameter larger than 350 µm.
(Østerhus, 2011a; modified)

Compare the figure above with achieved removal efficiencies well above 50 %. Hence, that this is ensured by cake filtration appears to be certain. When fouling theory is conferred, however, this could be generalized to include the other fouling mechanisms, both since pore blocking and constriction have been found to precede cake filtration and since these mechanisms themselves presumably contribute to the treatment efficiency. These considerations lead up to a basic assumption.

Salsnes filtration achieves high removal efficiency due to fouling mechanisms that prevent further penetration of particles through the sieve cloth.

Yet the question remains, how the filtration is best operated. A corollary to this basic assumption would imply operation with special attention to cake formation. At first, before any wastewater has been filtered through the sieve cloth, a major part of the particles are able to penetrate through the sieve cloth. A reasonable assumption could be that this tendency firstly decreases when large particles block the pores, i.e. that the initial fouling is described by pore blocking. However, the proportion of particles able to cause Hence, pore constriction should be taken into account. Following Hwang and Lin, this is performed by particles with diameter smaller than the pore openings. Once the pores are constricted, this could allow for a greater share of particles to contribute to blocking.

Hypotheses regarding prevailing fouling mechanisms could perhaps be tested also for Salsnes filtration by use of Hermia's equation (1) to find the blocking index n. A value close to 1.5 would then imply standard blocking, hence pore constriction. If the value increases, this would presumably imply that a greater share of fouling occurs by complete blocking ($n = 2$). At a critical stage, the value might drop to zero, as reported by Hwang *et al.* (2006), which would imply cake filtration, i.e. surface deposit.

Path of least resistance

The wastewater to be filtered follows the 'path of least resistance'. Darcy's law (2a) could perhaps be seen as a consequence of this principle; greater resistance leading to smaller flux under constant pressure. With constant resistance along a membrane, Darcy predicts that the filtration will occur at a slower rate. But for varying resistance, the wastewater would probably flow through the regions of lesser resistance, thus following the path in question.

Ho and Sydney (2000) observed that "at short filtration times, a significant fraction of the membrane remains unblocked by any protein aggregates, with most of the flow going through these unblocked areas". In one analysis, it was found that after 8 minutes of filtration only 6 % of the total filtrate flow went through the fouled regions even though these constituted 74 % of the membrane surface area. It was further observed that this led to fouling the initially 'non-fouled' regions, and hence referred to cake growth as a "self-leveling process".

Small effect of finer mesh

Rusten and Ødegaard (2006) concluded that “once a filter mat is formed on the sieve, there is practically no difference in the performance of sieve cloths within this size range”, referring to openings from 250 μm to 500 μm, reportedly “the proper choice for typical wastewater”. It has been argued that the enhanced treatment efficiency is due to fouling, perhaps primarily cake filtration, but it seems probable that fouling should occur at an earlier stage of filtration on a finer sieve. If the treatment efficiency is found to be nearly independent of the mesh size, it could perhaps be explained this way: a particle cake is established so quickly that the additional time this takes on a coarser sieve is small compared to the total filtration time.

Furthermore, this observation might support a theory that the initial fouling is primarily caused by pore constriction, since smaller particles in theory could contribute equally to this in both a fine (250 μm) and a coarse (500 μm) sieve. On the other hand, this could also mean that the proportion of particles able to cause pore blocking is roughly equal in both cases, but at the same time this possibility implies that only particles with a diameter close to the respective pore opening contribute to blocking, which correspond to an even smaller proportion of the particles.

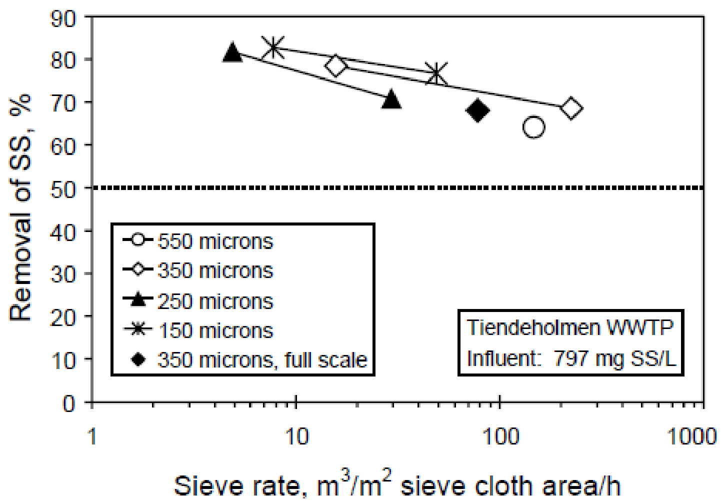


Figure 10. Treatment eff. for Salsnes filtration with different mesh sizes (Tiendeholmen WWTP). (Rusten and Ødegaard, 2006)

IDEA AND SETUP

The conducted experiments will be described by four series with somewhat differing procedures. The idea behind these, however, is the same. A general methodology is outlined, with closer descriptions included in the chapter about each series.

Idea behind experiments

It was described how the hydraulic pressure varies along the belt sieve during Salsnes filtration. The pressure difference, ΔP, together with the resistance, R, determines the filtrate flux, J, but it might also affects the fouling mechanisms (perhaps particularly through cake formation) that in turn determines R. This 'double effect' of ΔP makes the outcome (in this context: the treatment efficiency) of Salsnes filtration under different conditions difficult to predict.

Therefore, it is desired to explore the filtrate flux and resistance development under various pressure conditions, tentatively corresponding roughly to the conditions under Salsnes filtration. In the figure below, the belt sieve is divided into regions by red lines.

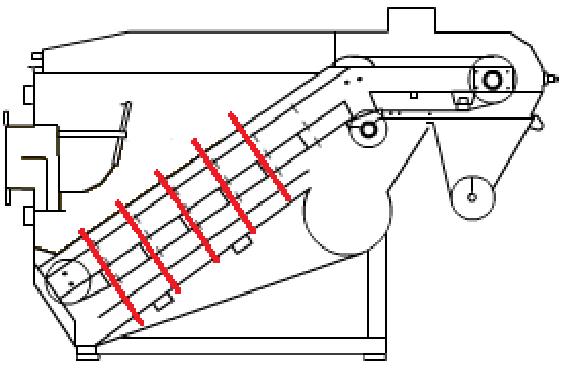


Figure 11. Salsnes filtration unit.
(Salsnes Filter a; modified)

In each of these regions, it could be approximated that specific pressure and resistance conditions are prevailing at a given time, thus resulting in a specific filtrate flux. By imitating the pressure condition in each region and registering the resulting filtered volume at different filtration times, it might be better understood how the Salsnes filtration unit should be operated.

When the relation between V and t is established, Hermia's equation (1) and numerical derivation could be used to explore the blocking index n, a parameter that can be expressed explicitly by use of logarithms ('lg').

$$n = \frac{lg[d^2t/dV^2] - lg[k]}{lg[dt/dV]}$$

(6)

The second derivative can be numerically approximated using central differences (Aarseth, 2009). This presumably encourage the use of central differences also for the first derivatives since these are directly compared to the second derivatives. (A common alternative would be the use of forward differences).

$$t'(V_j) = t'_j = \frac{t_{j+1} - t_{j-1}}{2\Delta V}$$

(7)

$$t''(V_j) = t''_j = \frac{t_{j+1} - 2t_j + t_{j-1}}{[\Delta V]^2}$$

(8)

When equation (6), (7) and (8) are combined, the following approximation is found.

$$n \approx \frac{lg\left[t_{j+1} - 2t_j + t_{j-1}\right] - 2lg[\Delta V] - lg[k]}{lg\left[t_{j+1} - t_{j-1}\right] - lg[\Delta V] - lg[2]}$$

(9)

It should be noted that use of the latter equation presupposes a known value for the constant k, a resistance coefficient as defined in (1). (During a numerical analysis, different values of k could be used to see if any of these would yield a constant value for n.)

