Master´s thesis

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Comparison of the AS-MBR and BF-MBR processes

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Abstract:

Active sludge membrane bioreactor (AS-MBR) is a process of membrane separation of activated sludge. This is increasingly becoming an alternative for wastewater treatment plants as improved effluent quality often is required together with special limitations. A major drawback for the process is however membrane fouling, which needs to be further handled in order to create a cost-beneficial option. Fouling can potentially be reduced by applying biofilm (BF) instead of activated sludge. Prospects of even more compact plants, with reduced aeration requirements, and improved effluent quality are other driving forces for investigation of BF-MBR. Thus, the overall objective of this thesis was to carry out a comparison between membrane performances in the two systems. This was done by operating two equal pilot plants in parallel for four months. The results revealed less fouling and better treatment in the AS-MBR. Additionally, it was found that AS-MBR reactor water contained significantly less submicron organic material which often is found to be an important foulant. In order to evaluate the impact on the membrane performance, the amount of suspended solid was increased in the BF-MBR. A clear improvement was found with increased amounts of suspended solids, and the final experiment indicated even better membrane performance when compared to the AS-MBR. Some suspended solid should therefore be present in order to form of a protective cake layer on the membrane surface. Increased operating problems regarding BF sludge needs however further analysis. The results obtained in this study supports that the BF-MBR membrane can be operated just as well the AS-MBR, or maybe even better under the right circumstances. Configurations with increased amounts of suspended solid in an external membrane reactor should therefore further be evaluated, as well as the prospects of an optimum concentration of suspended solid.

Head word:

1. Wastewater treatment
2. Biofilm membrane bioreactor
3. BF-MBR
4. Fouling

PREFACE

This thesis was executed from January to June 2010, at the Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, Trondheim.

The objective of the study was to operate and compare the membrane performances of an active sludge membrane bioreactor and a biofilm membrane bioreactor. As to several unexpected incidents with the pilot's operations occurred, the assignment became more challenging than first anticipated. This resulted in both reduced time for the main experiment, and reduced measurements. The initial approach was to investigate impacts of aeration in the systems, but this was not carried out due to time constraints. The amount of suspended solids was instead changed in the biofilm reactor during the experiment, and further applied for evaluating the potential for the biofilm membrane reactor.

First of all I like to express my gratitude to my supervisor Professor TorOve Leiknes at Department of Hydraulic and Environmental Engineering. It has been a true privilege to be able to use your laboratory facilities and exchange views with you. I would also like to thank PhD candidate Igor Ivanovic for exchanging valuable laboratory experiences and measurements. Last but not least I would like to thank Dr. Cheng Sun for helpful advices and valuable collaboration throughout the project.

Trondheim, Norway, June 2010

ABSTRACT

Active sludge membrane bioreactor (AS-MBR) is a process of membrane separation of activated sludge. This is increasingly becoming an alternative for wastewater treatment plants as improved effluent quality often is required together with special limitations. A major drawback for the process is however membrane fouling, which needs to be further handled in order to create a cost-beneficial solution. Fouling can potentially be reduced by applying biofilm (BF) instead of activated sludge. Prospects of even more compact plants, with reduced aeration requirements, and improved effluent quality are other driving forces for investigation of BF-MBR. The limited literature concerning BF-MBR illustrates however varying degrees of success. The first part of this report presents the available knowledge on fouling in both AS- and BF-MBRs.

The overall objective of this thesis was to carry out a comparison between membrane performances in the two systems. This was done by operating two equal pilot plants in parallel for several months, while water quality and fouling were measured.

The results revealed less fouling and better treatment in the AS-MBR. Additionally, it was found that the AS-MBR reactor water contained significantly less submicron organic material which often is found to be an important foulant. In order to evaluate the impact on the membrane performance, the amount of suspended solid was increased in the BF-MBR. A clear improvement was found with increased amounts of suspended solids, and the final experiment indicated even better membrane performance when compared to the AS-MBR. Some suspended solid should therefore be present in order to form of a protective cake layer on the membrane surface and prevent other foulants from adsorbing directly to the membrane. The suspended solids may also flocculate the smaller foulant prior to deposition on the surface. Increased operating problems regarding BF sludge needs however further analysis. The results obtained in this study supports that the BF-MBR membrane can be operated just as well the AS-MBR, or maybe even better under the right circumstances. Configurations with increased amounts of suspended solid in an external membrane reactor should therefore further be evaluated, as well as the prospects of an optimum concentration of suspended solid.

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NOMENCLATURE

SYMBOLS

J_T	Flux at given temperature, T, [LMH]
η_p	The permeate dynamic viscosity [Pa*s]
R_t	The total filtration resistance [m^{-1}]
T	Temperature, [°C]
TMP_T	Trans membrane pressure at a given temperature [Pa or bar]

ABBREVIATIONS

AS	Active sludge
BF	Biofilm
CAS	Conventional AS systems
CFV	Cross-flow velocity
CP	Cylindrical polypropylene
DO	Dissolved oxygen
EPS	Extracellular polymeric substances
FS	Flat sheet membrane
HF	Hollow fiber membrane
IFAS	Integrated fixed media activated sludge system
MBR	Membrane bio-reactor
MCE	Mixed cellulose ester
MF	Micro filtration
MWCO	Molecular weight cut off
PB	Polyethylene beads
PE	Polyethylene
PES	Polyethylenesulphone
PG	Polyethylene granule
PS	Polyethylene sheets
PSD	Particle size distribution
PVDF	Polyvenylidene difluoride
S	Polyethylene sponge
SAD_m	Specific aeration demand with related to the membrane, [m/h]
SAD_p	Specific aeration demand with related to the permeate volume [-]
SMP	Soluble microbial products
SRT	Sludge retention time
SS	Suspended solid
Stdev.	Standard deviation
TKN	Total Kjeldal nitrogen
TMP	Trans membrane pressure
UF	Ultra filtration

1 INTRODUCTION

The interest for advanced wastewater treatment increases in step with growing focus on requirements for water conservation. Urbanization further creates a demand of more compact wastewater treatment plants. Activated sludge membrane bioreactor (AS-MBR) is a response to these requirements as it provides a compact process with high effluent quality. AS-MBR is a process of membrane separation of activated sludge (AS), where the membrane replaces the conventional sedimentation step after an AS reactor. The risk of membrane fouling is however a major drawback for this process. Excessive fouling reduced the productivity as well as increases the need for membrane cleaning and hence increases operational costs while simultaneously decreases lifetime of the membrane. Thus, in order to provide a cost-beneficial process, fouling needs to be controlled. Exchanging AS by suspended biofilm (BF) could provide improved fouling control due to decreased amounts of suspended solid (SS). Other possible advantages with this exchange are prospects of an even more compact reactor, with lower energy demands, and higher effluent quality. However, literature reports varying results on the BF-MBR performance.

The overall objective of this thesis was by operating an AS- MBR and a BF-MBR pilot in parallel, to compare the two systems. The research became limited to investigate differences in fouling properties. In order to reach the overall objective, three main questions were to be answered;

- Which system performed best with respect to both fouling and effluent quality under the given conditions?

- Which fouling mechanisms were prevailing in the different reactors?

- How will varying concentrations of suspended solid influence fouling in the BF-MBR?

Relevant literature was collected from review papers of fouling in AS-MBRs, as well as the available research on wastewater treatment in BF-MBRs. The hypotheses in this study were that less fouling, decreased energy demand and improved effluent quality would be achieved in the BF-MBR.

2 LITERATURE REVIEW

This chapter deals with concepts of AS- and BF-MBR. Both reactors are presented with respect to system configurations, membrane feed water characteristics, operational conditions, membrane material, and how these characteristics can affect fouling. The chapter will end with a comparison of the two reactors.

2.1 THE BASIC PROCESSES UNITS

The AS-MBR consists of an active sludge process in combination with a membrane process, while the BF-MBR utilizes a BF reactor in combination with a membrane.

2.1.1 THE MEMBRANE PROCESS

A membrane is a perm-selective material that allows specific physical or chemical compounds to pass through more easily than others. The selectivity of the membrane depends mainly on pore size, and membranes are therefore separated into different classes depending on their pore size or molecular weight cut-off (MWCO). [1]

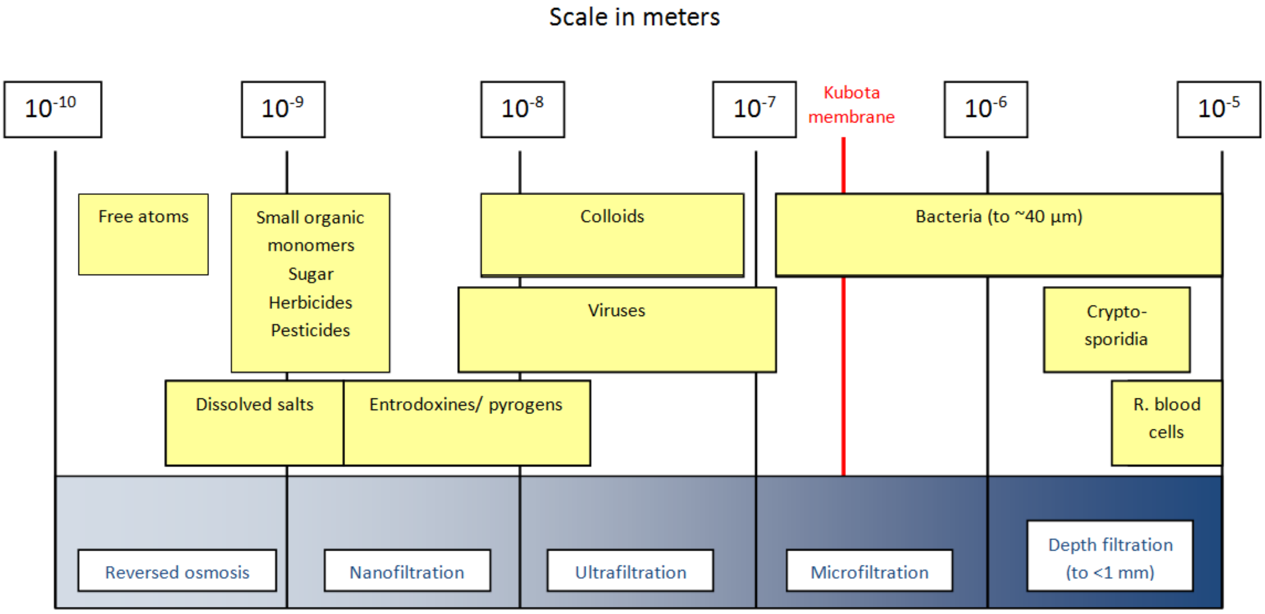


FIGURE 2.1 ILLUSTRATION OF THE APPROXIMATE CUT-OFFS' FOR THE DIFFERENT MEMBRANES. THE RED LINE ILLUSTRATES THE KUBOTA MEMBRANE THAT IS APPLIED IN THIS EXPERIMENT [2]

