A rotary drum filter as pre-treatment for a membrane bioreactor - operation, evaluation and optimization

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A ROTARY DRUM FILTER AS PRE-TREATMENT FOR A MEMBRANE BIOREACTOR – OPERATION, EVALUATION AND OPTIMIZATION.

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ABSTRACT

The study focuses on the optimization of the rotary drum filter performance as a primary, mechanical treatment of wastewater prior to the membrane bioreactor process. The examination and optimization of suspended solids (SS) separation efficiency by the drum filter and the dry solids content in the primary sludge were of the highest interest. Additionally, effectiveness of two different treatment strategies on aerobic line 2 at the Hammarby Sjöstad Wastewater Treatment Plant was compared and evaluated. The condition of mixed liquor from MBR was examined. The tests on the rotary drum filter showed that removal of suspended solids was more effective at the high backwashing sensor level. However a desirable SS concentration, below 100mg/l, in the effluent from the drum filter was not reached. In order to improve SS removal efficiency, a high-molecular cationic polymer as a flocculation agent was tested. Full scale polymer tests showed that it is possible to achieve over 60% of SS reduction and reach a desirable SS concentration in the effluent.

Optimization of the drum filter operational parameters enabled to reach the dry solids content in the primary sludge of 4%, a value that comply with the Hammarby Sjöstad WWTP goal. Comparison of different treatment strategies on line 2 revealed that the application of the reverse osmosis process as a last treatment step resulted in production of water that met standards posed in Hammarby Sjöstad environmental plan (N≤6mg/l, P≤0.15mg/l).

Oxygen uptake rate tests executed on the mixed liquor from the MBR indicated that mixed liquor was in a good condition and that was able to deal with highly loaded influent. Large population of Nitrosomonas bacteria was present in the activated sludge.

Key words: rotary drum filter; membrane bioreactor; membrane filtration technology; reverse osmosis; wastewater treatment.

1. INTRODUCTION

Hammarby Sjöstad is a newly created district in the central Stockholm. It has been the largest urban development project in Stockholm for many years. The old industrial and docklands area has been transformed into a modern, ecologically sustainable urban environment. When finished in 2012 it will constitute of 9 000 apartments for about 20 000 residents. Altogether 30 000 people are expected to live and work in the area.

Very ambitious environmental goals have been imposed on the project. The overall task is to lower the impact placed on the environment by emissions from the Hammarby Sjöstad district by 50% compared to corresponding levels for newly constructed housing areas dating from the early 1990s.

Hammarby Sjöstad has an eco-cycle model for managing energy, waste and sewage known as the Hammarby Model. Energy based on renewable fuels is produced in a district heating plant located in the area. Combustive waste is also recycled in the form of heat. Storm water is cleaned locally not to overload the wastewater treatment plant.

As far as water and wastewater is concerned the overall goal is to lower the consumption of potable water by 50%. Furthermore nitrogen and phosphorus concentrations in treated wastewater must follow strict standards. Reuse of nutrients, efficient utilisation of chemicals and energy are of the highest interest. To meet these goals the new technologies have been developed and tested in the Hammarby Sjöstad pilot treatment plant. As the result of the research a full-scale treatment plant for about 15 000 people will be constructed using the best available technology.

1.1. Objectives of the thesis

This thesis aims at optimization of treatment on line 2 at the Hammarby Sjöstad pilot wastewater treatment plant. It will include optimisation of:

- suspended solids separation efficiency by the drum filter
- dry solids content in sludge produced by the drum filter

but also examination of:

- condition of mixed liquor from the membrane bioreactor
- performance effectiveness of different line 2 configurations

2. BACKGROUND

2.1. Hammarby Sjöstad pilot wastewater treatment plant

The main goals imposed on the Hammarby Sjöstad treatment plant are: to reduce the nitrogen content in the treated wastewater to 6 mg/l and the phosphorus content to 0.15 mg/l, recycle 95% of the phosphorous and reuse for agricultural purposes, and finally to decrease the concentration of heavy metals and other harmful components by 50%.

To meet these goals the new technologies have been developed and tested in the Hammarby Sjöstad pilot treatment plant. It is a small-scale plant that has been built to treat sewage from 600 - 1 000 people. It consists of four lines treating sewage in a different manner using the latest technology. The first two are aerobic and the last two are anaerobic lines. The idea is to
examine and compare effectiveness of three major treatment strategies which are: aerobic processes, anaerobic processes and separation processes including membrane and filtration techniques. Performance of four parallel treatment lines is also to be compared with the conventional methods used at Henriksdal wastewater treatment plant (Paques, 2003).

The wastewater coming from Hammarby Sjöstad has different characteristics than other municipal wastewater since it is not mixed with storm water. It contains relatively high concentrations of nutrients and organic matter but low amounts of heavy metals and other hazardous compounds. There is also wastewater from Henriksdal WWTP to be tested in the pilot plant. The characteristics of wastewater coming to the pilot plant and influent to Henriksdal WWTP are given in table 1. The consequence of the evaluation of different treatment methods will be construction of local wastewater treatment plant for Hammarby Sjöstad that can handle high flows of sewage with maximum effectiveness and possible minimum area occupation.

2.2. Aerobic treatment - line 2

Line 2 utilizes aerobic methods for wastewater treatment. In the preliminary treatment, as the first step, screens and grid chamber are used to remove sand, gravel, sticks and other large objects to protect pumps and other equipment at the plant.

In the second step, the primary treatment, the goal is to reduce suspended solids as well as lower the phosphorous concentration by chemical precipitation. Traditionally it is performed in sedimentation tanks. However in line 2 Hydrotech rotary drum filter is used instead of primary sedimentation tank to separate suspended solids from wastewater. The advantage of a drum filter is its high effectiveness and low footprint.

The next step, called secondary treatment, includes a biological treatment process to remove dissolved organic matter and nutrients from wastewater. Here a membrane bioreactor (MBR) process has been applied. A process combines membrane technology with a biological technology. Membrane separation with Kubit-micro filter of 0.4 µm pore size is used to replace the conventional secondary sedimentation tank.

Under the research period sludge did not undergo any treatment. The primary sludge from the drum filter was thickened and dumped together with excess biomass from the MBR reactor.

### Different treatment strategies

**First scenario**

In the first scenario, the line comprised of the rotary drum filter as a primary treatment and membrane bioreactor as a biological step (Fig. 1). There was a UCT (University of Cape Town) process for combined nitrogen and phosphorus removal applied in the MBR.

In the UCT process a sequence of anaerobic, anoxic and aerobic steps is used to achieve both nitrogen and phosphorous removal. Nitrogen is removed by nitrification-denitrification. Nitrification is performed in the aerobic zone by two groups of chemosynthetic bacteria: the Nitrosomonas group that oxidizes ammonia to nitrite and the Nitrobacter group subsequently converts nitrite to nitrate. The biological process of denitrification transforms nitrate into nitrogen gas. It is achieved when heterotrophic bacteria use oxygen from the nitrate for organic carbonaceous oxidation. The process is performed in the anoxic zone, with absence of oxygen but presence of nitrate.

Biological phosphorous removal is accomplished by accumulation of polyphosphates in bacteria and subsequently wasting the sludge from the system. The bacteria must be exposed to anaerobic and aerobic conditions. Under anaerobic conditions bacteria hydrolyze accumulated polyphosphates and use released energy to absorb easily biodegradable organic matter. Under aerobic conditions the organic matter stored in the organisms is used for growth and to synthesize new polyphosphates.

Since complete nitrogen removal (nitrification/denitrification) was required under UCT process, an anoxic zone with recycle from the aerobic activated sludge tank received the wastewater to be treated first.

**Second scenario**

The second strategy combined the rotary drum filter and the membrane bioreactor with the one-step reverse osmosis plant as a final stage of wastewater treatment (Fig. 2). MBR configuration was changed in order to obtain water highly loaded with nutrients that was to be directed into the RO plant. To meet these requirements the drum filter effluent was pumped directly to the aerobic zone, bypassing anaerobic and anoxic zones. That MBR configuration enabled to oxidize organic matter without biological nitrogen and phosphorus removal.

**Table 1. The characteristics of wastewater from Hammarby Sjöstad and influent to Henriksdal WWTP (Björlenius, Hellström 2002).**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Hammarby Sjöstad influent [mg/l]</th>
<th>Henriksdal influent [mg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>560</td>
<td>430</td>
</tr>
<tr>
<td>BOB</td>
<td>260</td>
<td>190</td>
</tr>
<tr>
<td>Tot-N</td>
<td>70</td>
<td>38</td>
</tr>
<tr>
<td>Tot-P</td>
<td>10</td>
<td>6.3</td>
</tr>
<tr>
<td>Cd/P</td>
<td>23</td>
<td>5</td>
</tr>
</tbody>
</table>
The biological removal of nitrogen was hindered as the denitrification process could not be performed in case of lack of the anoxic conditions. However the nitrification could no be avoided due to the high sludge age. The high sludge age meaning the high mixed liquor suspended solids concentration of 16 - 17g/l, was the measure undertaken to control the oxygen concentration in the aerobic zone. As the consequence, the RO plant was fed with water containing nitrogen mainly in form of nitrate.

Exclusion of the anaerobic zone in the MBR allowed maintaining high phosphorous concentration in the soluble form in the MBR effluent.

2.3. Rotary drum filter

Surface filtration is a type of filtration that is used to remove particulate material suspended in a liquid by mechanical sieving by passing the liquid through a thin septum i.e. filter material.