General methodology

Although several experiments have been performed, a general methodology for these could be outlined. Easily explained, it has been attempted to filtrate wastewater through sieve cloths (hereinafter: referred to as *filters*) similar to those used on the Salsnes belts under different pressure conditions. The filters are circular with a filter diameter of roughly 10 cm (gives a surface area of approximately 79 cm^2).

On next page, the setup is explained by the use of a flow diagram.

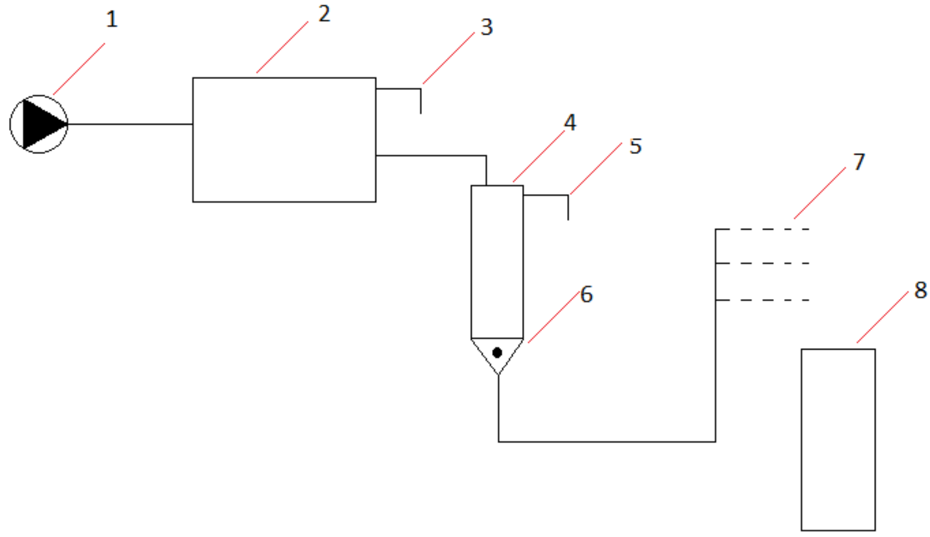


Figure 12. Flow diagram for experiment setup.

1. *Pump*. Connected to a wastewater tank.
2. *Tank*. Used to create an even flow into 'sieve unit' (4)
3. *Overflow 1*.
4. *Sieve unit*. Cylinder with a filter in the bottom.
5. *Overflow 2*. Used to maintain a constant water level on the feed side of the filter.
6. *Valve*. Regulates the flow out of the sieve unit.
7. *Adjustable outflow*. Used to adjust the water level on the filtrate side.
8. *Graduated cylinder*. To measure the filtrate volume V as a function of time t.

Also, there is a valve that regulates the flow from the tank (3) to the sieve unit (4). The flow diagram is used to describe a general procedure in the following.

i. The pump (1) is set at a constant pumping rate. A constant rate is not strictly necessary since there are other mechanisms that regulate the water level, but is found practical. The outflow (7) is set at a desired height.
ii. When the tank (2) is filled up to a certain level, wastewater is let into the sieve unit (4).
iii. The sieve unit (4) is filled up with wastewater until the overflow (5) is activated, i.e. until wastewater overflows. The idea is that this provides a constant water level inside the unit.

iv. The valve (6) is opened, letting wastewater into the graduated cylinder (8). The pump (1) provides incoming wastewater, so the filtrate flow is registered by measuring volumes in the graduated cylinder (8) as long as the overflow (5) is active. If no wastewater overflows, this is seen as an indication that the water level in the sieve unit (4) is no longer constant.

Test runs

In the first test run a filter with a mesh size of 350 µm was used. The pressure difference was set at approximately 80 cm. As expected, this resulted in a high flow rate. A large graduated cylinder made of a plastic barrel with a mark for every 10 litres of water was used to measure the flow. It was found that the overflow (5) stopped after a short filtration time, which indicated a larger outflow than inflow. Since no pump suitable for pumping of wastewater with a greater capacity was available, this signalled a need for other measures to control the flow.

While 350 µm sieve cloths are most commonly used for Salsnes filtration of municipal wastewater, other mesh sizes are also in use. For the second test run, a sieve with mesh size 90 µm was used, although this is finer than what is normally used for municipal wastewater. After approximately 4 minutes, the sieve was completely clogged, letting no water out of the sieve unit, only through the overflow. Yet, until clogging occurred, the water level in the sieve unit (4) decreased.

In the following runs, it was succeeded in keeping the water level in the unit approximately constant (presumably) by different means. These could also have been regarded as test runs, mainly because new adjustments were made underway to improve posterior tests, but interesting findings were made, so these are instead described as different series of experiments.

First series

This experiment followed the outlined general procedures, but with one crucial exception. The valve (6) was halfway shut to control the outflow. Moreover, instead of measuring filtrate volumes per time, the time was taken for fixed filtrate volume intervals. This could perhaps be regarded as the difference between *V(t)* and *t(V)*, respectively, thus no great difference, but there are two reasons why this was done. Firstly, the plastic barrel used as a graduated cylinder allowed only for measuring of every 5 litres of water, so intermediate volumes are difficult to read of accurately. Secondly, this was considered to be more practical for numerical analyses of the filtration curve.

The pressure difference is given by the hydraulic head h[5]. This generally applies throughout this part of the paper.

- Δh = 62 cm
- 210 μm

Under these conditions, six runs were carried out. (It was also attempted to use the same setup for a considerably smaller pressure difference.) Two inflow samples and one filtrate sample were taken for analyses of suspended solids content (SS).

The filter was washed in hot water between every run.

[5] Bernoulli: $h = z + {v^2}/{2g} + {P}/{\rho g}$; $h = z$ for $v = 0$ and $P = 0$

Results

The results are presented in the following figure with the filtrate volume *V* in litres along the horizontal x-axis and the filtration time *t* in seconds along the vertical y-axis.

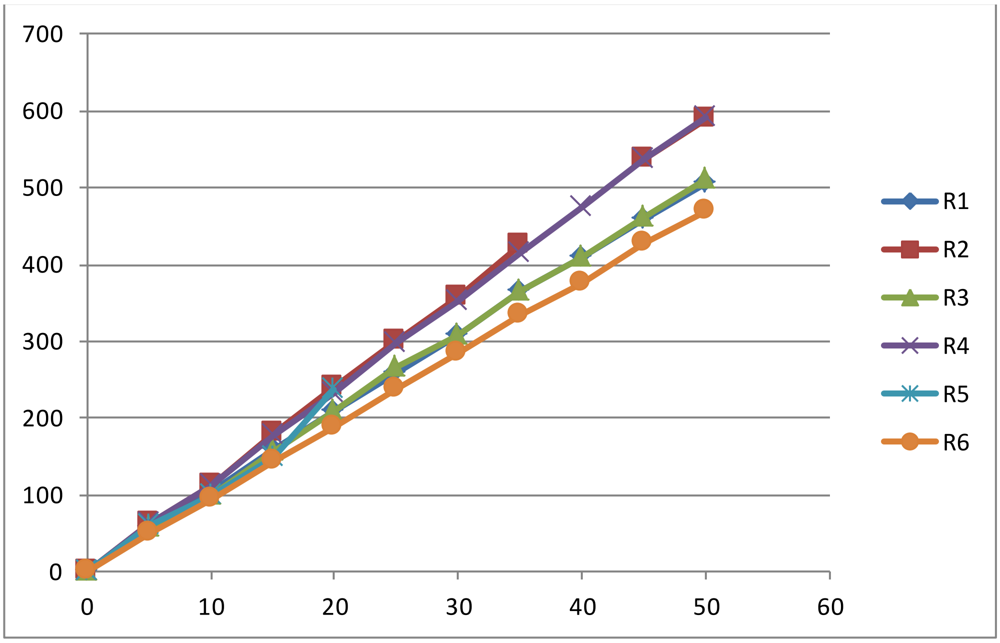


Figure 13. Filtration curves: *t(V)* [x: litres, y: seconds].