Figure 2.1 illustrates cut-offs by different membranes. The red line illustrates the micro filter (MF) utilized in the experiments. Most membrane filtrations applied for water and wastewater treatment are driven by the trans-membrane pressure (TMP). TMP is the hydraulic pressure gradient, given by the difference in pressure on membrane's feed and permeate side, respectively. Operating TMP increases with decreasing pore size, governed by increased hydraulic resistance of the membrane. [1]

2.1.2 CONVENTIONAL AS PROCESS

The conventional AS process (CAS) is a well known and widely applied system. Biomass is suspended in an aerated reactor, whereas bacteria aggregate to sludge flocs which can be separated from the water phase in a subsequent separation step. This separation step normally consists of a sedimentation tank in which the sludge will be pumped back to the aerated tank to maintain sufficient sludge concentration in the bioreactor. [3] The performance of the process is dependent of the conversion of colloids and suspended matter into biomass as well as the physical separation of produced biomass in the subsequent step. Hence, the overall efficiency of CAS primarily depends on the settling properties of the sludge. Replacing the sedimentation step with a membrane filtration step can solve difficulties with settleability in addition to form a much more stabile and compact unit. [4]

2.1.3 CONVENTIONAL BF PROCESS

Bacteria in the BF process are attached to solid surfaces. Substrates such as organic compounds and ammonia are transported into the biofilm biomass. The biofilm thickness will continue to grow as long as both oxygen and substrate can penetrate. Anaerobic conditions will take place near the biofilm media when biofilm thickness exceeds this level. Anaerobic conditions will result in detachment of biofilm flakes, which in turn enables new biofilm to form. [3] The BF processes are increasingly being favored over CAS due to several advantages with modern systems. There are many different BF systems on the market today, which all have their advantages and disadvantages. Examples include trickling filters, rotating biological contactors, fixed media submerged biofilters, granular media filters, fluidized bed reactors, and suspended plastic carriers. [3] The trickling filter is however not volume effective, while the rotating biological contactor often has problems with the mechanics. Uneven distribution of the load is the limitation for submerged fixed medias, while the granular media has to be operated discontinuously, and the fluidized bed has shown hydraulic instability [5]. Both trickling filters and submerged filters that utilizes granular media are also prone to clogging from wastewater, and have therefore loading rates limitations which can result in needs for extended pretreatment [6]. Suspended plastic carriers on the other hand are not prone to clogging, nor have any of the other issues. Another advantage with this technology is the system's compactness. Most attempts of combining BF with MBR have therefore applied the moving med biofilm process (MBBR) or other suspended BF media. [5]

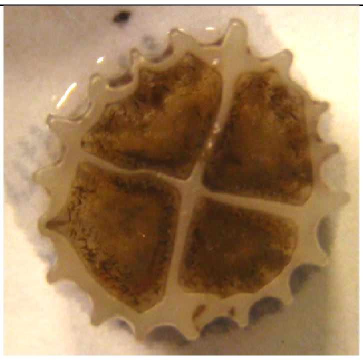
THE MBBR SYSTEM

MBBR was invented and developed by NTNU and SINTEF in late 80s [7]. The process had great success and is now established as a well-proven, robust, and compact reactor for wastewater treatment. The idea behind the process was to increase the specific biofilm area by utilizing the entire reactor volume for biofilm growth. This was achieved by letting BF grow on small plastic carriers kept suspended in the reactor by air or mechanical mixers. The advantages with this process are listed below;

- The process is capable of increasing the biological reaction rates through accumulation of high concentration of active biomass [8]
- The reactor plants requires less space [5]
- The effluent water quality is less influenced by biomass separation since the sludge return is eliminated and ten times less biomass have to be separated [5]
- The attached biomass becomes more specialized due to no biomass return and longer sludge ages. This facilitate an opportunity for nitrogen removal [5]
- This system is more resistant against both organic and toxic shock loads due to the thickness of the film [8]
- BF systems have more adequate oxygen transfer compared to AS system [4]
- The system is claimed to be less complex to operate [9]
- It is a flexible system. Almost any reactor shapes can be applied and the capacity can be adjusted by altering the filling fraction of carriers [10]

K1 is the original MBBR-carrier. K1 is made of dense polyethylene (PE) shaped as a plastic wheel. The density is right below water, and thus minimizes the required energy for keeping the carriers in suspension. The reactor volume can be filled by up to 67 % with this carrier. Other carriers with different shapes, materials, and sizes have later been introduced. K1 is however still the most applied and is illustrated in table 2.1. [5]

TABLE 2.1 THE K1 CARRIER [DATA FROM [5]]



9,1 mm in diameter
7.2 mm long
500 m^2/m^3 surface area per volume
335 m^2/m^3 growth area when 67 % filled

Reactor volume is determined on the basis of area load, filling fraction of carriers, targeting treatment efficiency, and effective specific biofilm growth area [7]. In order to retain the carriers within the tank, sieves must be installed both at inlet and outlet of the reactors. [11]

A specific coarse bubble configuration has been developed for aeration. This is due to the fact that coarse bubbles are both cheaper to produce and has shown to give acceptable mass transfer in MBBRs. The latter due to partly capture and break down of bubbles by carriers. [5]

Compactness of the process induces a low hydraulic retention time (HRT), typically between 1 - 1.5 hours depending on organic loads and wastewater strengths. [3]

Problems with foaming may occur due to operating problems or when initializing the system. The DO should be below 3 mg O/l in order to avoid this problem. Another common problem is flotation of carriers before growth of extensive biofilm. It may therefore take between 2 - 4 weeks before carriers start to perform sufficiently. Due to distance and turbulence, worms have trouble moving from one carrier to another. Extensive red worm growth should therefore under normal conditions not be an issue in suspended BF reactors. Several other BF systems have however experienced a growth of red worm population that feed on the biofilm and thereby reduced treatment efficiency. Exactly what promotes growth is not well understood. However, worms are obligate aerobes and high dissolved oxygen (DO) levels would favor growth. Red worm growth may also be encouraged when conditions change from high organic loads and low DO levels to lower loads and higher DO. As the worms detach from the media at DO near zero, worm growth control can be achieved by creating anoxic conditions for several hours [12]. This treatment step should preferable be in addition to some chlorination and should be repeated after about two weeks when the eggs are mature ready. A limited population of red worms will however normally exist in a well established BF reactor, and may also have a positive effective on the observed sludge yield. A final issue is settling of sludge. The settleability of the biomass decreases as load increases and can cause problem in the conventional clarification step after highly loaded MBBR. Applying membrane filtration have the potential to solve this problem [10]. [7]

2.2 MEMBRANE FOULING

Fouling is caused by rejected compounds that accumulate at the surface or within the pores of the membrane due to varying physical, chemical, and biological mechanisms. This causes reduction of flux at a constant TMP, or increased TMP at a constant flux. Several different definitions of fouling exist. The definition applied in this study includes both reversible and irreversible fouling[1]. [2]

2.2.1 FOULING MECHANISMS

The filtration resistance of the membrane is normally separated into the resistance caused by the clean membrane itself, adsorption within the pores, pore blocking, cake layer formation, and concentration polarization. All of these mechanisms are illustrated in figure 2.2 and explained further in the following. Which form of fouling that is dominant will vary as a function of wastewater quality, membrane reactor design, and operational conditions [13]. [1]

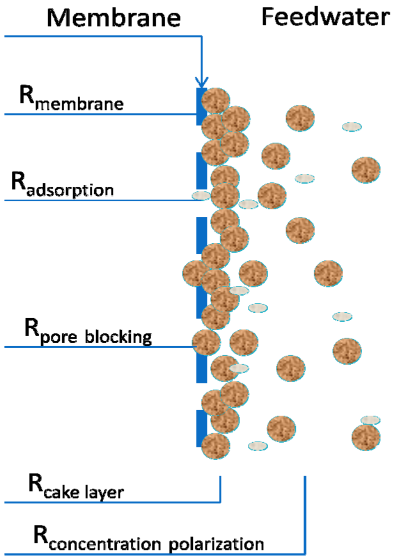


FIGURE 2.2 THE DIFFERENT FILTRETAION RESISTANCE MECHANISMS THAT OCCUR DURING MEMBRANE FILTRATION (MODIFIED FROM [1])

MEMBRANE RESISTANCE

This is the initial resistance, and could be determined by measuring the resistance of clean water filtration. [1]

PORE ADSORPTION

Particles and substances that get into the pore channel can adsorb to the walls within the membrane, and hence reduce the width of the channel. As this type of fouling general only can be removed by chemical cleaning, it is classified as irreversible fouling. [1]

PORE BLOCKING

Pore blocking occurs when particles get stuck in the pore opening and the number of available pore channels is reduced. This fouling mechanism is also classified as irreversible. [1]

CAKE LAYER FORMATION

Cake or gel layer formation occurs when particles and macromolecules accumulate at the membrane surface. The cake layer formation is the most important fouling mechanism in AS-MBR filtrations, and accounts together with surface biofilm for up to 90 % of the total resistance in submerged systems. The cake layer is often classified as reversible fouling because it to a great extent is removable by an appropriate physical washing protocol. The cake layer may be more or less permeable depending on the interacting forces within the layer and between the layer and the membrane [1]. Some basic rules to reduce the cake layer formation are listed below; [14]

- Lower suction pressure on the membrane surface. A membrane with high maintainable permeability is therefore beneficial
- Selection of reasonable operation fluxes for normal operation
- Reduction of dead zones in the module
- Avoidance of too high packing density of the layer, which could be done by the generation of larger flocs.
- Prevention of extracellular polymeric substances (EPS) formation and filamentous organisms by installing and maintaining adequate biological conditions.