A rotary drum filter is a cloth-medium surface filter. It can be of two types: vacuum or pressurised. Rotary filters are capable of meeting a wide range of moderate and slow setting liquid/solid separation requirements in process industries, foodstuffs, mineral engineering, and effluent treatment plants right down to laboratory sizes. They are used for filtering intake water from streams and lakes for municipal and industrial water supply systems. Furthermore they have found applica-
tion in fish farming systems where it is essential to prevent particles from fragmentation. Other applications are in plastic industries, power plants and breweries. In municipal wastewater treatment plants they are used for polishing effluent or can replace primary or secondary clarifiers (Hydrotech, 2005).

Drum filters have continuous operation with high wash efficiency at the low specific power requirements. They can be used with a wide range of cloths or filter beds and with various discharge methods for solids of various consistencies (Dickenson, 1992).

The rotary drum filter, model 801 manufactured by Hydrotech with the cloth of 100µm pore size is used in line 2 at Hammarby Sjöstad pilot plant (Fig. 3).

The operational principle is the continuous separation of solids attached to a screened surface perpendicular to wastewater flow. The device consists of a rotating drum whose body is covered with a screen made of polyester. Wastewater enters axially at open side of the drum and goes out radially through the screen by gravity. When the wastewater level inside the filtration chamber increases due to progressive screen clogging, reaching the sensor level, a sensor initiates the drum rotation and the screen backwashing, spraying water or air at high pressure over the opposite surface of the screen. The backwash water loaded with the solid deposits is collected in a gutter and transported by the screw out of the filter. There is also a second, alarm sensor installed inside the filter that initiates backwashing only with water when the main sensor fails (Fig. 4).

2.3.1. Cake filtration

During the filter operation and its exposure to the wastewater flow, two effects take place (Petersson 2004). The first one is a gradual reduction of the effective pore size of the medium, as some of the pores are partially blocked by particles so the filter becomes more efficient in removing fine particles. This can be caused by the retention of small particles within the pores by adsorptive forces. The second effect that takes place is the building up the cake (thick layer) of trapped particles on the media surface. Sludge cake itself functions as a filter which traps the smaller particles (Dickenson, 1992). Building up the sludge cake contributes to the increase of filtering resistance and decrease of the flow through the filter. When the flow is severely constrained due to the thickness of the cake it is removed by the backwashing.

2.4. Membrane filtration technology

Membrane processes have become a significant separation technology over the past three decades giving alternative to conventional techniques. Its application ranges from wastewater, potable water and process water treatment, pharmaceuticals production, food and beverages processing, power generation to separation processes applied in manufacturing of chemicals, fuels, electronics and many other products.

Membrane filtration includes number of different separation processes which are classified according to the size of separated species into four major groups (Fig. 5). For the removal of small particles, large colloids and microbial cells smaller than 10mm microfiltration (MF) is used. Ultrafiltration (UF) is used to separate emulsions, colloids, macromolecules and proteins smaller than 100nm. Nanofiltration (NF) is applied to separate antibiotics of size under 10 nm and ions like heavy metals. Finally reverse osmosis (RO) is used to separate dissolved salts and organics under 1 nm (Bergström et al. 2000).

The principle of membrane process is an existence of two bulk phases separated by the third one, the membrane. Membrane is an interphase between two bulk phases that acts as a filter which is selective to one of the species in the mixture. The movement of species across the semi permeable membrane is possible thanks to one or more driving forces. Those driving forces can be either chemical potential due to a concentration gradient, pressure gradient, or electrical potential (Sirkar, Winston Ho et al. 1992).

2.4.1. Membrane Bioreactor (MBR)

A membrane bioreactor is a system that combines activated sludge (mixed liquor) process with a microfiltration or ultrafiltration. Treated water is separated from purifying bacteria (activated sludge) by filtration through the membrane. A membrane process replaces the conventional secondary sedimentation normally used in activated sludge process.
The MBR can find many applications for example drinking water, industrial wastewater, landfill leachate, domestic wastewater, food and beverages processing, fabrication of cosmetics and metals, and in other industries. Currently it is mainly used for small capacity industrial waste plants. There are still not many such installations for municipal wastewater treatment. Several studies have shown that MBR is suitable for pretreatment of wastewater before reverse osmosis process.

There are two possible MBR configurations. One is the module that can replace clarifier downstream of the bioreactor (in-series). The other is directly submerged within the bioreactor. In-series MBRs typically utilize ultrafiltration membranes of various configurations. Submerged MBR is a system which typically uses shell-less capillary or hollow fiber microfiltration membranes with pore size between 0,1 and 0,4 µm (Cote et al. 1997). The terms related to MBR membrane filtration processes can be divided into two categories: membrane characteristics and filtration process (Van Der Roest, Lawrence & Van Bentem 2002).

**Membrane characteristics**

The flow of liquid through a specific membrane surface area is called flux and can be expressed by the following equation:

\[
\text{Flux} \left[ l / (m^2 * h) \right] = \frac{\text{permeate flow} \left[ l / h \right]}{\text{membrane surface used} \left[ m^2 \right]}
\]

To generate a flow through the membrane the liquid must have an associated driving force – a pressure drop. Pressure drop gives rise to two pressure points, static pressure at zero permeate flow and dynamic pressure with pressure flow. Trans-membrane pressure (TMP) can be determined from those two pressures:

\[
\text{Permeability} \left[ l / (m^2 * h * \text{bar}) \right] = \frac{\text{flux} \left[ l / (m^2 \text{bar}) \right]}{\text{TMP} \left[ \text{bar} \right]}
\]

The flux and TMP define the operating range of a membrane and must be related to the operating temperature. When the flux is divided by the TMP, the specific flow rate through a specific surface area for a particular pressure drop can be calculated. That is called permeability and can be expressed as:

The permeability at a given time describes the condition of the membrane in operation. The parameter is used to establish the onset of required cleaning for the
system being operated at the constant flow (constant flux). Process conditions and biological process influence the permeability. Permeability is a membrane characteristic and should not be confused with filterability which is sludge characteristic.

Temperature is an important factor in assessing membrane performance as it influences the viscosity of permeate and concentrate (biomass in the MBR). With the decreasing temperature, the water viscosity increases which causes the increase of the driving force or TMP needed to achieve the required flux, thus reducing permeability.

Fouling is another important factor that affects the membrane performance. Two types of fouling can be distinguished: macro (surface fouling) and micro (pore fouling). The macro fouling is caused by building up of solids on the membrane surface due to too high solids-flux toward the surface. As a consequence the pores are clogged and the surface available for filtration is reduced. Inorganic scaling can also take place forming non porous layer or scale over the surface. In the micro scale the pores can be blocked by soluble organic material. Scaling can also take place at the microscopic level. In that case pores are used as active sites for further, prolonged precipitation.

### Filtration process

During a process mode permeate is extracted from the bioreactor and membrane is aerated with coarse bubbles to keep solids from building up on the membrane. This process is interrupted with in-situ cleaning mode. Some membranes require a relaxation mode to stabilize the surface solids’ flux. The relaxation is a stop of permeate flow for a short period in order to return the elastic membrane to its original relaxed state. During relaxation the membrane is often aerated to remove solids build up on the membrane. Other membranes can utilize a back pulse mode when the permeate is stored in a Clean In Place (CIP) tank and used to flush the membrane in the opposite direction to the filtration.

Cleaning process can be divided into: maintenance clean (MC) and intensive clean (IC). Maintenance clean is a preventive, frequent cleaning with low chemical concentrations to prolong time between IC.

\[
\text{TMP [bar]} = \text{static pressure [bar]} - \text{dynamic pressure [bar]}
\]

Intensive clean is performed to return a membrane back to its original permeability after long operation using higher chemical concentrations and longer contact time than applied in MC. All membranes can be cleaned with chemicals. The chemicals being used are: sodium hypochloride (NaOCl), sodium hydroxide (NaOH), citric acid, hydrochloric acid (HCl).

### 2.4.2 Membrane bioreactor vs. conventional activated sludge process

Biological treatment of wastewater aims at removing non-settleable solids dissolved organic matter and carbonaceous biochemical oxygen demand (BOD). It is performed by populations of microorganisms which degrade organic matter by metabolizing it into gases and cell tissues that are removed from water by gravity separation.

One of the most common conventional biological treatment methods is activated sludge process where aerobic microorganisms are in a floc matrix in the aerated wastewater suspension. Organic matter is oxidized to carbon dioxide and water. Sludge containing microbes and non-biodegradable suspended solids is produced. Suspended biomass is subsequently separated and partially recycled.

A membrane bioreactor constitutes of an activated sludge process and ultra- or microfiltration membrane module instead of clarifier. Membrane acts as a barrier that captures biomass that can be reincirculated inside the bioreactor. The benefits of MBR process over conventional activated sludge process include: better solid removal (elimination of bulking), disinfection, reduced sludge production and development of slowly growing microorganisms such as nitrifying bacteria due to the high sludge age, increased volumetric loading, and retention of molecular compounds with high molecular weight contributing to better biodegradation. Last but not least MBR is very compacted process due to elimination of secondary sedimentation (Adham, Gagliardo 1998).

In optimization of conventional activated sludge process the key role constitutes kinetic decomposition of the organic matter by microbes and creation of flocs with effective settling characteristics. In order to achieve desirable effluent quality standards, sludge age ($\theta_s$) and loading rate called food-to-microorganism ratio (F/M) related to substrate utilization rate (U) of the reactor are factors that must be considered. To produce stable effluent of a high quality and sludge with good settlings characteristics, sludge age should oscillate between 5 and 15 days and F/M values from 0.05 to 1.5d$^{-1}$. Unlike conventional process, activated sludge formed in the MBR has significantly different characteristics. The range of $\theta_s$ and F/M values for membrane bioreactor is considerably different. In this process $\theta_s$ value often exceeds 30 days and F/M ratio falls usually below 0.1d$^{-1}$. In conventional reactor the range of those parameters observed for MBR would lead to sludge production of poor settling properties. However, in MBR process it is not a concern because filtration through the membrane effectively separates biosolids and the effluent quality does not depend on the settleability of flocs (Adham, Gagliardo 1998).