It can be seen that the filtrate flow rate for each run does not differ greatly from the others. Also, each run displays a rather steady flow rate.

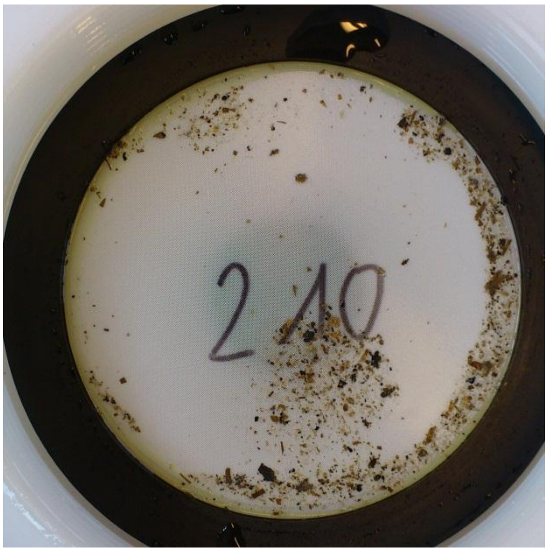
- *R1*: After approximately 4 minutes, the overflow (5) was not active. However, the water level seemingly did not decrease, so the registering was carried on. An inspection of the filter after the run revealed that no significant particle cake was formed.
- *R2*: The overflow was active during the entire run. No significant cake formation.
- *R3*: Similar to *R1*, the overflow stopped after approximately 4 minutes, but was again activated a few minutes later. A significant cake was formed this time. After the pump was stopped, the filtrate flow rate decreased drastically.
- *R4*: The overflow was active during the entire run. A significant cake was formed, but this time the outer areas of the filter appeared to be 'non-fouled', while significantly larger particle accumulation was found at the centre. The shape could

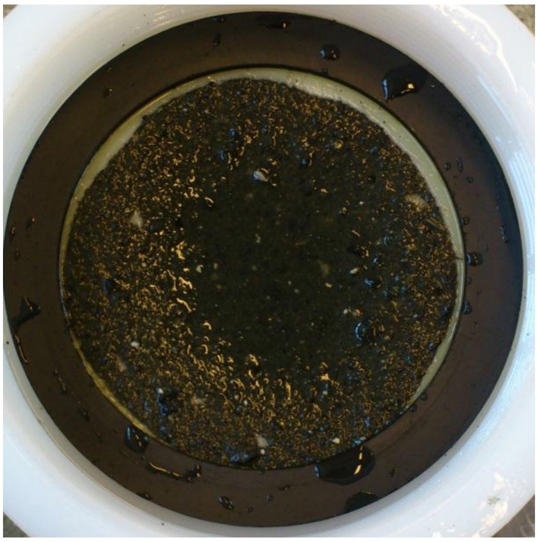
perhaps be described as a 'hump', where the top is represented by the thickest cake layer.

- *R5*: Before 3 minutes had passed, the water level inside the sieve unit (4) fell significantly. After this, the flow rate decreased, as indicated by the steeper incline showed on the curve in the above figure.
- *R6*: The overflow was active during the entire run. No significant cake was formed.

Pictures of the filter after the runs can be seen on the next pages.

The SS content was found to be 131 mg/l, 130 mg/l and 55 mg/l for inflow prior to the first run, filtrate after the first run and inflow after last run, respectively.





Picture series 1. Filter after *R1*, *R2* and *R3*.

Picture series 2. Filter after *R4*, *R5* and *R6*.

Discussion

Firstly, it should be noted that these runs are influenced by several inaccuracies. The use of the valve to control the outflow is clearly not ideal, partly since it could have resulted in slightly different openings for each run, but also since this increases the singular pressure loss. Secondly, the marks on the plastic barrel did not allow for accurate reading of filtrated volumes. Thirdly, it was not succeeded in keeping the water level completely constant at every run, as indicated by no overflow from the sieve unit.

Yet, at least one interesting observation was made. Significant cake formation was observed after two of the runs, and it seemed that the flow rates were not greatly affected by it, both since all six curves are quite similar and since the two curves of particular interest (*R3* and *R4*) showed no significant increase in filtration time per filtrate volume. However, no conclusion can be drawn based on such moderate sample sizes, but it may suggest a possible trend to be explored further.

Unfortunately, SS samples were not taken before and after each experiment, which could have revealed differences in treatment efficiencies due to cake formation, even though the filtrate flux seemed unaffected by it. The SS analyses taken displayed a high variation in SS content, but this could very well be due to the way the samples were taken. The inflow samples were taken straight from the hose connected to the tank (2), while the filtrate sample was taken from the plastic barrel (8) that contained the entire filtrate volume. Since the sample bottles contain small volumes, variations in the wastewater characteristic may have major effects on the outcome.

The shape of the cake layer after the third run (*R3*) might also indicate that particle accumulation and the water flow through the filter can appear at different places on the filter surface. When no significant decrease in the flow rates was detected, no relevant information about the fouling mechanisms can be found using Hermia's equation (1).

SECOND SERIES

The experiment setup was similar to that used in the first series, but a more accurate graduated cylinder (8) was used, with a reading mark for every 10 millilitre (ml). However, the time was taken only for every 100 ml, due to difficulties with more accurate readings. Two graduated cylinders with a capacity of 1 litre each were used. These had to be interchanged manually.

- *Δh = 14 cm*
- *210 µm*

For each run samples for SS analyses of the inflow and the filtrate were taken, except for *R4* where only an inflow sample was taken and *R5* where only a filtrate sample was taken.

The filter was washed in hot water between every run.

Results

The results are presented in a figure with the filtrate volume *V* in litres along the horizontal x-axis and the filtration time *t* in seconds along the vertical y-axis.

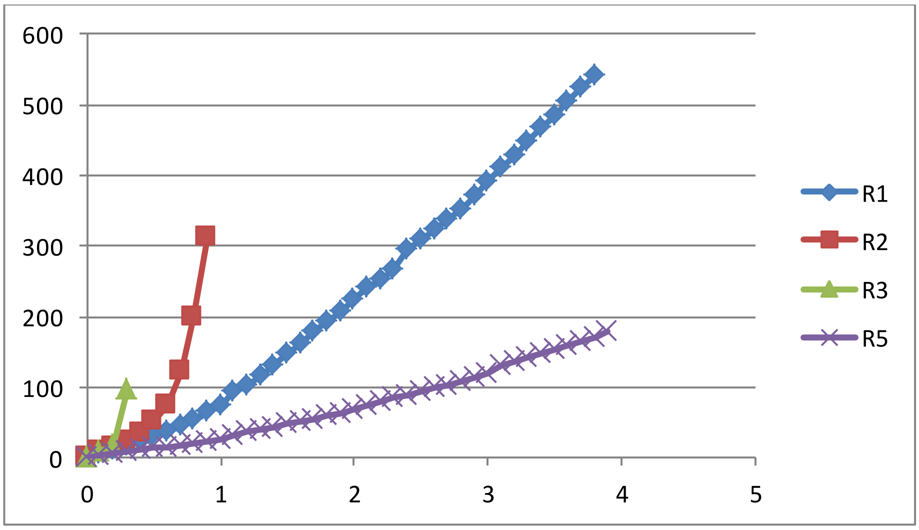


Figure 14. Filtration curves: *t(V)* [x: litres, y: seconds].

The four curves are clearly quite different. The second, third and fourth run (*R2*, *R3* and *R4*) showed a significant flow rate decrease after relatively short filtration time. (*R4* is not displayed in the above figure.) These three runs each resulted in a filter cake, but seemingly not as thick as for the two cases of cake formation in the first series.