Previous studies indicate that pore blocking is the dominant mechanisms in conventional MBRs when operated below the sustainable flux. Cake layer formation is the dominant mechanism above this flux. The blocking resistance has also been found to stabilize when high fluxes are obtained. This is due to a "second membrane" formed by the cake layer that protected the true membrane against blocking and adsorption. [15]

CONCENTRATION POLARIZATION

Concentration polarization may be defined as *"a concentration profile that has a higher level of solute nearest to the upstream membrane surface compared with the more or less well-mixed bulk fluid far from the membrane surface*" [2]. This phenomena results in back transportation of solvent from the permeate side to the feed side due to increased osmotic pressure. Ultra filtration (UF) and MF has a high MWCO, and the retained material does not have ability to build up an osmotic pressure difference. This type of fouling can therefore be ignored when wastewater treatment in MBRs are being considered. [1]

2.2.2 CRITICAL FLUX

The idea of critical flux for MF and UF filtration is that a flux where fouling not yet occur exists, and an increase in flux above this level leads to fouling. There are mainly two distinct definitions of critical flux today; the strongest one defines critical flux as the limit where clean-water flux is maintained. This is not practically possible to determine, due to some extent of irreversibly fouling in real situations. The weaker form of the definition therefore defines critical flux as the limit where operation below leads to a rapidly established flux which is maintained during start-up of filtration. [2] Critical flux depends on conditions such as the amount of back transported flow, turbulence, specific solute-membrane interactions, and solute size. Critical flux is typically determined in complex fluids by increasing the flux in steps while the stability of the TMP is monitored. The flux is reached when the TMP increases rapidly within one step, or when irreversibly deposition occurs [16].The critical flux represent fouling caused by deposition of suspended solid in the cake layer rather than fouling caused by colloids and soluble material. No standard protocol for the method exists, and the duration and height of the steps, as well as the initial state of the membrane, varies among studies. Comparing different critical fluxes are therefore difficult. The method has also been criticized for not being adaptable to long-term operation, when the fouling rates always are significantly smaller in the real operations, and a second increase of TMP often is observed. This method is however despite all its shortages an efficient approach to assess the fouling behavior of a given system and to compare different operation conditions within one pilot [16]. [14]

The term “sustainable flux” has recently been introduced due to all the problems with the critical flux in complex fluids. Sustainable flux can only be determined through long-term operation and is defined as the flux in which the TMP increase gradually at an acceptable rate and chemical cleaning is not necessary. [16]

2.2.3 FOULING MODELING

Darcy’s law describes the rate of permeate flux of pure solvent feed, flowing under laminar conditions, in tortuous membrane pores, and is frequently used as a basis for fouling modeling. Darcy’s law is expressed in eq. 2.1.

$$J = \frac{TMP}{\eta_p R_t} \tag{2.1}$$

Where J is the permeate flux given in L/m^2*h (LMH), TMP is given in bar, η_p is the permeate dynamic viscosity [bar*s], and R_t is the total filtration resistance [m^{-1}]. R_t is the sum of membrane resistance and fouling resistances in MBRs. Viscosity of clean water and permeate are often quite similar in MBRs, and the difference between them must be neglected in order to apply eq. 2.1 for temperature correction of the TMP. Many theoretical and empirical models for describing the membrane fouling phenomena have been proposed [14]. Several of these models are useful even though no computational model accurately describes MBR fouling [17]. [1]

2.2.4 FOULING AND MBRS

The fouling mechanisms are rather complex and can be caused by different substrates and interactions. Fouling is particularly a problem in MBRs due to high concentrations of total and suspended solids. [13] All parameters involved in the MBR design and operation affects the membrane fouling either directly or indirectly. Complex interactions between the parameters makes fouling hard to predict [16]. A simplified presentation of the different parameters as well as their impact on each other is presented in figure 2.3. The further discussion regarding AS- and BF-MBRs will be divided into the three topics shown in the chart.

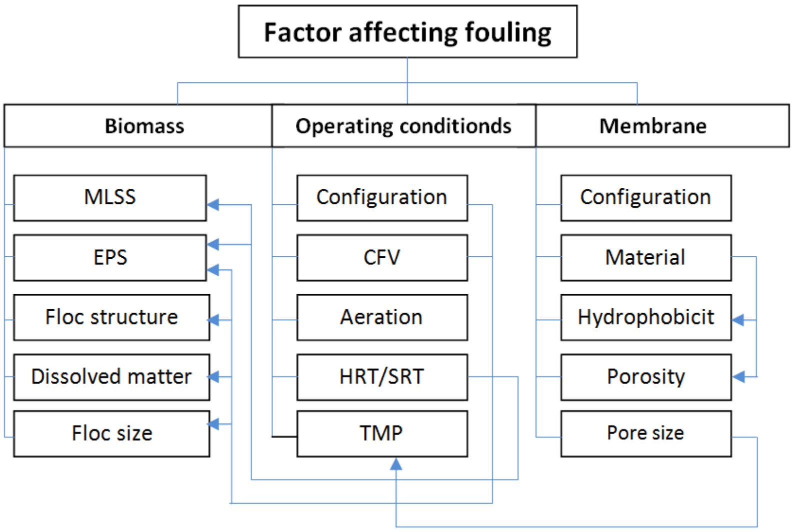


FIGURE 2.3 A SIMPLIFIED FIGURE OF THE DIFFERENT PARAMETERS AFFECT ON EACH OTHER AND FOULING. (MODIFIED FROM [14])

Fouling restricts widespread application of MBRs by reducing the productivity and increasing the maintenance and operational costs. Much research has therefore been conducted in to identify, investigate, model, and control fouling. A unified and well-structured theory on membrane fouling has however not been found. [14] Raw water, experimental setup, operational conditions, membrane types, and analyzing procedures vary among studies and hence complicate comparison and generalization of results. [2, 17]

2.3 AS-MBR –THE STATE OF THE ART

Introducing a membrane instead a settling tank after an AS reactor can among other advantages reduce the footprint of the plant by 50 % [18]. Either UF or MF membranes with pore sizes typically between 0.005 to 0.4 µm are applied. This pore size interval rejects almost all solids and can be a complete physical barrier for bacterial flocks. [16] MBR is a relative new technique that has achieved increased acceptances, and the appliance is expected to grow in the future [18]. The process is recognized as a high cost/high value treatment, and will only be applied were high quality effluent is required. Many countries are suffering under water scarcity and the water stress is expected to occur more frequently due to climate changes and population growth. This has resulted in an increased interest for freshwater conservation and pollution abatement, which could be seen in the more stringent legislations for both sewage treatment and industrial effluent discharge. This has further encouraged improvements in wastewater technologies and the interest for MBR has grown. Decreased investment and operational cost, together with increased acceptance of the technology have also affected the introduction of the technique in a positive direction. MBR is therefore increasingly becoming an alternative as older plants are getting ready to upgrade to meet increased flow or effluent quality demands without increasing their footprint. There is however still skepticism of investing considerable costs in a relatively new technique. The process may also be difficult to maintain and the fouling has to be further controlled in order to give a cost-beneficial process. [19]

2.3.1 HISTORY

The development of the MBR technique started in the late 60s [19]. The first generation MBRs utilized a side-stream, cross flow configuration. High energy demand to generate sufficient sludge velocities across the surface of the membrane was a huge disadvantage with this operation. The process was therefore considered nonviable for municipal wastewater treatment [20]. The breakthrough for the MBRs came nevertheless in 1989 when Japan started to submerge UF hallow fiber (HF) membranes into the reactors [16]. Further increase in fouling control was obtained in the early 90s when modest fluxes were accepted together with appliance of membrane air-scouring. The sludge retention time (SRT) has also decreased in time, leading to more manageable concentrations of SS, and hence less fouling. Immersed membrane configurations are frequently applied today, either as flat sheet (FS) or as HF membranes. Other configurations have later been developed but have not yet achieved the same acknowledgement as these two configurations. [18]

2.3.2 AS-MBR COMPARED TO CONVENTIONAL AS SYSTEMS

The need for sedimentation is eliminated in the MBR and the membrane can handle SS concentrations up to 20 g/l against 6 g/l in the CAS. The MBR therefore presents opportunities of reduced footprint, reduced sludge productions, and longer SRTs. The treatment efficiency in MBRs is also improved due to the complete removal of solids by the membrane, which also causes increased disinfection capacity. Reduction is often observed in MBRs' sludge productions and may offer a great advantage as the sludge handling is an expensive part of the overall treatment cost. [17] Increased rate of nitrification can also be achieved in MBRs since a larger amount of slow-growing nitrifying bacteria can be retained in the aeration tank at longer SRTs [14]. It is not easy to make a general economical comparison between MBR and CAS systems. Much research concludes that MBRs are competitive with other treatment systems, while other studies demonstrate the opposite [1]. The disadvantages connected to MBR are mainly energy demand, investment cost, and risk of fouling. The membrane lifetime greatly impacts the cost, but there is still limited knowledge of this due to the relatively short history of the technique. The possible advantages and disadvantages with MRR over CAS are listed in table 2.2. [18]

TABLE 2.2 ADVANTAGES AND DISADVANTAGES BY MBR COMPARED TO CAS-SYSTEMS [1][16][18][20]

ADVANTAGES	DISADVANTAGES
• A more stabile process which is more resistance against organic shock loads • Increased SS/SRT • Reduced footprint • Possibility of handling higher volumetric loadings • Easier to expand • Prospects of reduced sludge production • No problems with sludge bulking • The effluent quality is independent of the sludge properties • Complete solid removal causes high treatment of COD, BOD, SS, and heavy metals • Increased SRT gives an opportunity for complete nitrogen removal • Higher bio-P potential • The membrane offers improved disinfection capacity	• High investment cost • High energy demand and operational cost • Relatively new technique • Need of knowledge to operate • The membrane is fragile • Risk related to fouling • Risk related to replacement cost

2.3.3 MBR CONFIGURATION AND FOULING

The overall performance of an MBR is to great extent affected by the orientation of the membrane in relation to the flow and the configuration that is applied.