The MBR process provides high suspended solids and organic matter removal rates comparable to the conventional process. Typical water product qualities from MBR are <5mg/l suspended solids and <1 NTU
turbidity. Complete retention of suspended materials including bacteria and viruses is achieved enabling discharge to sensitive regions (Stephenson et al. 2000). It can be also used for nitrogen and phosphorus removal.

In MBR process a sludge age and hydraulic retention time (HRT) are independent. Thus MBRs can be operated at low HRTs and long sludge ages without biomass washout common in activated sludge. In the activated sludge process the sedimentation limits the biomass concentration that can be maintained. Application of membrane technology in the MBR process enables to intensify the process. Mixed liquor concentrations of 25000mg/l can be maintained for municipal wastewater treatment. Process intensification leads to reduction of the reactor volume thus the footprint (Stephenson et al. 2000).

Furthermore, complete solids retention and high biomass concentrations allow operation at low organic loading rates. Low food to microorganisms ratios of 0.05 – 0.15d\(^{-1}\) are reported (Van Der Roest, Lawrence & Van Bentem 2002). The lower loading rates reduce excess sludge production up to half compared with conventional process (Cote et al. 1997). Incoming organic feed is used up for maintenance of cells rather than growth.

Despite the undeniable advantages, the MBR process has also several disadvantages. The first to mention is the high cost of the membranes that is proportional to membrane surface. Membrane cleaning by backwashing with water containing chemicals is inevitable. Addition of small amounts of chlorine to activated sludge tank has no effect on biomass (Cote et al. 1997). To maintain adequate flux in the in-series modules two parameters should be optimized. Those are cross-flow velocity and the pressure generated by the recirculation pump. For submerged membranes the most important parameters are the air flow velocity and the cycling frequency of suction pumps.

The research studies show that combination of MBR with RO process can result in production of high quality reuse water from municipal wastewater. Evaluation of MBR-RO system has shown that it provides complete inactivation of viruses. Additionally treated water meets regulations for trihalomethanes (THM), chlorite, total coliform and nitrate/nitrite. The potential concern can present formation of THM due to cleaning of MBR reactor with chlorine and its incomplete removal by RO (Comerton et al. 2005).

2.4.3. Aerobic MBRs for municipal wastewater treatment

The application of MBR systems as municipal wastewater treatment is of the highest interest: Their operation and performance is a subject of many studies. The following is a description of MBR performances for domestic wastewater.

**Retention time and loading rate**

The volumetric loading rates between 1.2 and 3.2 kg COD m\(^{-3}\) d\(^{-1}\) and 0.05 to 0.66 kg BOD m\(^{-3}\) d\(^{-1}\) were reported which corresponded to 90-97% removal efficiency. The improved COD removal efficiencies can be related to complete retention of particles by the membrane, including suspended COD and high molecular weight organics as well as no biomass washout problems. The stable conditions in MBR systems are beneficial for growth of specialized microorganisms that able to remove slowly degradable components (Stephenson et al. 2000).

**Nutrient removal**

In MBRs microorganisms are completely retained by the membrane which encourages growth of specialized groups of bacteria like Nitrosomonas and Nitrobacter. The sludge age has influence on the nitrification process in MBR. With the higher sludge age the ammonia removal increases. The nitrification rate is also directly related to floc size. The smaller floc sizes improve nitrification (Stephenson et al. 2000).
**Biomass and sludge**

Mixed liquor concentration of 10000 to 20000mg/l are common for MBRs. Lower production of sludge by MBR systems compared with other wastewater treatment processes is related to long sludge ages and low sludge loading rates. The MBR sludge was more dewaterable, and dewaterability increased with the increase of sludge age (Stephenson et al 2000).

The metal analysis showed that MBR sludge contains higher content of cadmium, chromium and nickel and lower cooper, potassium, magnesium and mercury content that activated sludge. There was a correlation between dissolved oxygen (DO) and metal concentrations, indicating that the more metals were dissolved at low DOs (Stephenson et al 2000).

**Energy consumption and α-factor**

In MBR systems energy is used for pumping of feed water, aeration, retentate recycling and occasionally permeate suction. The overall power requirements for side-stream systems tend to be higher than for submerged reactors due to large pumping requirements to circulate biomass around a membrane loop (Stephenson et al 2000).

The high sludge concentrations that can be maintained in MBR systems result in low oxygen transfer rates. The oxygen transfer from air into water depends on the mean residence time of the bubble in water, size of air bubbles and characteristics of the transfer layer. The first two parameters depend on viscosity of the solution to be aerated and viscosity can be influenced by aeration/mixing device and sludge characteristics. Bacteria can influence the α-factor by the way they grow. There are hydrophobic, filamentous bacteria that create their own environment and increase viscosity. The α-factor depends thus on sludge concentrations and sludge characteristics (Van Der Roest, Lawrence & Van Bentem 2002).

The choice of a mixing/aeration device and reactor configuration is of great importance as viscosity strongly depends on the mixing energy (Van Der Roest, Lawrence & Van Bentem 2002).

### 2.4.4. Design and operation of the Kubota MBR

A Kubota process with the membrane units submerged into an activated sludge tank is applied in line 2 at Hammarby Sjöstad pilot plant. The Kubota unit comprises of two parts. The upper section contains 150 flat - plate, 0.4 µm pore size (MF) membranes slotted into a glass fibre reinforced plastic housing with a gap of 7 mm between panels (Stephenson et al 2000). Each plate is 1m high, 49cm wide and 6 mm thick. The total surface of a plate is 0.8m² (Van Der Roest, Lawrence & Van Bentem 2002). The lower section contains a course bubble diffuser mounted in housing which supports the upper section and directs bubbles and activated sludge flow between the membrane plates. An upward sludge crossflow over the membrane surface of approximately 0.5 m/s is generated by the bubbles. The crossflow minimises fouling phenomena and allows a low - pressure gravity filtration. The permeate flux is controlled by the liquid head above the membrane units. The gravity head is typically between 1 and 1.5 m. Thus the permeate flux determines the hydraulic retention time (Stephenson et al 2000).

### 2.5. Principles of the reverse osmosis (RO)

Reverse osmosis (RO) called also hyper filtration is one of the membrane separation processes. The semipermeable membrane acts as a barrier that allows water pass through it while rejecting the contaminants. It occurs when the water is moved across the membrane against the concentration gradient, from lower to higher concentration. The process is called “reverse” osmosis since it requires pressure to force pure water across a membrane, leaving the impurities behind. The pressure has to be applied to reverse the natural process of osmosis by overcoming the osmotic pressure which is related to concentration in the feed water. The higher is the salt concentration in feed water, the higher osmotic pressure. The principle of reverse osmosis process is presented in Fig. 6.

In reverse osmosis bacteria, viruses, salts, sugars, proteins, particles, dyes, and other constituents that have a molecular weight greater than 150-250 daltons can be rejected. Additionally process enables separation of ions such as salts. The bigger particles and the larger charge, the more likely they are rejected.

Feed water for the RO has to be pretreated to meet certain quality to prevent membrane fouling or damage. Suspended solids and colloidal materials have to be removed otherwise they will cause clogging leading to reduction of water flux through membrane and worse permeate water quality. Microorganisms must also be controlled as they foul the membrane by creating the slime layer. In addition salts, especially calcium carbonate and calcium sulfate, may precipitate on the membrane reducing water flux (Sirkar, Winston Ho et al 1992).

The operational variables for RO are feed flow rate, feed concentration, pressure, temperature and pH (Parekh 1988).

#### 2.5.1. One-step reverse osmosis process

Reverse osmosis process is applied in the simplest design as a single step. In one-step unit the feed water is directed to a membrane unit by a high-pressure pump. The feed pumping pressure must provide economically feasible permeate flow and should be higher than the concentrate osmotic pressure (Al-Enezi et al., 2002).
It is possible to run two reverse osmosis systems in series. The permeate product of the first step serves as the feed to the second step. Such a system is called two-pass reverse osmosis unit. Two-pass RO is applied when permeate from the single-step RO does not meet required quality. It is also used when the costs of polishing permeate from the single-step RO to reach a high quality of final product water exceed the cost of introducing second step RO.

The system where the concentrate from the first stage is used as a feed for the second stage is called two-stage RO system. Two-stage RO system is often applied to increase an overall water recovery rate.

The most examples of two-pass RO applications that can be found in the literature concern desalination of seawater. Introduction of second stage RO allows the tolerance of much higher salt passage through the first stage of RO not compromising the water quality. That gives the longer life time of first stage membranes what can be translated into reduction of operational costs. Concentrate from the second stage, that contains relatively low salt concentration, is fed back to the first step which additionally dilutes the feed to first stage RO.

Reverse osmosis units can be configured as split partial two-pass system (Fig. 7). In such a mode part of permeate from the seawater membranes serves as the feed to a set of brackish water membranes. Brackish contains more sea salts than freshwater but less than the open sea. Other part of permeate bypasses the brackish water membrane and is blended with the high quality permeate from brackish membrane to produce water of acceptable quality (Sirkar, Winston Ho et al. 1992). Advantage of such a configuration is reduced number of brackish water membranes, higher effective recovery rate and lower power consumption which considerably reduces capital and operational costs (Wilf, Bartels 2005). Further example shows that two-stage process can increase the water recovery ratio from 40 up to 60% (Taniguchi 2001).