The time measured for the first interval, from 0 to 100 ml, was not accurate. These are marked with grey letters in the table on the next page. For every litre of water, the graduated cylinder had to be changed, an operation that added extra seconds to the measured time of the first 100 ml. These intervals are numbered 11, 21 and 31 in the table below, and the relevant numbers are also marked with grey letters. 'Grey numbers' are meant to indicate that these should not be taken into account for any analysis.

j	t_j *R1*	t_j *R2*	t_j *R5*
1	6,71	7,56	3,26
2	5	6,51	2,48
3	5,42	8,82	2,19
4	5,8	12,26	2,64
5	7,49	15,29	2,71
6	7,54	23,45	2,57
7	7,94	47,75	2,86
8	9,29	77,09	2,86
9	9,72	114,25	2,72
10	9,73		2,89
11	19,1		5,77
12	8,49		3,92
13	14,91		3,63
14	14,78		3,17
15	14,6		3,66
16	15,02		3,45
17	15,93		3,91
18	15,13		4,33
19	15,39		4,03
20	15,38		4,57

j	t_j *R1*	t_j *R2*	t_j *R5*
21	16,47		5,91
22	13,23		5,34
23	14,22		5,21
24	26,83		3,97
25	14,87		5,76
26	13,63		4,58
27	13,93		5,4
28	14,2		5,3
29	21,99		5,2
30	18,81		6
31	19,01		9,52
32	18,55		5,36
33	19,34		6,46
34	17,9		5,43
35	19,26		6,64
36	19,23		6,39
37	18,69		5,58
38	17,82		5,96
39			5,91
40			

Table 1. Filtration times.

The numbers in the table above are used to find the first and second derivatives as given in equations (7) and (8). In the calculations the 'grey numbers' are replaced by the average of the values above and below (e.g. $t_{11} = \{t_{12}+t_{10}\}/2$), which in practice results in a linear development around these, something that in turn gives second derivatives equal to zero. Thus the table on the next page is obtained (using $\Delta V = 0.1\ l$).

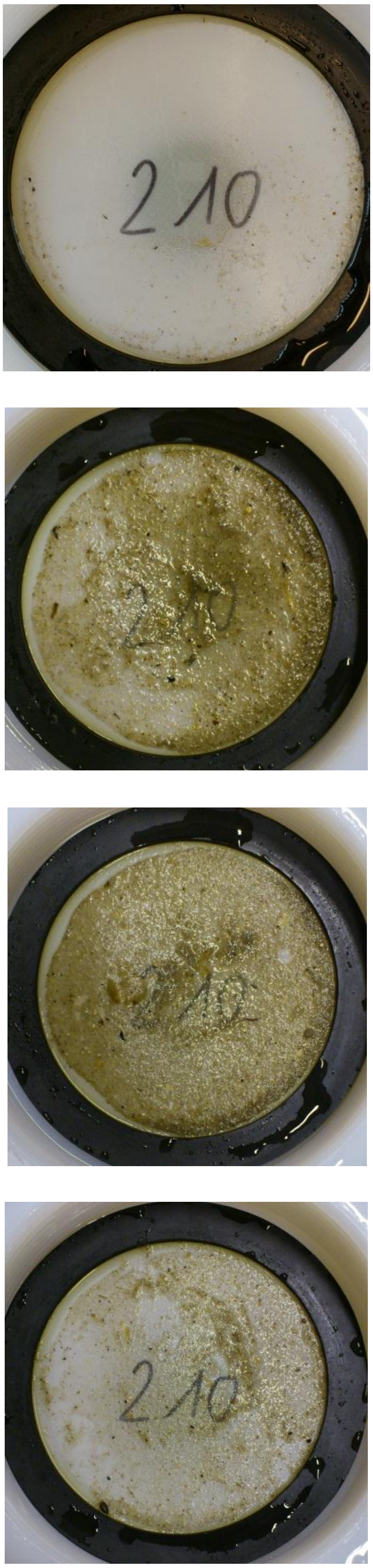
j	*R1* t_j'	t_j''	*R2* t_j'	t_j''	*R3* t_j'	t_j''
1						
2	2,1	42	6,3	126	-5,35	-107
3	4	-4	23,5	218	-3,1	152
4	10,35	131	32,35	-41	2,6	-38
5	8,7	-164	55,95	513	-0,35	-21
6	2,25	35	162,3	1614	0,75	43
7	8,75	95	268,2	504	1,45	-29
8	8,9	-92	332,5	782	-0,7	-14
9	2,2	-42			0,15	31
10	-3,05	-63			3,425	34,5
11	-6,2	0			5,15	0
12	29	704			1,125	-80,5
13	31,45	-655			-3,75	-17
14	-1,55	-5			0,15	95
15	1,2	60			1,4	-70
16	6,65	49			1,25	67
17	0,55	-171			4,4	-4
18	-2,7	106			0,6	-72
19	1,25	-27			1,2	84
20	-5,425	-106,5			4,625	-15,5
21	-10,75	0			3,85	0
22	-0,425	206,5			1,275	-51,5
23	68	1162			-6,85	-111
24	3,25	-2457			2,75	303
25	-66	1072			3,05	-297
26	-4,7	154			-1,8	200
27	2,85	-3			3,6	-92
28	40,3	752			-1	1,42E-12
29	23,05	-1097			3,5	90
30	-16,55	305			2,4	-112
31	-1,3	0			-3,2	0
32	3,3	92			3,9	142
33	-3,25	-223			0,35	-213
34	-0,4	280			0,9	224
35	6,65	-139			4,8	-146
36	-2,85	-51			-5,3	-56
37	-7,05	-33			-2,15	119
38					1,65	-43
39						

Table 2. First and second derivatives.

The results from the SS analyses are summarized in the table below.

	In (mg/l)	Out (mg/l)	Removal
R1	149	145	2,9 %
R2	158	162	-2,8 %
R3	238	192	19,6 %
R4	205	-	-
R5	-	164	-

Table 3. SS contents.



Picture series 3. Filter after *R1*, *R2*, *R3* and *R5*.

Discussion

Naturally, with a similar experiment setup to that for the first series, some of the same inaccuracies still apply. In addition the interchange between two graduated cylinders resulted in numbers so inaccurate that they could not be used for any analysis. The replacement of these with average values is undoubtedly a weakness, but an inspection of the numbers in table 2 reveals that no meaningful relation between the numerically derivatives for either run is found anyway. Hence, Hermia's equation cannot be used here to explore the prevailing fouling mechanisms. Of course, this should not be taken as a suggestion that the equation is not valid, but simply as a clear sign that the data are not accurate enough to obtain such information.

Yet, one interesting observation was made. The pressure difference of 14 cm (small in comparison to the corresponding value in the first series) seemingly resulted in a significant decrease in flow rate during cake filtration. This in spite of the observation that the cakes do not seem equally compact when compared to the ones in the first series. This could very well be due to the smaller pressure, which would be an interesting finding, but the wastewater characteristics are at the same time found to vary greatly throughout all experiments, so this cannot be asserted.

The SS samples taken are obviously not representative for the wastewaters since negative removal efficiency is found for *R2*. The analyses are presumably accurate (cf. appendix C), so the problem is most likely due to how the samples are taken. Since the sample bottles are small compared to the wastewater volume that is filtrated, several samples should have been taken for each inflow volume and each filtrate volume.

THIRD SERIES

Here, the pressure difference was increased with 7 cm from the previous series. Since this normally results in a greater flow rate, the time was taken for every litre, but the same graduated cylinders were still used.

- *Δh = 21 cm*
- *210 µm*

SS analyses of the inflow and filtrate from the first run were conducted. This time the samples were taken of gently stirred volumes from a plastic bucket.

The filter was washed in hot water between every run.

Results

The first two runs yielded no interesting results due to practical problems related to opening of the valve and interchanging of the cylinders, which was found more difficult for higher flow rates. For the two next runs, however, this was found to be less problematic, so these are the results that are reported.

The results are also here presented with the filtrate volume *V* in litres along the horizontal x-axis and the filtration time *t* in seconds along the horizontal y-axis.