DRIVING FORCE

Pressure is normally the operational driving force in MBRs. Extractive and diffusive MBRs also exist but are generally not applied for wastewater treatment. [2]

DEAD-END VERSUS CROSS-FLOW

The membrane in a conventional pressure-driven MBR process can be configured as cross flow or dead-end filtration. Both these configurations are shown in figure 2.4.

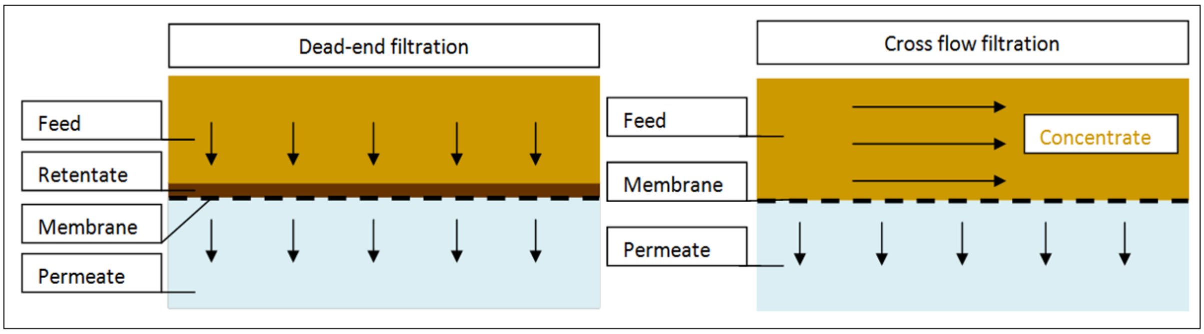


FIGURE 2.4 DEAD-END AND CROSS-FLOW ORIENTED MEMBRANES (MODIFIED FROM [1])

Cross flow configurations are normally favorable in MBRs due to a tangential flow that decreases the concentration of retained material. The cross flow also creates turbulence and promotes back transportation, and the cake layer is shown to be more compressible leading to reduced cake layer resistance [16]. These MBRs can therefore be operate with higher permeate fluxes or with more concentrated feed water. A disadvantage with the cross flow system is generally reduced permeate production due to the retentive stream and permeate applied for backwashing. They may also have a higher energy demand caused by energy for feed circulation [1]. Membranes in cross flow systems may be submerged into a reactor or placed in a side-stream. [2]

SUBMERGED VERSUS SIDE-STREAM

The membrane is immersed into the AS reactor in submerged configurations, while a side stream configuration has a membrane element outside the tank. Today, submerged configuration is preferred for domestic wastewater treatment in MBRs. [14] There is no strict distinction between these two systems, and a combination of them will be applied in this study. Figure 2.5 illustrates the two systems and a combination. [1]

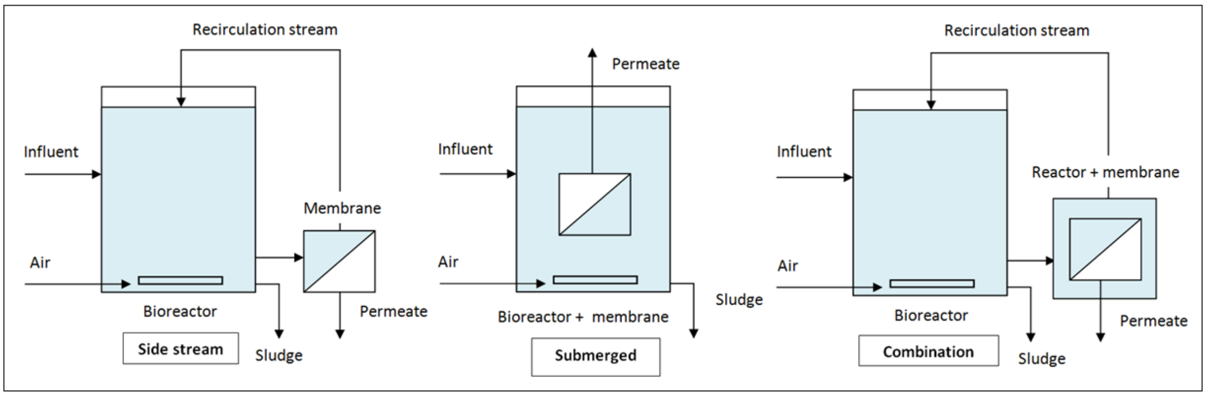


FIGURE 2.5 THE SIDE STREAM CONFIGURATION, THE SUBMERGED CONFIGURATION, AND A COMBINATION (MODIFIED FROM [1])

Circulation through the membrane compartment has shown to give improved membrane performance. Coarse air bubbles are therefore applied in the immersed set-up in order to produce in-tank circulations to suppress the fouling. Immersed systems are generally less energy demanding due to elimination of the water pumping. The break-up effect is also found to be smaller in immersed MBRs due to decreased shear stress. This causes a generally lower fouling potential in immersed systems. [2, 14]

There are also some advantages with the side-stream configuration: Membranes can be cleaned in situ without risk of harming the biomass with chemicals, membranes are more accessible which lead to less expensive maintenance and membrane replacement, and there is increased hydraulic control which can result in improved fouling control. Side-stream configurations can also generally be operated with higher SS concentration, and aeration can be optimized for mixing and membrane scouring separately. [2]

CONSTANT PRESSURE VERSUS CONSTANT FLUX OPERATION

Constant flux is currently preferred in many MBR applications and recent studies are therefore normally operated this way. Constant flux has proven to be particularly useful for filtration of complex fluids due to a general avoidance of excessive fouling. This makes it a cost effective operation for submerged MBRs. [16] The TMP increase in constant flux MBRs is an accelerating process where the fouling rate increases with increasing flux. Modest fluxes are therefore preferred for fouling control. Fouling development within one cleaning cycle may be described in three phases as shown in figure 2.6. [21]

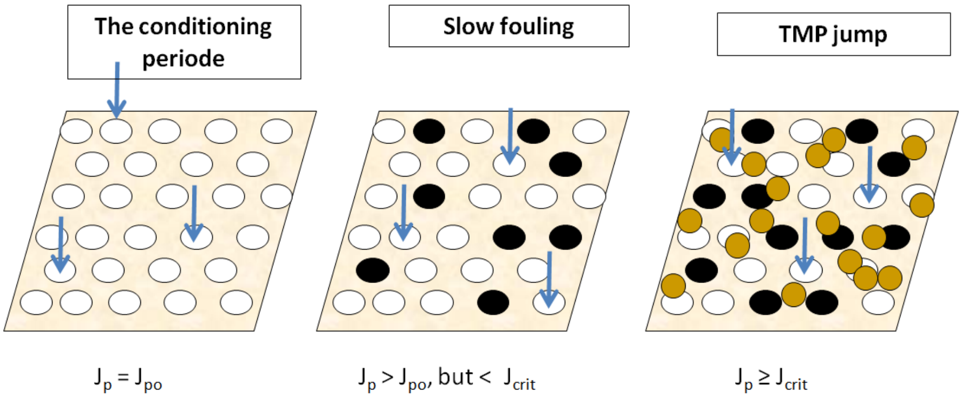


FIGURE 2.6 THREE PHASES OF FOULING IN CONSTANT-FLUX DRIVEN MBRS. [MODIFIED FROM [21]]

J_{po} is the starting flux, J_p is the flux applied at the given time, and J_{crit} is the critical flux. [21]

This first phase is called the conditioning period and has not been identified until recently, but may still be of great importance. Strong interactions between the surface and EPS and soluble microbial products (SMP) present in the water leads to rapid irreversible fouling. Passive adsorption of colloids and organics are almost independent of tangential shear and has even been observed for zero-flux operations. The size of this initial fouling has been reported to be between 20 – 2000 % of the clean membrane resistance. The effect of the phase depends on the pore size distribution and surface chemistry. The surface is expected to be more or less covered with SMP after this phase. [16, 21]

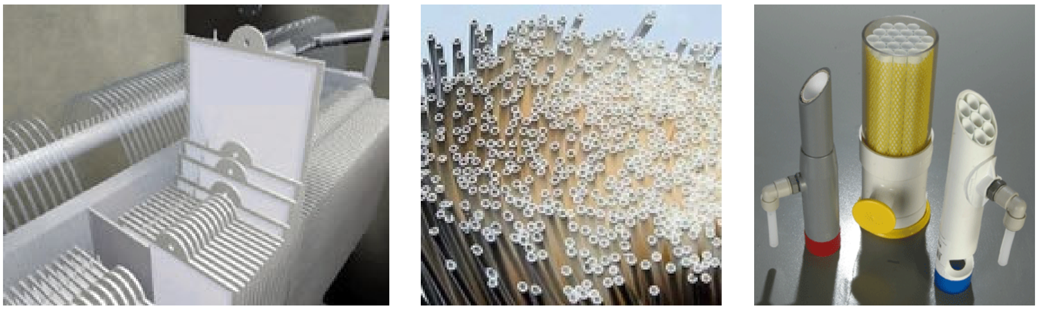
The second phase is referred to as the slow fouling phase. The biomass approaching the surface will attach more easily to previously adsorbed material. Further adsorption and deposition of organics will occur and the available number of pores be reduced. [16]