3. TESTS WITH THE ROTARY DRUM FILTER

3.1. Effects of backwashing sensor levels on the drum filter removal efficiency.

The aim of the experiment was to check the daily profile of the removal patterns in the drum filter working at two different backwash sensor levels. During the filtration the cake of trapped particles built up in the drum. This sludge cake functions itself as a filter which traps the smaller particles (see chapter 2.3.1.). With the higher position of the sensor in the drum the sludge cake is thicker so the cake filtration should be more effective and therefore the removal of particles should increase (Fig. 8). The relationships between the variables were found.

The goal with the experiment is to reach suspended solids concentration in the effluent from the drum filter that does not exceed 100mg/l.
### 3.1.1. Methodology

The level of a sensor inside the drum filter indicates the wastewater level in the drum at which the backwashing is initiated. It is possible to change the height of the sensor in the drum.

In the first test the sensor was set in the low position to maximize the frequency of backwashes. Backwashing is used to remove a sludge cake from the inner side of the drum. The test was performed during one day (2005-10-19). In the second test, the sensor was set in the high position and the test was repeated during one day (2005-10-26). Tests were performed on the filter cloth with the pore size of 100µm.

Composite samples of incoming wastewater and water outgoing from the drum filter were collected separately by the automatic samplers. Samples were collected for 24 hours, in 6 minutes intervals. Samples from each hour were collected to the separate bottle. The suspended solids and phosphorous concentrations were measured in every fourth sample to decrease the number of analyses.

Suspension solids (SS) concentration was measured according to the Swedish Standards, SS-028112-3 method: 50 ml of wastewater sample was filtrated through the MGA-glass fiber filter with the pore size 1,6µm and the known weight. Then the sample was dried in the temperature of 105 °C in the oven for minimum one hour. A filter with the dry sample was weighted again and suspended solids concentration was calculated. The results were given in milligrams per liter.

The dry solids (TS) amount in the sludge was measured as follows: the sludge sample of 20-40 grams was weighted together with the aluminum form and dried in 105 °C for two hours. The dry residue was weighted again with the form. The dry solids content was calculated as a difference between wet and dry sample after subtracting mass of the form. The value was given in percentages.

Analyses of total phosphorous, orthophosphates and turbidity were carried out with Hach Lange spectrophotometer, model Xion 500. Samples for orthophosphate were filtered prior to analysis. Conductivity was measured with the portable conductivity meter.

Data concerning the flow rate of wastewater incoming to the drum filter and backwashing frequency were collected from the internal database of Stockholm Vatten and the Hammarby Sjöstad pilot plant control system database. The sludge flow from the drum filter was measured manually with the stopwatch. The total sludge flow per hour was calculated knowing that the sludge pump starts every second backwash and each start lasts 12 seconds.

### 3.1.2. Results and discussion

**Suspended solids and backwashing**

Tests results show that suspended solids concentration in the incoming water varies during the day (Fig. 9). The highest concentration is observed during the morning and evening hours.
The characteristics of incoming water were different for two series of tests. The mean suspended solids concentration in the inflow to the filter in the first test, with low sensor level, was 142 mg/l. The mean suspended solids concentration in the inflow in the second test was 220 mg/l.

After the test with the high sensor level had been executed, it was observed that the alarm sensor during the test was set in slightly lower position than the main, high level sensor. Thus the alarm sensor was the one that indicated the wastewater level at which the backwashing was initiated, was not the correct sensor. Backwashing initiated by the alarm sensor is always with water. As the result the test conditions were different than had been planned.

The average suspended solids reduction at the low sensor level was 28%, respectively 50% the high level. The results show that removal of suspended solids was more effective with the high position of the sensor (Fig. 10).

Backwashing frequency was lower at the high sensor level (Fig. 11). High position of the sensor allows the wastewater to reach the high level in the filter until the backwash starts and contributes to building up thicker sludge cake. As the sludge cake is thicker, cake filtration occurs more effectively. That fact can explain better suspended solids removal at the higher position of the sensor.

Changes of the influent rates resulted in changes of backwashing frequency. Suspended solids load in the influent followed the fluctuations (Fig. 12). System failure resulted in the stop of the inflow to the filter, and subsequently the decrease of the backwash frequency. After restart of the system, the backwashing frequency increased again.

The backwashing frequency increased with the increased suspended solids load in the incoming water (Fig. 13). That was due to the fast building of the sludge cake which resulted in rapid increase of the water level in the filter. The result proved that the filter works properly.

Relationship between reduction of SS and their concentration in water incoming to the filter differs for low and high sensor level (Fig. 14). For the low sensor position the correlation is strong ($R^2 = 0.82$). Higher SS concentration in the incoming water results in more effective SS removal. The correlation between these parameters for the high sensor level is low ($R^2$...
The low correlation can be possibly due to insufficient number of samples that were analyzed. However, more likely the reduction values obtained in the test with the high sensor position are maximum that can be achieved as maximum SS reduction by the filter is assessed for 65%.

Relationship between SS concentration in the incoming water and their concentration in the effluent from the drum filter is low (Fig. 15).

Some studies show that suspended solids concentration can be related to turbidity (Bengtsson 2003). The relationship can be used as a fast and easy method of assessing suspended solids concentration in wastewater by measuring turbidity. However tests results performed at different sensor levels show that there is a medium correlation between turbidity and suspended solids concentration at high sensor level; $R^2 = 0.5$ for the incoming water and $R^2 = 0.62$ for the outgoing water. Relationship between those parameters at the low sensor level is low, respectively $R^2 = 0.13$ for incoming water and $R^2 = 0.18$ for outgoing water (Fig. 16, 17). Therefore turbidity can not substitute for SS analysis. The differences in correlations for the high...
A rotary drum filter as pretreatment for a membrane bioreactor – operation, evaluation and optimization.

Phosphorous removal

The reduction of phosphorous in the drum filter was low. The reduction was more efficient with the higher position of the sensor (Fig. 18). The mean total phosphorous reduction at the low sensor level was 4.5% and 11.3% at the high position.

The phosphorous in wastewater is present in both soluble and suspended form. Most of the total phosphorous occurs in form of dissolved ions. Only phosphorous bounded to suspended solids can be removed by filtration. Wastewater incoming to the Hammarby Sjöstad WWTP contains 75 - 80% of phosphorous in soluble form (Björlenius 2005). That can explain the low phosphorous removal efficiency by the drum filter. Maximum phosphorus removal rate depends on amount of suspended solids removed by the filter. Theoretical phosphorous reduction that could be achieved by the filtration, in case when all SS were removed, varied between 3 and 33% of the total phosphorous.

The removal of orthophosphates through the filtration was inconsistent during the testing day but in general it was not very high and ranged from 1 to 19%. There was also the increase of orthophosphate concentration in the effluent observed in the test with the high sensor level. That can be due to the release of orthophosphates by microorganisms present in the sludge cake under anaerobic conditions. It can be assumed that anaerobic conditions may exist in the cake which is thicker when the sensor level is set in the high position (Fig. 19).
Correlation between orthophosphates concentration and conductivity is above 0.5 for the incoming and outgoing water with both low and high sensor level (Fig. 20, 21).

In water, the conductivity is related to the concentration of ions capable of carrying electrical current. Orthophosphate ions dissolved in water are able to carry electrical current thus are related to the conductivity. However, they are not the only ions in wastewater that can conduct current. Other ions i.e. metal ions, potassium, magnesium also affect conductivity. Nevertheless, it can be stated that the decrease of conductivity in the outgoing water compared to incoming means that some dissolved orthophosphate ions have been removed. Conductivity can be therefore an easy and fast method to show phosphorous variations in wastewater.

The difference in the conductivity of incoming and outgoing water is slight. Some conductivity values of outgoing water are higher than the incoming water. That can be due to the hydrolysis and release of ions.

The results of analyses from tests on high and low sensor levels are presented in Appendix I.

### 3.1.3. Conclusions

- Tests were performed on wastewater with different characteristics which might affect results and made them difficult to compare with each other.
- Suspended solid removal efficiency at the low sensor level was low, in average 28%.
- Suspended solids removal was more effective at the high sensor level, at average 50%.
- Nevertheless SS concentration in the drum filter effluent was 108mg/l in average and thereby exceeded the desirable value of 100mg/l.
- Relationship between turbidity and suspended solids concentration is not strong; therefore turbidity can not be used instead of SS measurements.
- Phosphorous removal was low, up to 11%.
- Relationship between conductivity and phosphorous concentration is medium. Conductivity can be therefore used in order to assess phosphorous content in wastewater.
3.2. Optimization of the dry solids content in the primary sludge

Primary sludge is produced during mechanical wastewater treatment process. It consists mainly of water, which constitutes 93 to 99%. The other important component of sludge is the dry substance which is made of organic and inorganic substances.

Sludge treatment and disposal significantly contributes to the costs of operating treatment plant. There are several ways of sludge treatment and disposal like stabilization, thickening, dewatering or drying. In all cases the goal is to reduce the water content to reduce the volume of sludge to make a storage and transport cheaper.

Optimization of the primary sludge from the drum filter is aiming at reducing water content in the sludge outgoing from the filter. The goal set for the Hammarby Sjöstad plant is to reach 4 to 6% of dry solids (TS) content in the primary sludge. There are several factors that may contribute to increased dry substances content in sludge. Those factors are:

- sensor level in the drum filter
- backwashing
- drum rotation angle
- polymer and sludge addition
- sludge residence time in the thickener

**A sensor level**

Higher position of the sensor in the filter should result in increased dry solids (TS) content. A sensor indicates the wastewater level at which the drum rotation and backwashing is initiated (Chapter 2.3). The higher the positions of the sensor, the longer intervals between backwashes are and the thicker sludge cake that can build up on the filter. The frequency of backwashes is lower with the high sensor level so the sludge is less diluted with water.