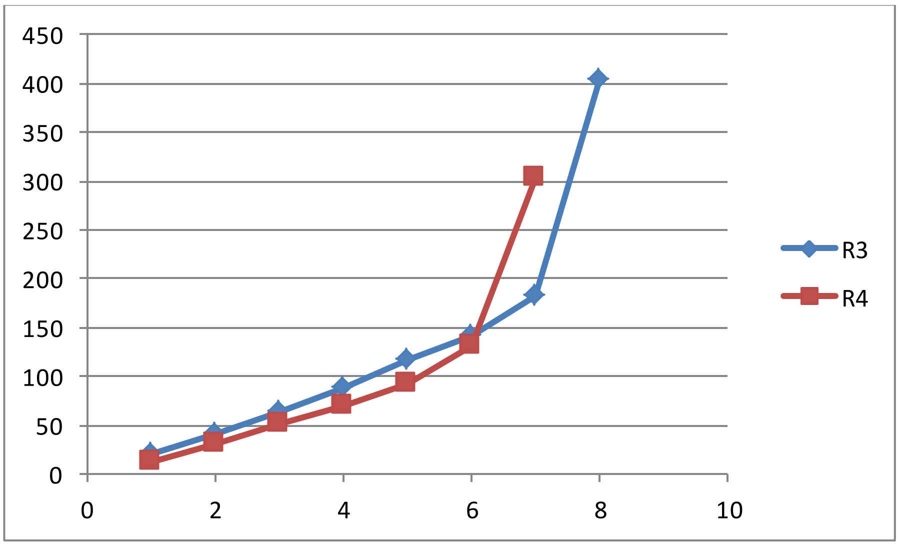


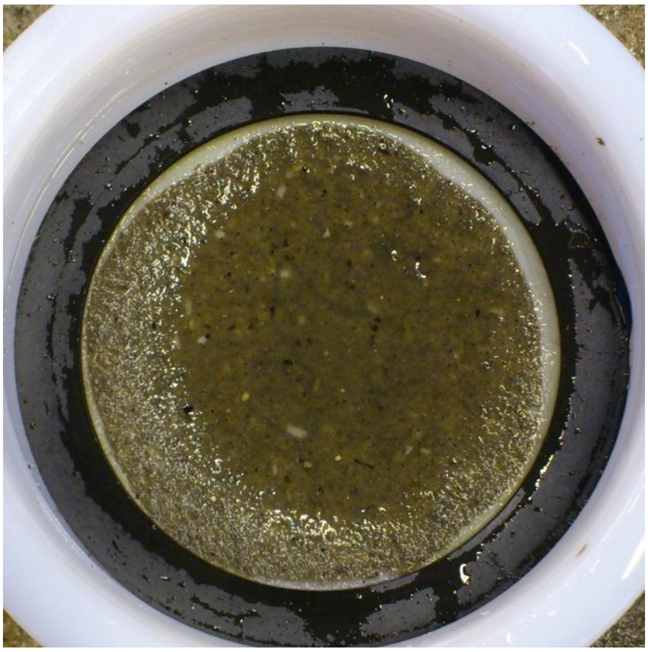
Figure 15. Filtration curves: *t(V)* [x: litres, y: seconds].

The first and second derivatives from the data are summarized in the table below.

j	*R3* t_j'	*R3* t_j''	*R4* t_j'	*R4* t_j''
1				
2	1,5	1	4	-6
3	1	-2	0	-2
4	3,5	7	1,5	5
5	0,5	-13	10	12
6	5,5	23	74	116
7	98,5	163		

Table 4. First and second derivatives.

Both runs resulted in significant cake formation that eventually resulted in complete clogging. (This was also the case for *R1* and *R2*.) The SS analyses indicated contents of 226 mg/l and 137 mg/l in the inflow and filtrate, respectively. This corresponds to a removal efficiency of 39.4 %.



Picture series 4. Filter after *R3* and *R4.*

Discussion

The observation that cake formation eventually resulted in complete clogging corresponds well with the observation of the two runs with most significant cake formation in the second series. The compactness of the cakes appears to be even more significant here. This series were run with a higher pressure difference than the second, but it cannot be asserted that more compact cakes is due to this when significant variations in wastewater characteristics have been found. However, the possibility that compact cakes result from high pressure difference should not be ruled out either.

Since the time was taken only for every litre, this resulted in few values t_j to analyse. The graphs clearly indicate when the clogging builds up in each case by a significantly steeper incline. The clogging is clearly due to surface deposit, i.e. cake filtration, but the data are not sufficient enough to reveal any clear relation between the first and second derivatives for neither run (cf. table 4), hence nothing about the initial fouling.

However, in the last interval (6–7) the second derivatives increase considerably with increasing first derivatives. By Hermia's equation (1), this is *not* in accordance with a cake filtration model ($n = 0$), but it is possible that surface deposit firstly occur late in the interval; thus, the effect would not be revealed numerically. The cake formation is evident (cf. picture series), so another possibility would be that the blocking index n as defined in (6) is not valid for Salsnes filtration.

FOURTH SERIES

The experiment setup was significantly modified for these runs in an attempt to obtain more detailed data. Firstly, the inflow to the wastewater tank in the laboratory was stopped prior to the first run to have a more stable wastewater characteristic during the entire series. (It was found necessary, however, to start up this inflow again prior to the fourth run.) Secondly, the filtrate volume was measured at constant time intervals; hence *V(t)* curves were obtained. During these runs, an assistant was responsible for time measuring. Thirdly, the valve (6) was completely opened in each run. Other than these three adjustments, the 'general methodology' was applied, but with overall greater accuracies, e.g. by marking points at hoses so they are connected similarly for each run. The two graduated cylinders with 1 litre capacity were used, interchanged by the person not responsible for time measuring.

Three different heights were tested, with steps of 3 cm. Five runs were carried out at the first height, two at the second height and one at the third.

- *Δh = 16, 19, 13* [*H1*, *H2*, *H3*]
- *210 μm*

SS samples were taken from collected volumes of inflow or filtrate.

Results

The filtration curves are here given with the filtration time in seconds along the *horizontal x-axis* and the filtrate volume in litres along the *vertical y-axis*. Hence, if these are to be compared with the filtration curves in the other series, it is stressed that different orientation of the concavity does in fact indicate the same tendency.

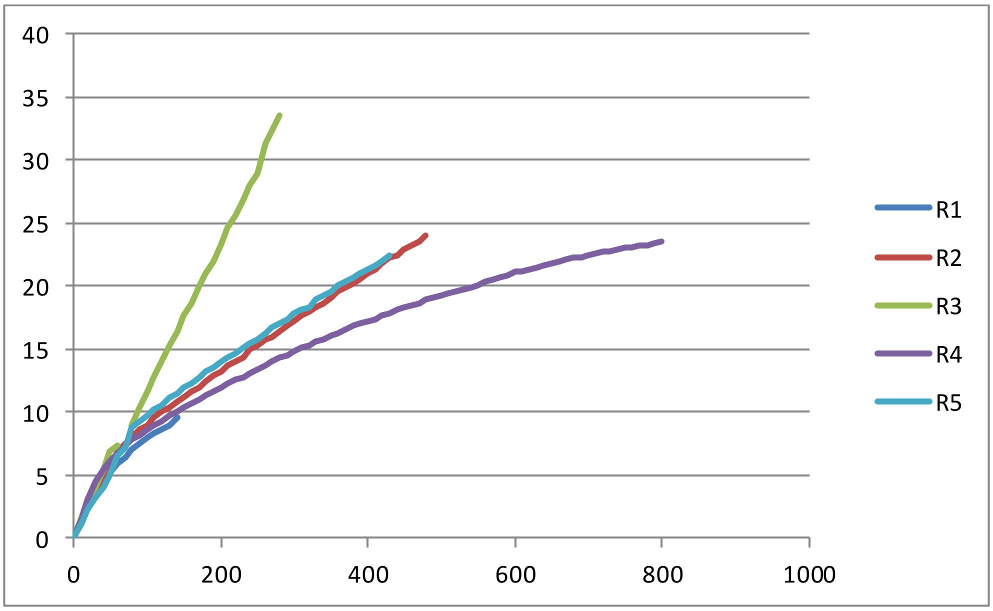


Figure 16. Filtration curves: *V(t)* [x: seconds, y: litres].