A TMP jump is observed in the third and final stage. The local fluxes in the remaining pores have to increase to keep the overall permeate flow constant. This can therefore cause the flux to exceed the critical flux, and deposit of a cake layer will occur with a self-accelerating nature. Several mechanisms may take place in this fouling stage. [2, 16]

The combination of initial constant TMP followed by a very low constant flux may reduce the surface fouling by reducing the convective force towards the membrane. There has also been some evidence that constant flux operation gives more irreversible fouling than constant pressure. [16]

DIFFERENT MODULES APPLIED IN THE MBR

The perfect membrane configuration has a high surface area, high degree of turbulence on the feed side, low energy demand, low cost, low facilitate cleaning demands, and a design that permits modularization. Some of these criteria are mutually exclusive. There are three different modules that can be applied in MBRs; FS, HF, and tubular modules. Each of these modules is shown in figure 2.7 and may be favorable in different situations. [2]



Flat sheet [22] Hallow fiber [23] Tubular [24]

FIGURE 2.7 THE THREE DIFFERENT MEMBRANE MODULES APPLIED IN MBRS.

Since the HF has a high membrane density and strength against vigorous backwashing, it is generally cheaper to manufacture than the other two. However, due to a well defined channel width, the fluid hydrodynamics and distribution can be better controlled in the FS and tubular modules. The HF modules may therefore be more prone to rapid fouling and require more frequently washing and cleaning, hence have a higher maintaining cost. [16]

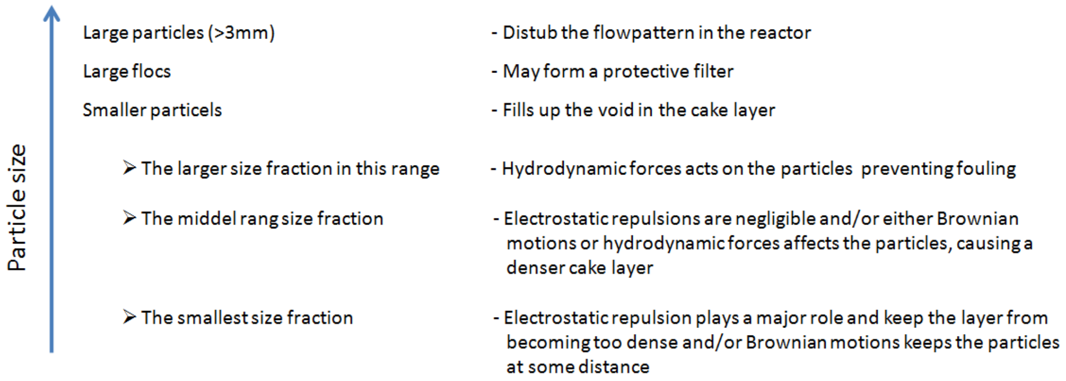
2.3.4 BIOMASS CHARACTERISTIC AND FOULING

Activated sludge contains feed water compounds, metabolites produced during biological reactions, and biomass. All of these compounds may contribute to membrane fouling, but fouling in AS-MBR seems to be mostly affected by interactions between the membrane and the biological suspension, rather than the wastewater compounds. Which fractions causes the most fouling is still not clear. Some studies reports that the SS is the most important foulant, while other identified it as the EPS. Others found that the submicron particles below 0.1 µm or the colloids or soluble fraction had the greatest affect [6]. The variation of these results may be due to different operating conditions, configurations, wastewater compositions and/or analytical procedures. [16]

PARTICLE SIZE DISTRIBUTION

The particle size distribution (PSD) from MBR biomass values vary widely in reported studies. The MBRs generally have however larger particles than CAS but with an additional peak with smaller particles due to retention of colloids and free bacteria. The mean particles are generally much larger than the pore sizes applied in MBRs, and they are therefore not expected to clog the pores, nor deposit at the surface. Biological flocs nevertheless play a major role in membrane fouling. [16]

The presence of hair and particles larger than 3 mm should be avoided in MBR reactors as they cause large problems by accumulation and disturbance of flow pattern around the membrane [17]. Smaller flocks may however act as a barrier for further foulants by forming a porous cake layer which works as a prefilter and prevent in-depth adsorption [25]. The smallest particles may on the other hand cause a denser cake layer with large resistance due to filling of the voids in the cake. The permeability of the cake layer passes through a minimum at increasing particle size in this range. There are currently two different explanations for this. One is that the electrostatic repulsions between the smallest particles in this range are stronger and becomes negligible after a certain particle size. The other explanation is that Brownian diffusion decrease the density of the smallest particles, while hydrodynamic forces affect the largest fraction of small particles, there are however no forces effecting the particles in-between (around 1 µm). Small flock fraction also decreases settleability of the sludge [14]. Impacts of different size fractions are illustrated in figure 2.8. [16]



Large particles (>3mm)	- Distub the flowpattern in the reactor
Large flocs	- May form a protective filter
Smaller particels	- Fills up the void in the cake layer
➢ The larger size fraction in this range	- Hydrodynamic forces acts on the particles preventing fouling
➢ The middel rang size fraction	- Electrostatic repulsions are negligible and/or either Brownian motions or hydrodynamic forces affects the particles, causing a denser cake layer
➢ The smallest size fraction	- Electrostatic repulsion plays a major role and keep the layer from becoming too dense and/or Brownian motions keeps the particles at some distance

FIGURE 2.8 THE ASSUMED IMPACTS FROM THE DIFFERENT PSD FRACTIONS

BIOMASS FRACTIONS

The active sludge biomass may be fractionated into three idealized classes according to the PSD; suspended solid, colloids and solutes. The colloidal fraction is in the middle range with sizes between 0.001 to 0.1 µm. This fraction will not sediment and is strongly affected by Brownian motions [26]. The literature disagrees about which fraction that has the largest impact on fouling [17, 27], and both suspended solids and colloids have been suggested as main foulants [14]. The soluble and colloidal fraction is generally referred to as SMP and has also been referred to as a major foulant. [16] Figure 2.9 illustrates the wide range of distribution regarding the fouling contribution from documented experiments. There exists no standardized method for fractioning these compounds, and the separation assumes no interaction between the different compounds of the biomass. Configuration, operation, wastewater composition, and membrane are also affecting the results and it is therefore impossible to generalize the contributions. EPS and other metabolic products have however been increasingly identified as the main foulants in aerobic MBR. [14]

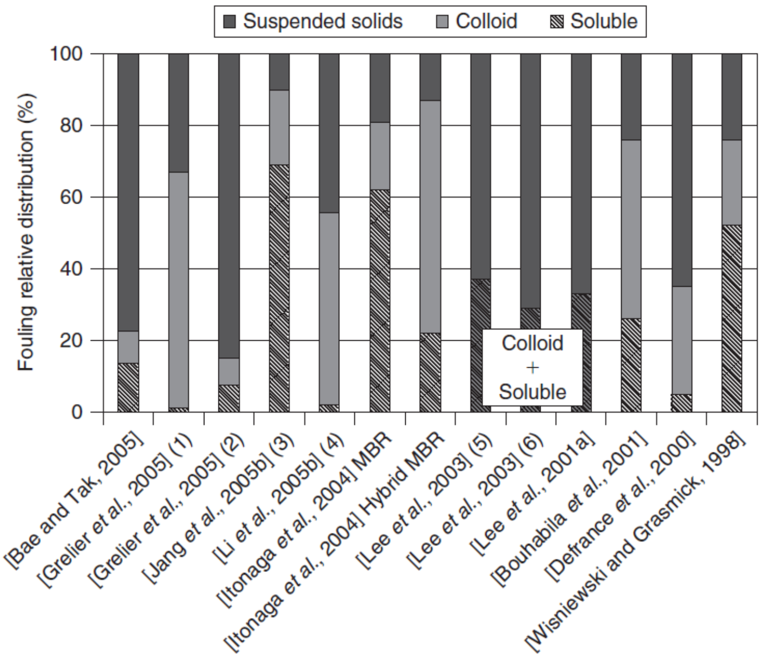


FIGURE 2.9 RELATIVE CONTRIBUTIONS OF THE DIFFERENT BIOMASS FRACTIONS ON MBR FOULING. (1–2): FOR SRT INCREASE FROM 8(1) TO 40 DAYS (2), (3): F:M RATIO OF 0.5, RESULTS BASED ON MODIFIED FOULING INDEX, (4): BASED ON FLUX REDUCTION AFTER 600 MIN OF EACH FRACTION FILTRATION, (5–6): FOR SRT INCREASE FROM 20 (5) TO 60 DAYS (6). [2]

SUSPENDED SOLID

The SS concentration mostly consists of bioflocs and attached EPS. Suspended solids were usually identified as the main foulant in the early days of MBRs due to a correlation with the fouling rates [6]. More recent studies have however included other aspects, and found that it may not be the SS concentration that causes the correlation. They suggest that it could be simultaneously increases in viscosity, SMP concentration, or amounts of solutes [14, 17]. Literature is however not clear on this matter; most studies report of increased fouling with increasing SS, while some reports of no or even a positive change, and yet others found a threshold limit where further increase in SS had a negative effect on the fouling. It has also been found that an optimum level between 8 - 12 g SS/l varying SS concentrations not affected the fouling. The lower fouling observed from high SS concentrations is explained by creation of a rapid and potentially protecting cake filter, which protects the membrane against pore clogging and adsorption. The suspended solid is generally assumed to be responsible for the cake layer formation. Formation of biomass cake in MBRs is however limited by modest fluxes and smaller species like SMP are therefore more likely to deposit. [16]