**Backwashing**

There is a double backwashing system in the drum filter. Backwashing can be performed either with water or air. The frequency of backwashing with water can be adjusted by setting time after which backwashing with water is activated. For example with the timer set for one hour there are backwashes only with air during that hour. After one hour the first time wastewater reaches the sensor there is a backwash with water. Extension of backwashing time with air should result in reducing water content in the sludge and increasing dry solids content.

**Drum rotation angle**

As described before, when wastewater in the filter reaches the sensor level, the drum starts rotating and backwashing is initiated. Part of the sludge cake does not reach the gutter during the rotation and not washed away. It stays under the gutter and waits until the next drum rotation and backwashing. The drum does not move back after backwashing but makes a circle. Sludge cake that lies over the water level and under the gutter has time to dry. The percentage of dry solids in the sludge increases. The aim is then to fit the appropriate angle by which the drum rotates to let the sludge cake dry.

**3.2.1. Methodology**

The dry solids content was measured according to the method described in chapter 3.1. Sludge samples were collected through the valve on the hose collecting sludge from the thickener. There was also suspended solids concentration measured in the incoming wastewater and effluent from the filter. Suspended solids concentration was measured according to the method describe in chapter 3.1. In each test samples for TS
and SS in/out were collected three times a day for a period of three days. The sludge from the filter was collected in the tank during each test to assess the sludge flow. The sludge in the tank was then stirred and three samples were taken to measure the average, mixed TS.

There was always the low and the high level of each factor tested to decrease the number of tests and simplify the experiment. Factors that were supposed to be tested were:

- low sensor level in the filter with backwashing with water after 10 minutes
- high sensor level in the filter with backwashing with water after 10 minutes
- high sensor level in the filter with backwashing with water after 1 hour
- drum rotation angle

**Calculation of the drum rotation angle**

The drum rotation velocity was measured experimentally. The drum rotates with the constant velocity of 0.64 rad/sec. The time of rotation can be adjusted. Initially it was set for 3 seconds. The desirable angle of the drum rotation has to be assessed to make the sludge cake section, exposed to drying, possibly the longest. Knowing the rotation angle and the angular velocity of the drum, the time of rotation can be easily calculated from the formula:

\[
\Delta t = \Delta \alpha / \omega,
\]

where: \( \Delta t \) – drum rotation time [sec]; \( \Delta \alpha \) – rotation angle [rad]; \( \omega \) – angular velocity [rad/sec]

**3.2.2 Results and discussion**

The first tests were performed with the high sensor level and backwashing with water after 10 minutes. In the next series of tests the time of backwashes was prolonged to 1 hour and sensor remained at the same level.

The results of TS from two series of tests were very similar. It was concluded that the level, at which the backwashing was initiated, was not indicated by the right sensor but the alarm sensor which was situated below the right one. The backwashes initiated by the alarm sensor are only with water. The average TS content obtained in the tests was 1.9%.

Due to lack of time the test span was reduced. The best presumed configuration with a high sensor level together with backwashing frequency with water set for one hour was tested. The average TS content from this series of tests was 4.2%.

Test with a high sensor position and shorter backwashing with water intervals, of 10 minutes, resulted in 3.6% TS content in the sludge. Tests on the most appropriate rotation angle were abandoned due to lack of time.

**3.2.3 Conclusions**

The sensor placed in the high position together with one hour backwashing with water frequency was the configuration that gave the best results concerning dry solids content in the sludge (Fig. 22). The achieved value of dry solids over 4% is high and satisfactory.

**3.3. Chemical precipitation/flocculation**

Chemical precipitation involves addition of chemicals to alter the physical state of dissolved and suspended solids and facilitate their removal. In chemical precipitation three major inter-linked processes must be considered (Bergström 2000). The first is the coagulation, in which the added chemicals cause a reduction in particle charges and enmeshment of particles. To facilitate this process chemicals are added to a rapid mixing tank. It is followed by flocculation, in which coagulated particles form stable flocks by the use of flocculation tanks with slow stirring. Different agents, such as polyelectrolytes, improve the flocculation process. The purpose is to increase the particle size of the precipitated material so that it can be separated more effectively (Henze 2000). The last step is flocks separation by sedimentation, flotation or filtration.

**Figure 22. Mean dry substance contents in the primary sludge from test with alarm sensor level, high sensor level and backwash with water after 1 hour, high sensor level and backwash with water after 10 minutes.**
3.3.1. Usage of polymers for flocculation

Flocculant polymers (polyelectrolytes) are used to enhance the flocculation of suspended solids in the treatment of wastewater. They can be either natural or synthetic. Synthetic polymers consist of simple monomers that are polymerized into high-molecular-weight substances. They can be anionic, cationic or nonionic depending on their charge when placed in water.

Polymers can act in three different ways. They can act as coagulants that neutralize the charge of the wastewater particles. Cationic polymers are used for this purpose as wastewater particles are normally charged negatively. The second mode of action is the formation of interparticle bridges. In this case anionic and nonionic polymers become attached at a number of adsorption sites to the surface of the particles. The bridge is formed when two or more particles are adsorbed on the polymer. The third type of action is when the charge neutralization and bridge formation occurs simultaneously which results from using cationic polymers of extremely high molecular weights (Tchobanoglous 2003).

3.3.2. Laboratory scale flocculation

Suspended solids concentration in the effluent from the drum filter does not comply with the goals set for the Hammarby Sjöstads WWST. Although the change of the operational parameters - height of the backwashing sensor level, resulted in the increase of SS removal efficiency, the results were still not satisfactory. Therefore flocculation as a method to improve the suspended solids removal was considered.

A laboratory scale test on the high-molecular-weight cationic polymer as a flocculation agent was performed to test its possible applicability in the full-scale. Different dosages of the polymer, sludge and filter cloths were tested.

Laboratory scale test is a fast and easy method that gives an overview of flocculation effectiveness enabling to shorten full scale tests time. The aim of the laboratory scale tests was to screen which combination of the polymer, sludge dosages and filter cloth porosity gave the best results concerning suspended solids removal. Subsequently the best combinations were tested in full scale.

Concentration of suspended solids in wastewater incoming to the drum filter is high, 200-500mg/l. Most particles carry negative charge. That was the reason to choose the cationic high-molecular polymer for testing as it can neutralize the negative charge of the particles and possibly form large, strong flocks that do not pass through the filter cloth. The NORD FLOC C-192 polymer, manufactured by SNF Nordic AB was tested. Characteristics of the polymer are given in Table 2.

Hammarby Sjöstads wastewater contains a large fraction of small particles which makes it difficult to flocculate. To overcome the problem, addition of sludge was considered as the source of bigger particles. That can result positively in two ways. First, it facilitates flocks formation. Secondly, it contributes to building up a thick sludge cake of grater porosity as made of bigger flocks (Karlsson 2004). Less compacted sludge cake allows higher flow and better cake filtration process (chapter 2.3.1).

3.3.3. Methodology

Each series of tests was performed on wastewater collected from the Sjöstads incoming water sink to the bucket at one, certain time. Tests performed on water of the same quality enabled to compare results.

In each test, one litre of representative water from the bucket was collected to the bicker. Required volume of polymer and eventually sludge was added at the beginning of the 10 seconds-fast mixing. Sample was mixed by the flocculator placed in the bicker. Next, the sample was mixed slowly for 3 minutes. After flocculation, the sample was filtrated through the filter with selected pore size. The results of each test were judged visually and analytically. Flocks size, flocks formation time, filtrate purity, filter clogging were assessed visually. Suspended solids concentration in wastewater and filtrates as well as dry solids content in the sludge were analyzed in the laboratory according to the method described in chapter 3.1.

Preparation of the polymer

Polymer, used for tests, is delivered in form of granules which are dissolved in water. There was 0.2% water solution of the polymer used for tests.

3.3.4. Results and discussion

Best results of suspended solids removal were achieved with addition of 8 and 5 ppm of polymer. Flocks that were formed with addition of those dosages were large and strong. They did not brake during filtration or pass to the filtrate. They did not clog the filter and were easily removed from the filter surface by water. The polymer dosages below 5 ppm gave rather poor suspended solids reduction and worse flocks and filtration characteristics.

Addition of sludge did not improve SS reduction although it slightly improved flocks formation and their strength. Better results were achieved with addition of sludge from MBR. Addition of sludge without polymer resulted in negative suspended solids reduc-

<table>
<thead>
<tr>
<th>Name</th>
<th>NORDFLOC C-192</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>SNF Nordic AB</td>
</tr>
<tr>
<td>Form</td>
<td>granules, solid</td>
</tr>
<tr>
<td>Colour</td>
<td>white</td>
</tr>
<tr>
<td>Preparation</td>
<td>cationic, water soluble</td>
</tr>
</tbody>
</table>

Table 2. Characteristics of the polymer used for flocculation.
tion which indicates that flocks were passing to the filtrate due to their poor quality. The filter of 60µm pore size gave the best results.

Results from the lab-scale flocculation tests are presented in Appendix II.

3.3.5. Conclusions and recommendation for full-scale flocculation

Laboratory scale flocculation tests show that addition of 5ppm of the NORD FLOC C-192 polymer per 1 litre of wastewater is the lowest effective dosage and is sufficient to perform a good flocculation. Addition of sludge does not seem to be necessary, however in the full-scale flocculation tests it should be taken into consideration as it may contribute to formation of less compact sludge cake and better filtration. The use of the filter cloth with 60µm pore size is recommended.