The filtrate volumes for the first 140 seconds (each interval: 10 seconds) of filtration are also given in the table below. It is found that the flow rates are decreasing for each run, except for *R3*.

i	$(\Delta V)_i$				
	R1	*R2*	*R3*	*R4*	*R5*
1	1,1	1,1	1,6	1,5	1,2
2	1,3	1,3	1,5	1,5	1,1
3	1,1	1,1	0,9	1,5	0,9
4	1,1	0,9	1,4	1	0,9
5	0,6	0,9	1,5	0,6	0,9
6	0,7	1,6	0,5	0,6	1,6
7	0,5	0,6		0,6	0,6
8	0,6	0,5		0,5	1,6
9	0,5	0,6	1,3	0,4	0,5
10	0,5	0,4	1,3	0,4	0,4
11	0,3	0,5	1,1	0,4	0,5
12	0,4	0,5	1,3	0,3	0,4
13	0,3	0,4	1,3	0,4	0,5
14	0,5	0,4	1,1	0,3	0,4

Table 5. Flow rates.

For the pressure difference of 19 cm (*H2*), it was succeeded to measure the flow rate only for the first run. During the second run under the pressure difference of 13 cm (*H3*), the outflow pipe from the sieve unit broke. Hence, only one run for each of these pressure conditions was carried out. In the figure below, these are compared with the average values from *H1*.

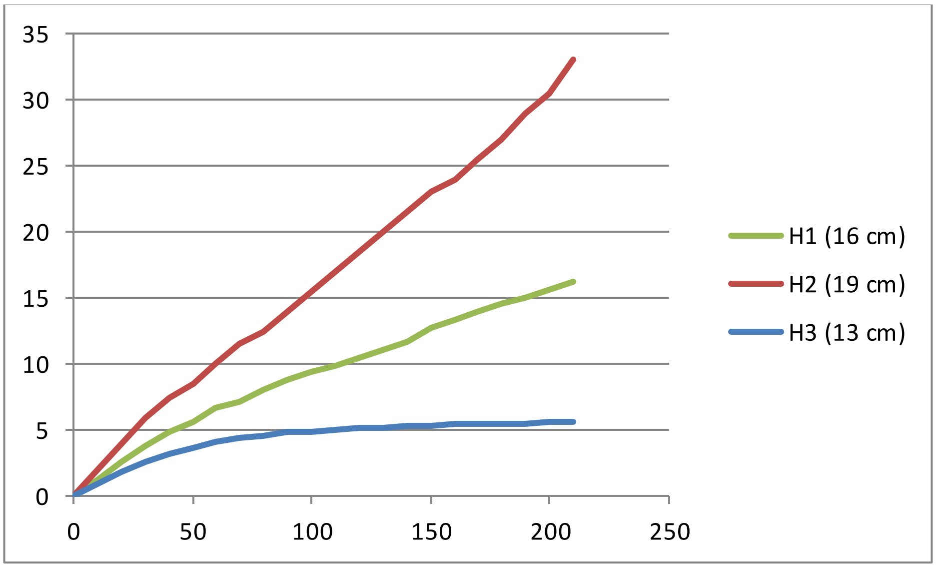


Figure 17. Filtration curves: *V(t)* [x: seconds, y: litres].

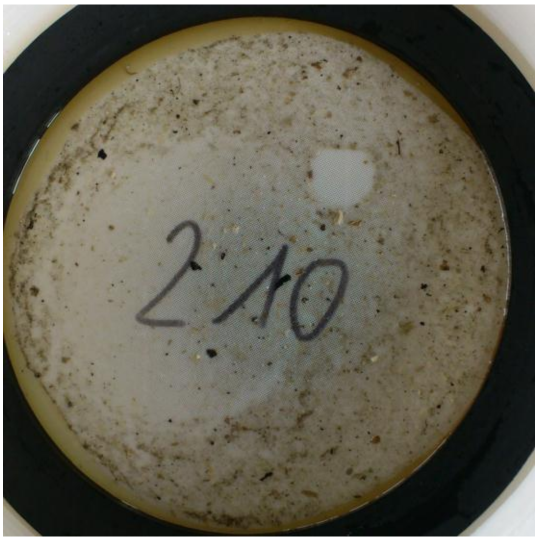
On next page the found SS contents are given in a table.

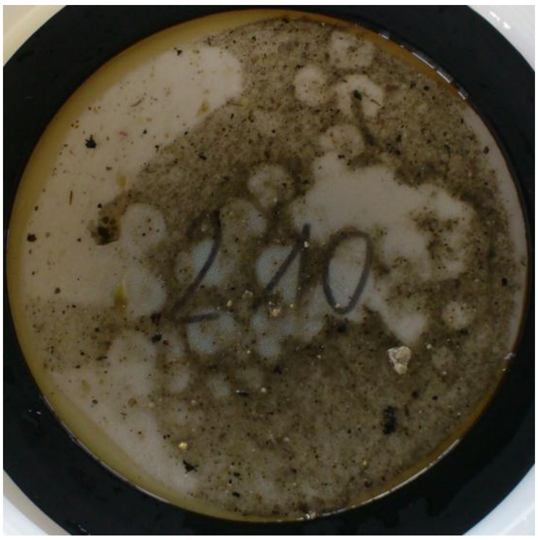
	SS (mg/l)	Removal
In	159	
H1 R1	142	11 %
H1 R2	109	32 %
H1 R4	103	35 %
H1 R5	99	37 %
H1 mean	113	29 %
H2 R1	65	59 %
H2 R2 b	113	29 %
H2 R2 e	94	41 %
H2 mean	91	43 %
H3	58	63 %

Table 6. SS contents.

'H1 mean' is the calculated average SS content of the filtrate samples from four of the runs under the first pressure condition. For the second run under the second pressure condition, *H2 R2*, two samples were taken, one for the first filtrate litre (indicated by *b*) and one for the last (indicated by *e*), in an attempt to determine the difference between pure sieving and cake filtration. By this it is seen that the removal efficiency is larger under cake filtration. The average SS content from the three samples of *H2* is also included in the table as 'H2 mean'.

No significant cake formation was observed during either runs (perhaps except from *H2 R2*; cf. picture series 6 below). A thin, inhomogeneous layer of particles was normally the result, but these layers were found to be highly permeable also when the pressure difference was increased by lowering the outflow (7) under draining of the sieve unit.





Picture series 5. Filter after $R1$, $R2$ and $R4$ (all $H1$).

Picture series 6. Filter after *R1* and *R2* (both *H2*).

Discussion

As expected, the greatest pressure difference (19 cm) resulted in the highest flow rate and the smallest pressure difference (13 cm) resulted in the lowest flow rate. However, the results under these two pressure conditions are based on only one run each, so it should be clear that this forms valid no basis for drawing conclusions. (Regardless, the observation that the flow rate and pressure difference are positively correlated is considered as a certain fact.)

The shapes of the three curves indicate that for smaller pressure differences, more significant decrease in filtrate low rate occurs. This corresponds well to what has been found during in the foregoing series. However, the surface deposits were considerably more moderate this time. This suggests that other factors are affecting the filtrate flow rate. It seems likely that the capacity of the overflow (5) is insufficient, so that a constant pressure is not maintained inside the sieve unit (4). This would imply that the feed pressure was affected by the water level in the tank (2)[6]. The curve for *H2* displays a rather constant flow rate, which could have been regarded as a proof to the contrary, but a greater flow out of the unit necessarily results in a smaller overflow under equal pump rates, thus smaller overflow capacity is required. Moreover, it should be noted that one of the curves under *H1*, namely *R3*, showed an equivalent development as the one run under *H2.*

The inflow to the wastewater tank was started again prior to the fourth run. This decision was made since no clear cake formation was observed during the three first runs. It seems likely that settling in the wastewater tank provided a certain level of pretreatment, dependent of the retention time, so the found treatment efficiencies cannot be classified as 'typical' for sieving, even if the samples would turn out as representative for the volume to be tested.