Results from 20 full scale MBR plants indicate that they frequently are operated with an SS around 10 mg/l. [14]

EXTRACELLULAR POLYMERIC SUBSTANCE

EPS has in the recent years been reported in much research as a main factor impacting MBR fouling. Both better filterability and settling behavior have been illustrated at lower EPS levels. EPS is biological polymers of microbial origin, and consists of insoluble macromolecules which in most cases are polysaccharides and proteins [17]. EPS is produced by active secretion, shedding of cell surface, or by cell lysis, and is considered to be the construction material for bioflocs, biofilm, and activated sludge liquors. EPS may occur as flock-bounded EPS (SS), or as free/soluble EPS (SMP). Literature presents however several contradictory results on how EPS' impact on fouling. One study reported linear relationship between membrane fouling and EPS concentrations. Another study related 90 % of the cake resistance to EPS. Others have found that it is particularly the irreversible fouling that is attributed to the EPS [13]. And yet others found that EPS only has an impact between 20 - 80 mg EPS/g MLVSS. Many found indications that particularly the carbohydrate fraction of the soluble EPS has major role in fouling formation. Others suggested that both proteins and carbohydrates in the EPS around the cells are key parameters for floc formation. A proposed explanation for EPS impact on fouling is that a highly hydraulic barrier formed by the EPS fills the voids between the deposit cells in the cake layer, and thereby reduce the filterability. Another theory is that high amounts of EPS can prevent formation of larger flocs and therefore lead to inadequate flocculation and possible more fouling due to the flock size. Excessive production of EPS may also lead to higher hydrophobisity and more irregular shaped flocks. Too low EPS concentration could on the other hand cause floc deterioration. It may therefore be an optimum EPS concentration at which floc structure is maintained and high fouling propensity is avoided. There are many uncertainties about what influences the EPS production, but SRT is probably the main parameter affecting the EPS characterization. A clear reduction in EPS level has been observed up to 30 days SRT. And an optimum SRTs and organic loading for minimizing the SMP production have been demonstrated. The amount of EPS (SMP) also increases with decreasing temperature, which is probably due to increased EPS producing bacteria. The environmental stress with the temperature decline could also stimulate microorganisms' EPS production. [14, 16, 25]

Most studies rely on extraction of EPS from flocs and the relatively large amount of SMP is not considered. This limits the value of the different results [14]. There are also many ways of analyzing the EPS concentration and to break up the microbial flocks in order to measure the total EPS. This complicates the comparison between different results, and may be one of the reasons for the contradictory results. [17]

Bounded EPS aggregates bacteria cells into flocs or biofilm at the same time as it forms a protective barrier around the bacteria and retains the water. This flock bounded EPS can therefore make a highly hydrated gel matrix out of polymeric network where the microorganisms are embedded. This provides a significant barrier in MBR filtration [16, 25]. The bioflocs attached to the membrane may also be a major nutrient source for biofim growth at the membrane surface. [16]

SMP is originated from the influent water, cell lysis, or break up of flocs. These macromolecules absorb to the membrane, block the pores, or create a gel layer at the membrane surface. [17] The SMP fraction has been reported to be responsible for 17% to 81% of the total fouling. The large range in results is probably due to different operating conditions and biological stages. Use of synthetic sewage in several experiments may also affect these results, as synthetic sewage contains less SMP. The SMP is assumed to be responsible for the pore blocking of the membrane. [16]

FILAMENTOUS BACTERIA

Excess growth of filamentous bacteria is responsible for severe MBR fouling. The extent of these bacteria correlates to increase in EPS levels, lowered zeta potential, more irregular shaped flocs, and increased hydrophobisity. [16]

VISCOSITY

The viscosity of the biomass is closely related to the SS concentration. An existence of a critical SS value where the viscosity exponentially increases has been reported to be between 10 - 17 g SS/l for different operating conditions. Viscosity impacts the system by decreasing the air bobble sizes for scouring, and damping the HF movements. It also reduces the mass transfer and therefore the DO in the water. All of these effects can cause increased fouling with increased viscosity. The capillary suction time (CST) is closely related to the viscosity. [16]

HYDROPHOBISITY/SURFACE POTENTIAL OF THE BIOMASS

The hydrophobic interactions occur from van der Waals forces between molecules and results in a natural tendency of attraction between membranes and solutes if the chemical structure is similar. The direct impact of floc hydrophobicity is hard to assess, but high hydrophobicity generally causes better flocculation and less interaction with hydrophilic membranes. A decreased cake layer resistance is therefore often observed with hydrophobic feeds. The carbohydrate fraction of the SMP has a more hydrophilic nature than the hydrophobic proteins, and sludge with lower proteins/carbohydrate-ratio will therefore more easily adsorb to hydrophilic membranes [28]. [16]

The cake layer permeability also increases with the surface potential of the particles up to a threshold value. This happens due to increase in the inter-particular repulsion which leads to a less dens cake layer. [16] The biomass normally has a negative to neutral surface charge, which is the same as for normal membranes. High ionic strength may therefore compress the double layer around the colloids and reduce the repulsion between membrane and colloids. [29]

2.3.5 OPERATING PARAMETERS AND FOULING

The most important operating parameter regarding fouling might be the SRT and the flux. Also HRT, aeration, cleaning procedure, and temperature are of great importance.

SLUDGE RETENTION TIME

The SRT affects the fouling by controlling biomass characteristics such as SS, PSD, sludge morphology, DO, settling characteristic, and concentrations of SMP and EPS [14, 16]. There are inconsistent results on SRTs impact on fouling. Some studies report an optimized SRT, others found no difference with changing SRT, and yet others illustrated decreased fouling with increasing SRT. The explanation for the contradictory can be that increased SRT in itself not necessarily reduces fouling, since other operation parameters also have a major impact. [17] The advantages of long SRT are generally reduced sludge production with better dewatering and settling properties, and reduced fouling [14, 25]. The improved sludge properties are probably due to increased amount of non-flocculating organisms that provide less biopolymer production and better degradation of macromolecules [25]. The observed reduction of fouling is partly explained by observed decrease of EPS/SMP, and a slightly increase in the mean particle size [14, 25]. However, long SRT also results in a significant increase in SS concentration, which further can increase fouling. The additional air requirements for scouring and keeping the SS in suspension can break up the bio flocks and cause extra cell lysis, and by that increase the fouling potential. Long SRT will also lead to accumulation of inert material in the tank, and materials such as hair and lint could clog the membrane module. Another problem with increased SRT is increased feed viscosity due to the SS, which may reduce the effect of bubbling. Overall it seems to exist an optimized SRT where the SMP concentration is minimized, the membrane clogging is controlled, and the oxygen transfer efficiency remains sufficiently high [2]. This SRT is however hard to determine due to difficulties of acclimatizing an MBR to new SRTs. SRTs in today's MBRs are generally between 10 and 20 days. [16]

FLUX

The selection of flux is an important factor when determining fouling rate. A high flux will give a significantly more rapid cake layer formation due to layer compression [16]. But also the internal and/or irreversible fouling will increase. The optimized flux (sustainable flux) should therefore be determined [14]. Most MBRs are operated with low flux to minimize fouling. Flux rates between 10 to 35 LMH are therefore commonly applied, and a net flux around 25 LMH for municipal wastewater in combination of physical cleaning every 10-12 minute is normal for all configurations. [2]

HYDRAULIC RETENTION TIME

There is an indirect correlation between HRT and fouling, where the fouling generally increases with reduced HRTs. This is because a decreased HRT provides more nutrients to the biomass with a following improved biological growth, and hence increase SS concentration and changes in the SS characteristic. [14] A shift towards larger particles has lately also been observed when the organic loadings are increased [13]. Depending on the membrane, the HRT generally varies from 7 to 22h in MBRs [16].

CROSS-FLOW VELOCITY

Cross-flow velocity (CFV) has been demonstrated to have a major influence on fouling. This can be induced by coarse air bubbles in submerged systems or flow stream in side stream configurations. The CFV improves the back transportation of particles by shear or shear-induced diffusions [17]. It has therefore been observed no flock deposit at high CFVs, while a small TMP increase still was illustrated due adsorption. Hence the critical flux has been reported to increase almost linear with the CFV. Increased CFV has particularly shown a greater impact when SS concentration is high or pore size of the membrane is small. Increase CFV to increase the flux will however simultaneously decrease the TMP, which further will lower the permeability. Although much variation is reported in literature, increased cross-flow will in general cause increased sustainable flux up to a threshold level. Increased CFV could cause deflocculation and release of EPS/SMP above this value, which counteract the scouring effect. [14] The effect of CFV is also reduced on smaller particles, hence the cake layer is made of these [16].

AERATION

An MBR system may be aerobic, anaerobic, or aerobic-anoxic. The aerobic system is commonly applied for both industrial and municipal wastewater treatment. The anaerobic MBR is mostly utilized for industrial wastewater with high organic loadings, and the aerobic-anoxic system may be applied when complete removal of nitrogen is required. [14] Anaerobic and anoxic MBRs are beyond the scope of this thesis.