3.4. Full scale flocculation

The aim of the experiment was to test, in the full scale, the applicability of the NORDFLOC C-192 polymer as a flocculation agent in order to reduce suspended solids content down to a desirable value of 100mg/l SS in the drum filter effluent. Suspended solids concentration of 100mg/l corresponds at average to over 50% reduction of suspended solids by the drum filter. The results from the laboratory scale tests gave the guidelines concerning the dosages of the polymer and sludge for the full scale tests.

3.4.1. Methodology

Drum filter configuration

Configuration of the drum filter has been changed and adjusted to perform full scale flocculation tests (Fig 23). In all tests, the polymer and eventually sludge was introduced into the tank with the hydraulic retention time 10 seconds and rapidly mixed with the incoming wastewater to initiate the flocks’ formation. There was no mixing device installed in the tank. Subsequently wastewater was directed by gravity to the slow mixing tank with the retention time of 3 minutes in order to form large and strong flocks before introducing to the drum filter. The wastewater retained in the slow mixing tank was mixed by air bubbles to avoid flocks and particles sedimentation.

Sample collection

Samples of wastewater incoming to the line 2 and outgoing from the drum filter were collected separately by the automatic samplers. The samplers were programmed to collect water samples every six minutes for 24 hours. Samples from each hour were collected to the separate bottles. Than the wastewater samples from three bottles were mixed to reduce number of analyses.

![Figure 23. The drum filter configuration for the full-scale flocculation.](image)
Analyse method

Suspended solids (SS), dry solids (TS), conductivity and orthophosphates were measured according to the method described in chapter 3.1.

Data concerning backwashing frequency and incoming flow were collected from the internal database of Stockholm Vatten.

Sludge flow was assessed in two different ways. In the reference test and tests with only addition of polymer, sludge was collected during the testing day and hour average was calculated. This method could not be repeated during tests with sludge addition since sludge collected in the tank was constantly recirculated. Therefore, sludge flow was calculated from the unit sludge flow per sludge pump start.

Tests conditions

Three types of tests were performed in the full scale:

- with polymer
- with sludge and polymer
- reference test – without polymer or sludge

Polymer dosage was constant in time. It was always 3,9 liter of 0,2% polymer added per one hour. Polymer was being dosed by a peristaltic pump.

Sludge from the drum filter was collected in the tank. It was pumped back to the rapid mixing tank by the rotating positive displacement pump to be mixed with the incoming wastewater and the polymer. Dosage of sludge was constant in time and amounted to 23 l/h.

All tests were performed at a high sensor level. Other operation parameters like: backwashing frequency, sludge pump start and operation time, sludge screw operation time were the subject of optimization. The filter of 100µm pore size was used in the tests.

3.4.2 Results and discussion

The results from full-scale flocculation tests are presented in Appendix III.

Suspended solids reduction and dry solids content

Test with polymer

Two tests with polymer only were performed. During those tests, sludge was transported away from the drum filter to the thickener by the screw triggered with each water backwash. Once initiated, the screw was rotating for 12 seconds. The pump, pumping sludge from the thickener, was initiated with every second backwash and run for 12 seconds. Frequency of backwashing with water was set for 10 minutes.

First test with only addition of polymer was disordered due to the sampler stop. The sampler collecting incoming wastewater samples stopped after 12 hours due to the program failure. Suspended solids reduction in the test was between 61 and 75% (Fig. 24).

The dry solids content in the primary sludge from the drum filter during testing day ranged from 3.8 to 4.7% (Fig. 25).

The test with addition of polymer was repeated. The second test was held under the same conditions as the first one, with addition of the same dosage of polymer and no dosage of sludge. The removal of suspended solids ranged from 58 to 78% (Fig. 26). Drum filter effluent samples collected between 2 am and 7 pm were non-representative due to stop of the pump supplying water for the backwashing.

The dry solids content in the primary sludge during that test ranged between 2.6 and 2.9% (Fig. 27).

Test with sludge and polymer

Two tests with both polymer and recirculated primary sludge were conducted. The actual dosage of polymer was higher than intended as the polymer was also recirculation in the sludge. The drum filter operation parameters were changed during the first test to

Figure 24. Suspended solids reduction in the first test with polymer.
facilitate its execution. During first three hours, the test was performed under the same conditions as the one with polymer only. However, recirculation of sludge caused increased production of primary sludge in the drum filter and its overflowing from the thickener. Sludge pump operation parameters were changed. Sludge pump was set to be triggered on every backwash and run for 20 seconds to increase amount of sludge removed from the thickener.

First test with addition of polymer and sludge gave the removal efficiency of suspended solids ranging from 53 to 72% (Fig. 28). Results obtained between 6 pm and 8 am were disordered due to the filter cloth clogging. There was no backwashing during this time. Filter was clogged due to a large amount of sludge that was introduced to the filter during the test. That caused wastewater passing the filter without filtration and resulted in high suspended solids concentrations in the effluent from the filter.

The dry solids content in that test was between 2.6 and 4.8% (Fig. 29).

During the second test with the polymer and sludge, backwashing frequency with water was prolonged from 10 minutes to 1 hour as the backwashing with air seemed to be more effective due to the drop of backwashing water pressure. The screw was set to con-
A rotary drum filter as pretreatment for a membrane bioreactor – operation, evaluation and optimization.

stantly carry away sludge from the filter to remove large amounts of solid deposits collected in the gutter.
Second test gave suspended solids removal efficiency of 53 - 72% (Fig. 30). The dry solid content was 4.8 to 5.0%.

Reference test
The last test was conducted without addition of polymer or sludge. That was used as a reference to the previous tests. The test was performed under the same operation conditions as the test with the polymer only. In the test the suspended materials were removed by the drum filter with the efficiency of 34 - 57% (Fig. 31).
The dry solids content in the sludge ranged from 3.3 to 4.8% (Fig. 32).
Operation parameters of the drum filter under flocculation tests are summarized in Table 3.
There was no correlation between suspended solids concentration in the influent and their reduction for tests with only polymer and both sludge and polymer (Fig. 33). Medium correlation was observed for the reference test.
Medium correlations between suspended solids concentration in the incoming wastewater and their concentration in the effluent from the filter for tests with both polymer and sludge as well as the reference test can be observed. The lowest correlation was observed for the test with polymer addition only (Fig. 34).

Orthophosphates reduction

The drum filter ability to remove phosphorous was tested during the first test - with addition of polymer. The removal efficiency was low, 2-8% since no chemical precipitation took place. Only phosphorous in suspended form could be removed by filtration. Orthophosphates were not analyzed in other tests.

Conductivity

Conductivity measurements were supposed to give...
information about removal efficiency of inorganic compounds, especially phosphorous. The results indicate that relationship between conductivity and orthophosphates concentration is high (Fig. 35). Thus conductivity can be used as an easy and fast method to assess the phosphorous content in water.

### 3.4.3. Conclusions

Results from the full scale flocculation tests show that the most effective removal of suspended materials was achieved with addition of the polymer without sludge (Fig. 36).

The average suspended solids reduction during tests with polymer addition only was 67%. Tests with addition of both polymer and sludge gave slightly lower reduction of 64%. However, in both series of tests, SS concentration in the drum filter effluent did not exceed 100 mg/l – a desirable value. Addition of sludge, that was supposed to improve flocks formation and sludge cake filtration, did not give intended results.

Phosphorous removal was low and ranged at 2-8%. Addition of polymer did not influence MBR performance. There was no increased foam production or MBR membrane fouling observed.

However, recirculation of sludge influenced the drum filter performance. Large amount of sludge introduced to the filter caused the filter cloth clogging. After adjusting backwashing frequency the problem was solved.

Constant dosage of polymer or sludge in time can result in their overdose when the incoming flow decreases.

### 4. TESTS ON THE MEMBRANE BIOREACTOR

Tests on the oxygen uptake rate were performed in order to examine the condition of the mixed liquor in the MBR and study the activity of the nitrifying bacteria.

#### 4.1. Oxygen uptake rate of sludge from MBR

The oxygen uptake rate (OUR), called also oxygen consumption or respiration rate, is a measure of the rate of oxygen utilization by wastewater mixed liquor. That gives information about condition of the sludge. The oxygen uptake rate for activated sludge ranging between 20 and 40 g O₂/ (kg VSS*h) signifies that sludge is activated which indicates presence of many living micro organisms and sufficient substrate in form of organic matter. A low respiration rate of 5-10 g O₂/ (kg VSS*h) may signify that sludge is poisoned, there is no easily degradable organic matter present or that sludge has been stabilized (Henze, M., et al. 2000).

![Figure 35. Conductivity vs. orthophosphates concentration.](image-url)
Respiration rate defined as the milligram of oxygen consumed per gram of volatile suspended solids (VSS) per hour is called specific oxygen uptake rate (SOUR).

4.1.1. Methodology

Preparation of Allylthiourea stock solution

Allylthiourea (ATU) is a selective inhibitor of the Nitrosomonas group, used to inhibit nitrification.

200 ml of stock solution containing 2g ATU per litre was prepared. The stock solution was made as follows: 400 mg of ATU was dissolved with water and diluted to 200 ml in the flat-bottomed bottle. 10 mg of ATU per one litre of sludge should be added to successfully inhibit nitrification. 5 ml of stock solution was added per each litre of sample.

The test performance

Each test consisted of three parts. First, 1 litre of mixed liquor sample from MBR was aerated for 4 minutes. After aeration was stopped, the dissolved oxygen concentration was measured for 4 minutes. Secondly, 1 litre of the filtrate from the drum filter was added to 1 litre mixed liquor sample and the procedure was repeated. Finally, 20 mg ATU was added to the 2 litres-mixed sample and measurements were repeated. Samples were mixed during the measurements by a magnetic stirrer. The bucket placed in the water bath was used to keep the constant temperature.