However, the difference in the SS content between the first and last filtrate litre for *H2 R2* is believed to be somewhat representative since these are resulting from filtration of the 'same' incoming wastewater. The inflow SS value of 159 mg/l is probably not correct for this run, but a possibly lower value would in fact yield greater difference in removal efficiency than 29 % to 41 %. Either way, this finding seems to at least partly confirm the basic assumption that high removal efficiencies are achieved due to fouling.

[6] From this, the assumption '*P = 0*' in the footnote on page 33 would not be valid. Hence, each experiment should have been characterized with the height difference Δz instead.

CONCLUSION

In this paper it has been attempted to better understand how Salsnes filtration should be operated. It was assumed that operation first and foremost had to take into account how fouling and cake filtration was affected by it, not only to the level of incoming wastewater. This assumption was not tested directly, however, but it is conceivable that it could a form the basis for further research. If the decreasing tendency in filtrate flow rate that was found in the fourth series of sieving is due to fouling, then this suggests that it is caused by other fouling mechanisms than surface deposit since no significant filter cakes were observed after the runs. Hence, the generalization in the basic assumption could be valid.

The conducted experiments were designed to reveal how the fouling development, cake filtration, filtrate flux and hydraulic resistance were related to the pressure difference between the feed side and the filtrate side on a sieve, the analogy to transmembrane pressure for membranes. The obtained experimental data are not appropriate for quantitative analyses. Therefore, this conclusion contains mainly suggestions that may be explored further and hints about implications that these may have for Salsnes filtration, this by connecting aspects from the theoretical and the experimental part.

Pressure effect on cake filtration

Relatively large pressure differences seemingly resulted in that the filtrate flux was less affected by cake growth. This is implied when the first series are compared with the three other. A thick cake would still enhance the treatment efficiency, so this would suggest that a certain pressure during operation is required.

In several experiments it was found that the filtrate flux decreased drastically when the pump was stopped. This is due to decrease in pressure difference, but the flux decrease was large and occurred quicker than what could have been expected. This suggests that small changes in the pressure conditions may cause relatively large difference in the amount of wastewater that is filtrated through a cake, thus affect the treatment efficiency to a significant degree (i.e. large effect of marginal pressure).

General recommendations for future work

The outlined experiment setup seems appropriate to test the effect of varying pressure differences, but the performance could be improved in future experiments.

- *Improved pump capacity*. To ensure that the filtration rate is not limited by the inflow.
- *Greater overflow capacity.* To ensure a constant water level in the sieve unit.
- *More accurate registering of filtrate flow.* To obtain better data for analyses. For instance, a digital weight could register this continuously.
- *Homogenous wastewater characteristics*. In order to compare the results from different runs to each other and treat the obtained data statistically, this seems necessary.

If more accurate data are obtained, these could reveal the initial fouling development by equation (9), if Hermia's equation (1) is found to be suitable for sieving and Salsnes filtration. These results could then be compared to experiments with Salsnes filtration to see how the fouling development is affected by rotation of the belt sieve, thus possibly under turbulent conditions. One hypothesis that could be tested is whether rotation, i.e. movement of the cloth perpendicular to the flow, promotes fouling by pore constriction. If at the same time pore constriction is found to result in higher levels of cake formation, as suggested by Hwang and Lin (2002), then it appears beneficial to pay special attention to this. Perhaps this could lead up to a "three mechanism model", similar to the one developed by Orsello, Li and Ho (2006).

Furthermore, this could explain the finding mentioned in the introduction, that too low frequency (2 Hz) resulted in low treatment efficiency. In other words, higher rotation speed (up to a certain point) promotes pore constriction that in turn promotes cake formation. Another possible explanation is outlined in the succeeding section.

Possible implications for Salsnes filtration

For low frequencies, it is presumed that a cake is formed on the lower part of the sieve belt, under relatively high pressure. It seems that this results in a rather compact cake with low permeability. When this cake subsequently is moved further up where the pressure is lower, this could result in very low flow through the cake, as implied in the above section regarding pressure effect on cake filtration. Prior to this thesis it was questioned whether a high pressure would break up the cake, but it seems that this possibility can be ruled out.

Furthermore, this consideration may also have implications for the choice of mesh size. If finer mesh results in quicker establishment of a cake, which intuitively seem like an advantage, this could at the same time result in a less permeable cake since it would be established under higher pressure. By the 'path of least resistance', more wastewater would then filtrate through the cleaner part of the belt sieve further down on the feed side.

This seems to represent a significant challenge in the aim towards "optimum performance": the cleanest part of the sieve belt, thus the part with lowest resistance, experiences the largest pressure difference. The 'path of least resistance', thus also Darcy, hence predicts that most of the wastewater filtrates through this part. Ho and Sydney (2000) suggest that this could be taken care of by cake growth as a "self-leveling process", but it seems uncertain if a rotating sieve belt allows for 'self-leveling cake growth' in the same manner as a stationary membrane.

Hence, it may seem that the main objective behind Salsnes filtration is to facilitate uniform flux, to the extent possible, over the entire wetted sieve area (A_0). By Darcy, this would require a constant ratio between ΔP and R. When R presumably increases up along the belt sieve due to thicker cake, this means that ΔP also must do so. It may seem difficult to achieve this by simple means, but to strive for a smallest possible decline in the ratio might still prove advantageous.

APPENDICES

A: PRIMARY TREATMENT

EU primary treatment objectives

In the Urban Waste Water Directive (Council Directive, 1991) the following is stated.

> 'Primary treatment' means treatment of urban waste water by a physical and/or chemical process involving settlement of suspended solids, or other processes in which the BOD_5 of the incoming waste water is reduced by at least 20 % before discharge and the total solids of the incoming waste water are reduced by at least 50 %.
>
> [Page 42]

By article 4 (1), it is required that urban wastewater from agglomerations of 10 000 population equivalents[7] (p.e.) and above, and for discharges to fresh-water and estuaries from agglomerations of 2 000 p.e. and above, undergoes secondary treatment before discharge. However, 4 (2) allows for "less stringent" treatment under conditions where effective biological treatment is difficult to apply. Under such conditions, the maximum concentration of total suspended solids is set to 60 mg per litre. In the Norwegian guidelines (Ødegaard *et al*, 2009) this limit applies as an additional primary treatment requirement. A maximum concentration for BOD_5 of 40 mg O_2 per litre is also given. Hence primary treatment plants are evaluated on the basis of these values, repeated in the table below.

	Min. reduction [%]	Max. concentration [mg/l]
BOD_5	20	40
TSS	50	60

Østerhus (2011b) mentions sieving, sedimentation, floatation and depth filtration as relevant separation methods for primary treatment. It seems that sedimentation is the

[7] 1 p.e. corresponds to a BOD_5 of 60 g O_2 per day

most common solution. Rusten and Ødegaard (2006) support this claim by stating that "historically, primary treatment has been synonymous with sedimentation in clarifiers".

Pre-treatment

In the Norwegian guidelines (Ødegaard *et al*, 2009), it is stated that pre-treatment normally consists of screens, sand trap and possibly grease trap. Sedimentation preceding biological or chemical treatment, pre-sedimentation, can also be seen as a type of pre-treatment. Østerhus (2011a) recommends particle removal by enhanced primary treatment as the first step in his "wastewater treatment philosophy". Hence, the term 'primary treatment' is also used to describe pre-treatment.

It should be noted that Østerhus (2011b) mentions that "fine sieve plants may be beneficial as pre-treatment for more advanced plants".

B: MEMBRANE TECHNOLOGY

Leiknes (2010b) uses the following definition of a membrane.