FIGURE 2.10 MBR AERATION SYSTEM WITH DIFFUSER AND MIXER. [30]

The aeration-system is an important design parameter and contributes significantly to the energy demand. One study indicated however that the impact on fouling from aeration is only about half as significant as the SS concentration [25]. Aeration in submerged MBR has multiple functions and the air is applied for CFV, biotreatment, and flock agitation. All these functions have different aeration demands. Large bubbles are preferred for mixing and scouring, while dissolution for biotreatment demands smaller bobbles which also are significantly more expensive to produce. Fine bubble diffusers have therefore traditionally been applied for biomass aeration while separated course bubble aerators have been utilized for membrane scouring [31]. Figure 2.10 illustrates a typically configuration of a MBR aeration system with fine bubble diffusers and mixers. [2]

Improved scoring effect by temporary absence of flux is called relaxation. This improves performance of the system and is the current state-of the-art for MBRs. Relaxation may further be improved by combining it with reversed flow for HF membranes. [17] The membrane aeration is generally based on previous experiences or recommendations from the supplier. The membrane scouring can be given as specific aeration demand related to the membrane or permeate volume and is a key contributing factor to the energy demand of submerged systems. [32]

The air also mixes the water and can aggregate flocks and hence decrease the fouling. Increased aeration of the membrane will therefore have a positive effect up to a threshold limit. Increased aeration above this limit will break up the flocks and release EPS. [2]

The average DO level in the reactor is controlled by the aeration rates and affected by both the biomass aeration and scouring in integrated systems [25]. The DO affects several parameters such as PSD, biofilm structure, and amount and composition of SMP. Higher DO levels generally lead to less fouling. This is due to lower specific cake resistance caused by larger particles. Significant changes in the microbial communities have also been reported, which may result in increased COD levels at increasing DO. COD is an indicator for SMP, but the contribution is found to be insignificant compared to the positive effect of a more porous cake layer. The ratio of protein/carbohydrates in the EPS has also been observed to decrease with increasing aeration, when microorganisms may produce/contain less protein and more carbohydrates at increased DO due to the faster growth [28]. Fouling in MBR can also be partly due to biofilm created at the membrane surface. The biofilm can cause excess fouling due to large adhesion strength between the biofilm and the membrane, and cohesive strength within the film. Due to the increased thickness, the film becomes partly anaerobic after a while. The transition from aerobic to anaerobic condition seems to create large amounts of EPS and this could also be a reason for increased fouling at lower DO. [16]

CLEANING PROCEDURES

Cleaning the membrane can be done both physically and chemically, where successful cleaning procedures generally employs a combination of the two [14]. Figure 2.11 illustrates the different cleaning options for MBR membranes. [2]

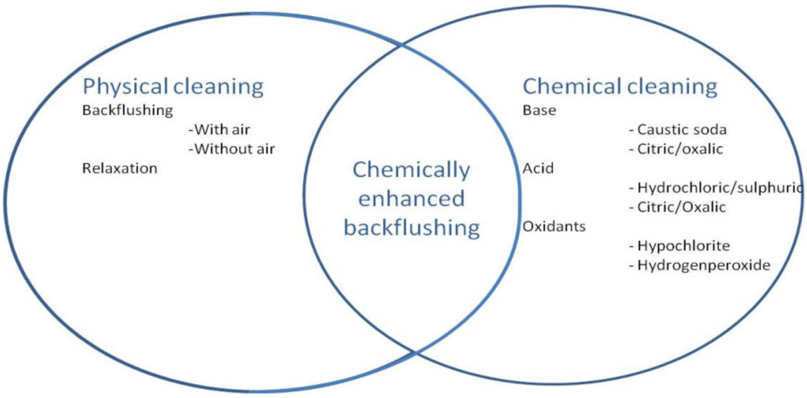


FIGURE 2.11 THE DIFFERENT MEMBRANE CLEANING METHODS [MODIFIED FROM [2]]

Physical cleaning removes reversible fouling. This is less efficient than chemical cleaning but has many other advantages; it is a more rapid process that generally takes less than two minutes to carry out, it does not demand chemicals or produce chemical waste, and it is less harmful to the membrane. There are, as illustrated in figure 2.11, two main options of physical cleaning; backwashing and relaxation. Backwashing is simply flushing the membrane with permeate in the reverse direction. This is not an option for FS membranes due to risk of membrane breakage [16]. The cleaning flux is normally accomplished by 1-3 times the operational flux where 5 – 30 % of the produced permeate is applied [2, 16]. The operational flux determines the period between physical cleanings, but it seems like less frequent backflushes with a longer duration have a higher efficiency. Backflushing can further be improved by combining it with air or relaxation, and backflushing with air is often employed in aerobic MBRs. The air prevents compaction of the cake layer and reduces the internal pore clogging of the membrane [14]. Problems with this technique are however that some membranes may partly be dried out by the air and problems with membrane breakage [16]. Relaxation significantly improves the membrane productivity. This encourages the reversibly foulants to move away from the membrane surface by diffusive back-transportation due to concentration gradients. Enhanced relaxation by additional air scouring is generally applied for both HF and FS MBRs. The process lasts for 1 - 3 minutes and is typically performed every 8 - 15 minutes. A problem with relaxation is however that it might not be economically feasible for large scale MBRs. Intermittent suction also provides an alternative for physical cleaning in submerged aerobic MBRs [14]. Recent studies indicate however that a combination of backwashing and relaxation provides the optimum result. [2]

The effect of physical cleaning tends to decrease over time due to a build-up of irreversible fouling and therefore creates a need for chemical cleaning. The chemical cleaning is expected to completely recover the flux. The virgin membrane permeability will however never be practically reached as irrecoverable fouling will build up and eventually cause the need of membrane replacement. However, chemical cleaning produces toxic or contaminated waste which needs to be handled [14]. [2] The chemical usage also impacts the biological system and the membrane integrity [1], and has a knock-off effect for the expected membrane life time. Different cleaning chemicals may be applied depending on the cause of fouling. [29] There is a lack of systematic studies of the effects of cleaning reagents on MBR membranes, and each of the main MBR suppliers have their own chemical cleaning recipe which usually will be applied [2, 16]. All chemicals applied for MBRs are however based of sodium hypochlorite (NaOCl) to remove organic matter and an organic acid to removes inorganic foulants. NaOCl is an oxidant that oxidizes organic polymers into more oxygen-containing compounds. The new functional groups generally increase the hydrophilicity of the polymers and hence decrease the fouling. The acids are primarily employed for remove scales and metal dioxides from the fouling layers. Chemical cleaning depends on chemical reactions, and the efficiency is affected by parameters such as mass transfer, concentrations, temperature, length of cleaning period, and hydrodynamic. [29] The chemicals can be applied in situ, ex situ, or added to the backflushing water for chemical enhanced backwash. Chemical cleaning can be divided into chemical enhanced backwashing, maintenance cleaning, and intensive chemical cleaning. Chemical enhanced backwashing is applied on daily basis; the maintenance cleaning is performed every third to seventh day while the intensive cleaning is performed once or twice annually [16]. Backflushing is normally not possible for FS membranes and relaxation combined with chemical cleaning will generally be applied.[2]

Recent studies indicate that sonification effectively remove the cake layer of MBR membranes, due to breakdown of the fouling cake. The method is however not effective against all kinds of fouling, but a combination of sonification, backwashing, and chemical cleaning appears to obtain an almost complete recovery of the membrane filterability. [16]

TEMPERATURE

The temperature mainly affects the filtration by changing the permeate viscosity. A normalized operating flux of 20 °C is therefore commonly utilized when results are compared [29]. Eq. 2.2 illustrates normalization of the flux based on eq. 2.1. R_t and J is assumed constant.

$$TMP_{20} = \frac{\eta_{p-20}}{\eta_{p-T}} * TMP_T \qquad (2.2)$$

$$\eta_{c,w-T} = -7.139 * 10^{-9} * T^3 + 9.685 * 10^{-7} * T^2 - 5.528 * 10^{-5} * X + 1.775 * 10^{-3} \qquad (2.3)$$

Where TMP_{20} and TMP_T is the TMP corrected to 20 °C and at the actual temperature, T, while η_{p-20} and η_{p-T} is the clean water viscosity at 20°C and at the actual temperature. Eq. 2.3 displays the correlation between clean water viscosity of different temperatures within a reasonable range, and is utilized for estimating the permeate viscosity [33]. Different hydraulic resistance has however been observed at lower temperatures even after normalizing the flux. There are several possibly explanations for this behavior at lower temperature; [16]

- Increased feed viscosity may reduces air bubble size and hence the scouring effect of the membrane
- Increased deflocculation and release of foulants such as EPS
- Reduced particle back transportation velocity due to Brownian diffusion
- Decreased biodegradation of COD which causes higher amounts of solutes and particular COD in the feed.

All of these effects will most likely cause extended fouling at lower temperatures. The operation conditions should therefore be manipulated in cold periods, with lower filtration fluxes and/or intensified scouring [15]. Figure 2.12 illustrates an overview of the different mechanisms that may take place at lower temperatures, and how they impact the fouling.

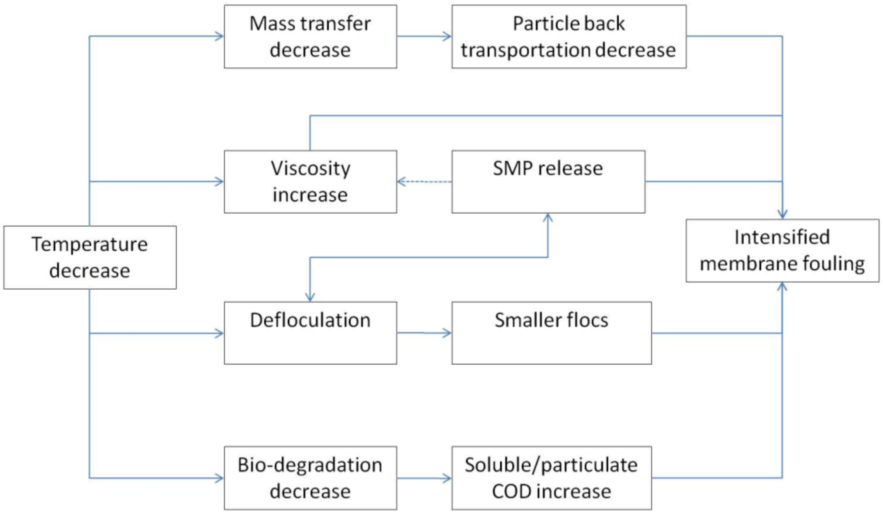


FIGURE 2.12 *THE EFFECTS OF TEMPERATURE DECREASE ON FOULING. (MODIFIED FROM* [15]*)*

UNSTEADY STATE OPERATION

Variations in operational factors such as flow, HRT, organic loadings, and oxygen supply occur frequently in real situations. Unsteady state operation will therefore take place regularly. These changes seem to increase the fouling of MBRs, which partly is due to variations in the nature and structure of the polysaccharides in the feed. The start-up phase of an MBR can also be described as an unsteady phase and data from this period could be valuable for understanding the fouling properties under unsteady conditions later. [16]

2.3.6 MEMBRANE MATERIALS AND FOULING

Membrane properties such as pore size, porosity, surface energy, charge, roughness, and hydrophobicity all have a direct impact on the fouling [14]. Lower fouling is generally attributed to smooth hydrophilic membranes with high porosity and a narrow pore size distribution [16].