Dissolved oxygen concentrations and temperature were recorded in 15 seconds intervals for the first minute and subsequently every 30 seconds for next 3 minutes. The measurements were performed with the portable oxygen meter.

Mixed liquor samples from MBR and drum filter effluent samples were taken at regular time intervals. Tests were performed three times a day for two weeks to examine the daily variations.

Calculation of OUR

The observed readings of dissolved oxygen (DO) in mg/l versus time in seconds were plotted on the graph. The oxygen uptake rate was obtained by calculating the slope of the linear parts of the recorded DO profiles (Fig. 37).

To determine the oxygen uptake rate in mg O$_2$ per litre per hour, the following equation was used:

\[
\text{OUR} = \frac{(y_2 - y_1)}{(x_2 - x_1)} \times 3600
\]

where:

- \(\text{OUR}\) – oxygen uptake rate, mg/(l*h)
- \(y_2\) – high value of oxygen concentration, mgO$_2$/l
- \(y_1\) – low value of oxygen concentration, in mgO$_2$/l
- \(x_2\) – time corresponding to the low value of oxygen concentration, seconds
- \(x_1\) – time corresponding to the high value of oxygen concentration, seconds

The following steps demonstrate how the oxygen uptake rate was calculated from the given equation:

\[
\text{OUR} = \frac{(5.3 - 1.1)}{(240 - 15)} \times 3600
\]

\[
\text{OUR} = 67.2 \text{mgO}_2/ (l*h)
\]

Subsequently oxygen uptake rate was converted into grams of oxygen consumed per kilogram of volatile suspended solids per hour (SOUR).

Mixed liquor volatile suspended solids (MLVSS) is the fraction of the suspended solids in activated sludge mixed liquor that can be driven off by combustion at 550 degrees Celsius. That indicates the concentration of micro organisms available for biological oxidation.

MLSS readings were used for the calculations. The average MLSS during the testing period (14.11.2005 – 25.11.2005) was 14600mg/l. It was assumed that MLVSS constitute 82% of MLSS.

To calculate SOUR in grams of oxygen per kilogram VSS per hour the following formula was used:

\[
\text{SOUR} = \frac{\text{OUR}}{14.6 \times 0.82}
\]

where:

- \(\text{SOUR}\) – specific oxygen uptake rate, gO$_2$/ (kgVSS*h)
A rotary drum filter as pretreatment for a membrane bioreactor – operation, evaluation and optimization.

**OUR – oxygen uptake rate, mgO$_2$/ (l*h)**

14.6 – average mixed liquor suspend solids, g/l

0.82 – percentage of mixed liquor volatile suspended solids

Concentration of MLSS in the mixed sample, after addition of the drum filter effluent to the MBR sludge sample, decreased by half.

**4.1.2. Results and discussion**

The oxygen consumption during the first part of the test, when only mixed liquor from MBR was tested, ranged between 12 and 43 mgO$_2$/ (l*h). The results reflect the actual condition of the mixed liquor in the bioreactor. The OUR represents the oxygen uptake by the heterotrophic organisms for the substrate oxidation and endogenous respiration as well as the oxygen consumption of the nitrifying bacteria.

Addition of the effluent from the drum filter to the mixed liquor sample caused increase of the oxygen uptake that ranged between 58 and 137 mgO$_2$/ (l*h). The increase of oxygen consumption in the mixed sample was due to the increase of the easily degradable organic matter and nutrients load supplied with the drum filter effluent. The oxygen was not the limiting factor since the sample was always saturated prior to DO measurements. The oxygen was consumed by the heterotrophic organisms and nitrifying bacteria.

The increase of the oxygen uptake after addition of dissolved organic matter and ammonia indicates that micro organisms present in the activated sludge become active again after supplying them with accessible nourishment and oxygen. This signifies that the sludge was in a good condition. It was capable of dealing with excessive (increased) amount of the substrate.

In the third part of the test, ATU was added to the mixed sample to determine nitrifying activity of the sludge. ATU inhibits oxidation of NH$_4^+$-N to NO$_2^-$-N by *Nitrosomonas* group of bacteria. However it does not inhibit the *Nitrobacter* group. The OUT determined in that part of the test was considered as the oxygen uptake due to the oxidation of organic matter by heterotrophic organisms and oxidation of NO$_2^-$-N to NO$_3^-$-N performed by *Nitrobacter* group of bacteria.

The difference between OUR without ATU and with ATU addition represents the amount of oxygen consumed for ammonia oxidation. The oxygen uptake rate due to NH$_4^+$-N oxidation varies from 45 to 87% of the total OUR. The proportions of the oxygen uptake for ammonia oxidation to oxygen uptake for organic matter oxidation differ in time. That can be due to the fluctuations of the drum filter effluent composition.

The average oxygen consumption rate by the *Nitrosomonas* group was 47 mgO$_2$/ (l*h) and accounted for 62% of total OUR in average.

The results of the oxygen uptake rate tests are presented in Figure 38.

**Specific oxygen uptake rates, for samples with only MBR sludge, varie between 1 and 3 gO$_2$/ (kgVSS*h) (Fig. 39). The low SOUR values may signify that there are too many solids for the substrate loading or that sludge has been stabilized due to the substrate scarcity. The results indicate that organic matter and ammonia had been removed in the MBR.**

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The SOURs for samples with addition of the drum filter effluent ranged between 10 and 23 gO$_2$/ (kgVSS*h). The high SOUR values signify that the sludge was activated at the presence of the substrate.

Calculated SOUR values may slightly differ from the actual due to the inaccurate assumption of mixed liquor volatile suspended solids concentrations in the bioreactor.
4.1.3 Conclusions

- The low oxygen uptake rates for the mixed liquor from MBR signify that dissolved organic matter and ammonia were removed from the bioreactor.

- Addition of the drum filter effluent to the mixed liquor sample was the measure of the influent organic load and its biodegradability. The increase of the oxygen consumption was observed. The results indicate that activated sludge is in a good condition, many living organisms are present and they are active.

- At presence of *Allylthiourea* it was possible to distinguish between the oxygen uptake for the dissolved organic matter oxidation and oxygen uptake for oxidation of ammonia. The results showed that more than half of the oxygen was utilized for the ammonia oxidation. That indicates that there is a numerous population of nitrifying bacteria present in the sludge.

5. COMPARISON OF DIFFERENT TREATMENT STRATEGIES ON LINE 2

Two different line configurations were examined under the research period of the thesis in order to compare their treatment effectiveness (see chapter 2.2).

5.1. Results and discussion

First scenario – a rotary drum filter and a membrane bioreactor

The quality of the effluent from the membrane bioreactor and the removal patterns were examined. The investigation spanned period when the UCT process was applied in the MBR and this process was stable. Suspended solids removal efficiency by the drum filter averaged 58%. Their concentration in effluent from the drum filter amounted to 120 mg/l in average thus exceeding the desirable value of 100mg/l. Suspended solids concentration in the MBR effluent was marginal (SS<2mg/l).

The COD concentration in the MBR effluent was in average 29 mg/l and BOD7 – 1.25 mg/l. The removal efficiencies were 95% and 99.6% respectively. The
removal of organic compounds amounted to 95% and their concentration in the effluent was 8.5 mg/l in average.

The laboratory analyses showed that nitrogen and phosphorous concentrations in the effluent from the MBR exceeded the standards posed by Hammarby Sjöstad plant and amounted in average to 5.6 mg/l and 13.8 mg/l, respectively. Total phosphorous removal efficiency was 49.5% and total nitrogen 77%.

The results of the influent to line 2, drum filter effluent and MBR effluent analyses are presented in Appendix IV.

Second scenario – rotary drum filter, membrane bioreactor and reverse osmosis unit

The aim of the tests was to determine the water recovery rate as well as the effluent (mixed permeate) and the concentrate quality from the reverse osmosis plant. Effluent from the membrane bioreactor was directed to RO unit.

The results showed that it was possible to concentrate wastewater 50 times (volume reduction factor = 50) that corresponded to the water recovery rate of 98%. At that VRF concentrations of total phosphorous and total nitrogen in the RO effluent were far below the Hammarby Sjöstad standards for discharge water and amounted to 0.04 mg/l and 1.9 mg/l respectively. The nitrate nitrogen reduction efficiency was 97% and the total phosphorous 99.6% at VRF=50. The content of organic compounds was marginal (TOC<2 mg/l). The results of analyses for VRF 50 are presented in Table 4.

The high nitrogen removal efficiency was achieved as the nitrate nitrogen, which was the main source of nitrogen in the effluent from MBR, occurred to be better separated by the MBR membrane than ammonium nitrogen. Nitrate ions (NO₃⁻) have higher molecular weight than ammonia ions (NH₄⁺) and therefore were more effectively retained by the RO membrane.

Slightly acidic characteristics of wastewater from the MBR due to high concentrations of nitrate ions and low suspended solids concentration resulted in the low membrane fouling and scale formation on the membrane. No pH adjustment was necessary.

In the full scale neutralization of effluent from RO before its discharge to the recipient may be required. The acid characteristics of permeate is a consequence of higher mobility of H⁺ ions than OH⁻ ions through the membrane during the concentration process.

Furthermore, as one of the goals of the Hammarby Sjöstad project is to maximize resource recovery, it was considered to use a concentrate from the RO with the high nutrient content as a byproduct of the RO process for agriculture purposes. However, in order to utilize the concentrate as a fertilizer it is essential that there are no undesirable chemicals, which may pose the risk, introduced to the soil. The heavy metals concentration in the product used in agriculture that does not exceed the strict standards is of the highest importance.