> A membrane is a permselective barrier, or interface between two phases, and the separation process takes place due to a specific driving force transporting a compound through the membrane from one phase to the other.
>
> [Page 1]

Similar to the case with Salsnes filtration, membrane separation is not always regarded as filtration since the capture and separation of particles occurs on a surface layer. Hence, the term *membrane technology* is used. Membranes are often classified with respect to their pore sizes, as given in the following list.

- Microfiltration (MF): 0.1–5 μm[8]
- Ultrafiltration (UF): 0.01–0.1 μm
- Nanofiltration (NF): 0.001–0.01 μm
- Reverse osmosis (RO): 0.0001–0.001 μm

(The Membranes Research Environment)

Note that these numbers vary in different sources. The Membranes Research Environment defines the different types of membrane filtration with respect to pore size, which gives a non-overlapping range that indicate which particles are removed in the respective membrane category by the relevant particle size. I should be noted that this is not always the case. Leiknes, for instances, uses an overlapping range.

[8] 1 μm = $1 \cdot 10^{-6}$ m

C: SS ANALYSES

The suspended solids content in a sample was found by weighing. The procedure is outlined below.

1. The wastewater sample was collected by different means in sample bottles that could hold roughly 200 ml.
2. Before each analysis, the bottle was turned in an attempt to have the particles equally distributed throughout the sample.
3. A certain volume of each sample was carefully metered using a graduated cylinder with reading marks for every millilitre. Each volume was written down.
4. The volume was then filtrated through filters able to retain particles larger than 1.2 µm. Each filter had been weighed accurately on beforehand. The weighing included three filters for measuring of initial water content due to air moisture.
5. To remove water, the filters were put in a drying oven overnight.
6. The filters were again weighed. The weight difference minus the found initial water content was ascribed to the particle content in the samples. The same weight was used. (The accuracy of the weight that was used is 0.0001 grams.)
7. The SS content was then found by dividing the particle weight of a sample by the filtrated volume (see step 2).

Undoubtedly, the most significant source of error is found in step 1, as discussed in relation to the experiments. If each filtered volume (step 4) is in fact representative for the sample could be questioned, but this is probably of minor significance.

The calculated values are found in the table below. Three of the samples were not marked properly, which is the reason why some cells are left blank. Two of these are ‘H3 R2 Out’ and ‘H3 R3 Out’, but which two are uncertain.

Sample				SS (g)	V (ml)	SS (mg/l)
Inflow 1	0,1236	0,1232	0,1298	0,0066	50	131
Inflow 2	0,1249	0,1245	0,1295	0,0050	90	55
Outflow 1	0,1237	0,1233	0,1322	0,0089	68	130
H2 R1 In	0,1230	0,1226	0,1310	0,0084	56	149
H2 R1 Out	0,1243	0,1239	0,1309	0,0070	48	145
H2 R2 In	0,1234	0,1230	0,1314	0,0084	53	158
H2 R2 Out	0,1240	0,1236	0,1324	0,0088	54	162
H2 R3 In	0,1230	0,1226	0,1355	0,0129	54	238
H2 R3 Out	0,1241	0,1237	0,1335	0,0098	51	192
H2 R4 In	0,1228	0,1224	0,1331	0,0107	52	205
H2 R5 Out	0,1240	0,1236	0,1330	0,0094	57	164
H3 R1 In	0,1219	0,1215	0,1333	0,0118	52	226
H3 R1 Out	0,1220	0,1216	0,1289	0,0073	53	137
	0,1225	0,1221	0,1299	0,0078		
	0,1255	0,1251	0,1296	0,0045		
	0,1243	0,1239	0,1325	0,0086		
In	0,1233	0,1229	0,1312	0,0083	52	159
H12 R5	0,1238	0,1234	0,1287	0,0053	53	99
H12 R1	0,1236	0,1232	0,1313	0,0081	57	142
H12 R2	0,1238	0,1234	0,1292	0,0058	53	109
H12 R4	0,1246	0,1242	0,1302	0,0060	58	103
H22 R1	0,1235	0,1231	0,1265	0,0034	52	65
H22 R2 b	0,1222	0,1218	0,1283	0,0065	57	113
H22 R2 e	0,1264	0,1260	0,1313	0,0053	56	94
H32	0,1232	0,1228	0,1261	0,0033	56	58

Blind sample				
109	*0,3725*	*0,3714*	*0,0011*	*0,000367*

Table 7. SS content in all samples.

BIBLIOGRAPHY

Aarseth JB (2009). *Numeriske beregningsmetoder*. Konstruksjonsteknikk, Norwegian University of Science and Technology, Trondheim, Norway.

Blankert B, Betlem BHL & Roffel B (2006). Dynamic optimization of a dead-end filtration trajectory: Blocking filtration laws. *Journal of Membrane Science 285* (1–2), 90–95.

Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment. *Official Journal of the European Communities*. (L135) 40–52.

Droste RL (1997). *Theory and practice of water and wastewater treatment*. Hoboken, New Jersey: John Wiley & Sons, inc.

Grenier A, Meireles M, Aimar P & Carvin P (2008). Analysing flux decline in dead-end filtration. *Chemical Engineering Research and Design, 86* (11), 1281–1293.

Hermia (1982). Constant pressure blocking filtration law—application to power-law non-Newtonian fluids. *Transaction of the Institution of Chemical Engineers 60*, 183–186.

Ho & Sydney (2000). A combined pore blockage and cake filtration model for protein fouling during microfiltration. *Journal of Colloid and Interface Science 232* (2), 389–399.

Hwang KL, Liao CY & Tung KL (2007). Analysis of paticle fouling during microfiltration by use of blocking models. *Journal of Membrane Science 287* (2), 287–293.

Hwang KL & Lin TT (2002). Effect of morphology of polymeric membrane on the performance of cross-flow microfiltration. *Journal of Membrane Science 199* (1–2), 41–52.

Leiknes TO (2010a). *Filtration*. Unpublished manuscript, TVM 4145, Norwegian University of Science and Technology, Trondheim, Norway.

Leiknes TO (2010b). *Membranes*. Unpublished manuscript, TVM 4145, Norwegian University of Science and Technology, Trondheim, Norway.

Paulsrud B (2000). *Salsnes Filter fine mesh sieves for primary treatment – performance test at Tiendeholmen WWTP* (Report No. 00-045). Oslo: Aquateam.

Orsello CD, Li W & Ho CC (2006). A three mechanism model to describe fouling of micro-filtration membranes. *Journal of Membrane 280* (1–2), 856–866.

Rusten B & Ødegaard H (2006). Evaluation and testing of fine mesh sieve technologies for primary treatment of municipal wastewater. *Water Science & Technology, 54* (10), 31–38.

Salsnes Filter (a). *Salsnes Filter demo*. Retrieved February 21, 2012, from http://www.salsnes-filer.com/public.aspx?pageid=44700.

Salsnes Filter (b). *Products*. Retrieved February 22, 2012 from http://www.salsnes-filter.com/public.aspx?pageid=44549

Salsnes Filter (b). *SF models*. Retrieved February 24, 2012 from http://www.salsnes-filter.com/public.aspx?pageid=44701

The Membranes Research Environment (n.d.). *Pore size*. Retrieved March 30, 2012 from http://www.membranes.edu.au/wiki/index.php/Pore_Size#Microfiltration_.28MF.29

Tien C (2002). Cake filtration research—a personal view. *Powder Technology 127* (1), 1–8.

Tracey EM & Davis RH (1994). Protein Fouling of Track-Etched Polycarbonate Microfiltration Membranes. *Journal of Colloidal and Interface Science167* (1), 104–116.

Ødegaard H, Rusten B, Storhaug R & Paulsrud B (2009). *Veiledning for dimensjonering av avløpsrenseanlegg* (Report No. 168–2009).Hamar, Norway: Norsk Vann.

Østerhus SW (2011a). *2b Wastewater characteristics*. Unpublished manuscript, TVM 4126, Norwegian University of Science and Technology, Trondheim, Norway.

Østerhus SW (2011b). *3 Primary treatment*. Unpublished manuscript, TVM 4126, Norwegian University of Science and Technology, Trondheim, Norway.