No standards for the RO concentrate as a fertilizer were found. Thus heavy metal concentrations were compared with the maximum metal content in sludge approved for the agriculture purposes and expressed by the metal to phosphorous ratio. The results showed that phosphorous recovered in the RO concentrate was not contaminated with heavy metals (Table 5).

Estimated energy consumption during the study amounted to 37 kWh/m². Such energy utilization seemed to be high when compared to the RO plant used in the previous studies at the Hammarby Sjöstad plant. In those experiments the total energy consumption was 23 kWh/m² and regarded as unacceptable (Blennow, 2005). In a full-scale RO the energy use is estimated for 5-10kWh/h² (Bergström, 2006).

5.2. Conclusions

Comparison of different line 2 configurations indicates that the application of the reverse osmosis technology as a last step in the wastewater treatment process provides water of the higher quality than process with only drum filter and membrane bioreactor. In the contrary to MBR effluent, the quality of the RO water product met the Hammarby Sjöstad standards. The high water recovery rate obtained in the RO signifies that the process can be performed efficiently.

Slightly acid characteristics of water incoming to RO plant, due to the nitrification process in MBR, had positive effect on the flux through the membrane and minimized the occurrence of scaling and fouling phenomena.

Additionally, good characteristics of concentrate as a byproduct from the RO allow its application for the agriculture purposes.

The main concern while operating the reverse osmosis plant is the energy consumption as it accounts for a major cost-effective factor in a RO system. The biggest cost is for the pumps that transport the feed solution under high pressure through the module. Estimated energy use for the utilized pilot plant was high.

Table 4. The results of analyzes from line 2 at VRF=50.

<table>
<thead>
<tr>
<th>cond. [µS/cm]</th>
<th>pH</th>
<th>SS [mg/l]</th>
<th>TS [g/l]</th>
<th>PO4-P [mg/l]</th>
<th>Tot-P [mg/l]</th>
<th>NO3-N [mg/l]</th>
<th>NO4-N [mg/l]</th>
<th>Tot-N [mg/l]</th>
<th>TOC [mg/l]</th>
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<td>662</td>
<td>5,66</td>
<td>2</td>
<td>0,41</td>
<td>8,1</td>
<td>9</td>
<td>35</td>
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<td>-</td>
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<td>Effluent</td>
<td>17</td>
<td>4,68</td>
<td>-</td>
<td>0,06</td>
<td>0,04</td>
<td>0,9</td>
<td>&lt;0,5</td>
<td>1,9</td>
<td>&lt;2</td>
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<tr>
<td>Concentrate</td>
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<td>-</td>
<td>14,65</td>
<td>270</td>
<td>270</td>
<td>1200</td>
<td>43</td>
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</table>
Possible need for the neutralization of effluent from the RO plant due to its acid characteristics should be taken into consideration.

6. FINAL DISCUSSION AND CONCLUSIONS

The thesis aims at optimization of the rotary drum filter performance used as a pretreatment for the membrane bioreactor. The performance of different line configurations was compared and evaluated taking into consideration the treatment effectiveness. The condition of mixed liquor from MBR was also examined.

The drum filter removal efficiency

The removal efficiency of the drum filter working at the low and high backwashing sensor levels was examined. Tests results enabled to draw the following conclusions:

- The removal of suspended solids by the drum filter was more effective at the high sensor level due to the thicker sludge cake that resulted in better filtration.
- Desirable suspended solids concentration, below 100mg/l, in the effluent from the drum filter was not reached even at the high sensor position.
- Low relationship between turbidity and suspended solids concentration was found, thus the measurement of turbidity could not replace suspended solids analysis.
- Total phosphorous and orthophosphate removal efficiency was low due to the high content of phosphorous in the dissolved form.
- There was relationship between conductivity and phosphorous concentration observed which enabled to use conductivity as an easy method to show the variations of phosphorous in wastewater.

Chemical precipitation/flocculation tests

In order to increase the removal efficiency of suspended solids and possibly phosphorous by the drum filter, the high-molecular cationic polymer as a precipitation/flocculation agent was tested.

The laboratory scale flocculation experiments were carried out first, in order to determine the dosages of the polymer and sludge that are the most appropriate for the full scale flocculation tests.

The results showed that:

- The suspended solids reduction by over 60% can be achieved.
- Addition of 5ppm of the NORD FLOC C-192 polymer per one litre of wastewater was the lowest effective dosage and sufficient to perform good flocculation.

The flocculation tests in the full scale showed that:

- The most effective removal of suspended materials was obtained with addition of the polymer without sludge.
- In both types of tests, with polymer only, and polymer and sludge addition, suspended solids reduction excided 60%.
- Suspended solids concentration in the effluent from the drum filter did not exceed a desirable value of 100 mg/l.
- Addition of the polymer and sludge did not increased phosphorous removal efficiency by the drum filter - phosphorous reduction was low and ranged between 2 and 8%.
- No influence of the polymer on the drum filter and MBR performance was observed.
- No foaming or membrane fouling in the MBR observed.
- Recirculation of sludge affected the drum filter performance.
- Introduction of large amounts of sludge to the filter caused filter cloth clogging. After improvement of the backwashing by increasing frequency of backwashes with air, the problem was solved.

Optimization of the dry solids content in the primary sludge

Experiments aimed at reducing water content in the sludge outgoing from the drum filter in order to reach the goal set by the Hammarby Sjöstad plant of 4 to 6% dry solids in the primary sludge.

The tests with different drum filter operational configurations showed that:

- The high position of the sensor level in the drum together with the frequency of backwashing with water set for every hour was the configuration that gave the best results concerning dry solids content.

Table 5. The metal/phosphorous ratio in the final RO concentrate product and maximum metal content in sludge approved for agriculture use (Levlin, 1999).

<table>
<thead>
<tr>
<th></th>
<th>Cd</th>
<th>Hg</th>
<th>Pb</th>
<th>Cu</th>
<th>Zn</th>
<th>Ni</th>
<th>Cr</th>
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<td>Line 2, VRF=50</td>
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<td>0.0001</td>
<td>0.008</td>
<td>1.37</td>
<td>1.92</td>
<td>0.55</td>
<td>0.11</td>
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<tr>
<td>Sludge approved for agriculture</td>
<td>0.0667</td>
<td>0.0833</td>
<td>3.33</td>
<td>20</td>
<td>26.7</td>
<td>1.67</td>
<td>3.33</td>
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</table>
The dry solids content reached with those operational parameters were higher than 4% in average thus satisfactory.

**Examination of the MBR mixed liquor condition**

The results of the oxygen uptake rate tests showed that:

- The MBR sludge is in a good condition.
- There were many active organisms able to deal with the highly loaded influent.
- The tests proved that the MBR process was in function.
- Dissolved organic matter and ammonia were removed in the bioreactor. Over half of the consumed oxygen was utilized for the oxidation of ammonia, which signifies that there was a large population of *Nitrosomonas* group of bacteria present in the activated sludge.

**Comparison of different treatment strategies on line 2**

Two line 2 configurations were examined. The first configuration comprised of only rotary drum filter as a primary treatment and membrane bioreactor as biological treatment combined with the membrane separation. In the second scenario, the existing configuration was supplemented with the reverse osmosis unit as the last treatment step.

The study reviled that:

- The effluent from MBR did not meet the standards for discharge water posed in Hammarby Sjöstad environmental plan (N≤6mg/l, P≤0.15mg/l).
- Application of the reverse osmosis technology enabled to produce water of required quality.
- High water recovery rate obtained in the RO showed that process can be carried out efficiently.
- The aerobic treatment in line 2 consisting of the drum filter and MBR seemed to be appropriate pre-treatment method before RO.
- Due to the nitrification process in MBR, the influent to RO unit had slightly acid characteristics which positively affected the RO performance.
- Application of the microfiltration in the MBR resulted in marginal suspended solids concentration in water coming into the RO plant, thus eliminating costs of additional SS removal.
- It was possible to recover nutrients in the RO process. Good concentrate (a by-product from RO) characteristics enabled to apply it in agriculture.
- The only objection concerning operation of the reverse osmosis plant is the energy consumption.
- It was estimated that energy use for the tested pilot plant was high.
REFERENCES


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Other references:

Björlenius, Berndt: project manager, Hammarby Sjöstad WWTP. Personal communication October 2005


[1] Hydrotech - rotary drum filters manufacturer wed side:

http://www.hydrotech.se/
APPENDIXES I-IV
Appendix I

The results from the test with the low sensor level.

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The results of second full-scale flocculation test with polymer and sludge - 2006-01-23.

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Appendix IV

Influent to line 2 - results of daily samples analyses.

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The drum filter effluent - results of daily samples analyses.

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**Lokalt reningsverk för Hammarby Sjöstad, etapp 1 – Projektpublikationer**

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Nr 20 Utvärdering av anaerob behandling av hushållsspillvatten och tekniker för efterbehandling, examensarbete av Catharina Gannholm

Nr 21 Avloppsvattenrening i anaerob membranbioreaktor med VSEP-enhet, examensarbete av Andreas Carlsson

Nr 22 Avloppsvattenbehandling med anaerob membranbioreaktor – En jämförande systemanalys avseende exergi, miljöpåverkan samt återföring av närsalter, examensarbete av Cecilia Hessel

Nr 23 Utvärdering av förfällning vid Sjöstadsverkets anaeroba UASB-linje, examensarbete av Mila Harding

Nr 24 Utvärdering av fluidiserad bädd – kartläggning av orsaker till sandflykt, projekarbete av Jonas Karlsson

Nr 25 Behandling av svartvatten och matavfall med anaerob membranbioreaktor och omvänd osmos, examensarbete av Karoline Andersson och Marie Castor

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