MATERIAL

Polymers and ceramics are the main materials currently applied for MBR filtration [1]. Ceramic membranes have illustrated a superior chemical, thermal, and hydraulic resistance. This is however not the main option in domestic wastewater treatment duo to the cost. Membranes made out of stainless steel have also lately been applied in anaerobic MBRs for wastewater treatment, and good hydraulic performance and fouling recovery have been observed. [16] Organic polymers are however the most commonly applied membrane for both water and wastewater treatment. The most frequent polymer in MBRs is polyvenylidene difluoride (PVDF), but materials such as polyethylenesulphone (PES), polyethylene (PE) and polypropylene (PP) are also widely applied. Nearly all the membranes are anisotropic, which means that the membranes consist of a number of different layers. This is typically a thin selective surface layer supported by a ticker, more open and rougher layer. The membranes applied in MBRs also generally have a high porosity with a narrow pore size distribution. It is important that the material can handle a wide range of temperatures, and that it is mechanically strong. The membranes also need to be resistant against chemical attacks from both oxidants and pH. The material applied should in addition have some resistance against fouling. [2]

Research has indicated that PVDF and mixed cellulose ester (MCE) are more prone to cake formation while pore blocking is the major fouling mechanism for PES membranes. [16]

HYDROPHOBICITY OF THE MEMBRANE

Hydrophobic membranes tend to react with hydrophobic materials in the feed, which leads to increased cake layer formation [16]. Applying hydrophilic membranes can therefore reduce the extent of fouling and these membranes generally have a higher critical flux [17]. The benefit may however only be significant for the initial fouling [16]. All of the most frequent applied polymers for MBR membrane are however hydrophobic. A number of methods to modify the surfaces into being more hydrophilic are therefore utilized, and the method applied is often the main difference between the different membranes. [1]

PORE SIZE

The effect of pore size on membrane fouling is strongly related to the PSD in the feed. Particles smaller than the pore sizes can be transported into the pores and block them, while larger particles may accumulate at the surface and create a cake layer. Many studies have tried to explore this matter, but no general trend between hydraulic performance and pore size has been found. Some studies report that the critical flux decreases with increasing pore sizes, while other found the opposite results in the MF range of membranes. [16] One study illustrates that the smallest pore size membrane fouled more during the first 15 minutes while the largest pore size membrane fouled more after 100 days. This indicates that there exists an optimum pore size for given feed and operation. Such behavior could be explained by faster cake layer formation of smaller membrane due to the large cut off, while a larger amount of compounds get into the pores and leads to extended internal pore clogging in larger membranes. Other studies have however found the opposite results. Less fouling has also been observed in MBR membranes with more elliptical pores rather than circular. [16] Most MBR membranes for wastewater treatment apply UF membranes with a pore size smaller than 0.1 µm. These remove flocs, bacteria, parasites, and partly viruses. MF membranes are however also applied. [8]

PORE SIZE DISTRIBUTION AND POROSITY

A narrow pore size distribution reduces the inhomogeneous flux that causes excessive fouling by local fluxes above the critical flux. Narrow pore size distribution is therefore beneficial for the permeability. A high porosity also decreases the local flux at the pores' entrance, which may have the same benefit. Interconnected pore structure can be an additional advantage due to reduced effect of surface blockage. Some studies have however showed that membrane with sponge like microstructure is more prone to pore fouling. [16]

MEMBRANE MORPHOLOGY

The membrane morphology determines the initial fouling mechanisms and the initial macromolecular transmission of the membrane. Rougher membranes are considered to be more susceptible to cake layer formation. [16]

KUBOTA SUBMERGED MEMBRANE

Kubota is the main manufacture of FS MBR membranes [16]. The membrane module was developed in Japan in the late 80s, and the system has been applied in MBRs wastewater plants since the 90s [34-35]. Today there are more than 2 000 Kubota MBRs all over the world (i.e. numbers from 2006). [19, 34] Kubota submerged membrane are FS membranes operated with cross-flow configuration. The membranes are made of chlorinated PE and have a hydrophilic character. They are ultrasonically welded on both sides of a very robust non-woven support layer, and a felt spacer is placed between the membranes and the plate, leading the filtered water in channels to the top of the sheet. [34] The pore size is generally 0.4µm, but the formation of cake layer during operation makes the effective pore size considerably lower. The membrane may therefore retain coliform bacteria and viruses as well. Figure 2.13A shows the setup and surface of one single sheet. [35]

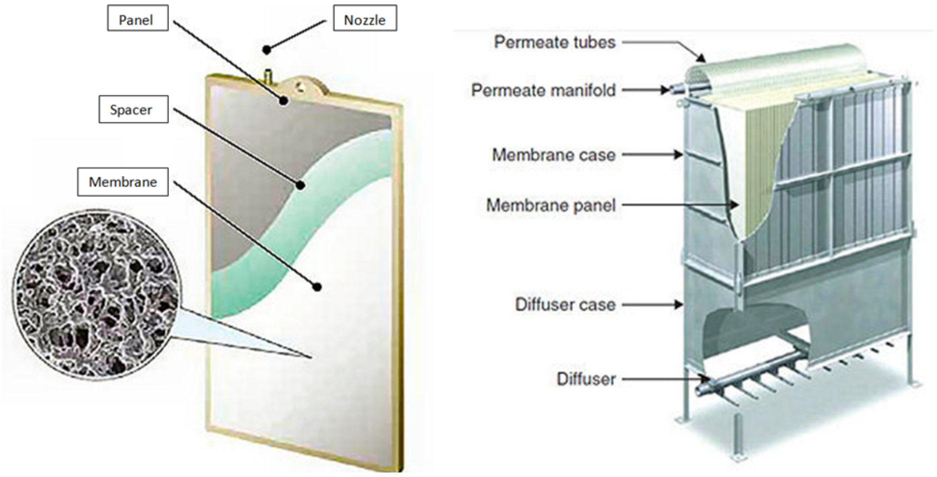


FIGURE 2.13 A- THE SETUP OF A KUBOTA FLAT SHEET B-THE DIFFERENT PARTS OF A SINGLE-DECK KUBOTA SYSTEM [36]

The flow through the membrane is driven by either suction or gravity and permeate is extracted from the top of each plate. Aeration is applied at the bottom of the tank with a coarse bubble aerator. A reactor normally consists of a diffuser case and a membrane case where an FS membrane is placed at every 7th mm. The first Kubota design, shown in Figure 2.13B, was a single-deck configuration where a membrane module could contain up to 200 membrane plates. A double-deck design was later introduced. This design largely improved the efficiency, and the capital cost decreased due to a doubling of the membrane surface-area at the same volume, together with halving the number of required diffuser cases. The operational cost also decreased due to a decrease in specific membrane aeration demand. Kubota has lately developed a module where the membranes interlock to eliminate the need for separate housing for the membrane plates. This configuration provides an even greater surface area per plate and further reduces the aeration demand. [34] Table 2.4 lists the recommended operating parameters for such systems. SAD is the specific aeration demand regarding both membrane and permeate.

TABLE 2.3 – NORMAL OPERATING CONDITIONS FOR KUBOTA MEMBRANES [MODIEFIED FROM [32]]

OPERATIONAL PARAMETERS	VALUES
Net flux - Normal	8.3 – 12.5 LHM
- Peak	32.5 – 42 LMH
HRT	10.5 – 15.4 h
SRT	27 – 70 days
SS	10.5 – 12 g/l
Cycle	8 min filtration, 2 min relaxation
Chemical cleaning	0.5 % NaOCl, 1 % oxalic acid
SAD_m [m^3/h]	0.75 $Nm^3/(h*m^2)$
SADp - Normal	60-90 m^3air/m^3 permeate
- Peak	18 – 23 m^3air/m^3 permeate

2.3.7 FOULING CONTROL

There are several other strategies to reduce the potential of fouling. These can be divided into improving the anti fouling properties of the membrane, operating the system under specific little-fouling conditions, and pre-treat the biomass suspension to limit the fouling propensity. Some of these are listed in table 2.5. [16]

TABLE 2.4-OTHER STRATEGIES FOR ACCHIEVING INCREASED FOULIMNG CONTROL [16]

MEMBRANE MODIFICATION	RECTOR DESIGNS	BIOMASS MODIFICATIONS
-Pre-coating the membrane with TiO_2 or ferric hydroxide flocks -Encouraging formation of a protective cake layer by adding coarse pore sized substrates	-Spiral flocculators -Vibrating membranes -Helical baffles - Sequencing batch reactors - Suction mode -High performance compact reactor -Novel types of air lift - Porous and flexible suspended membrane carriers - Sparging aerators Etc.	-Adding ferric chloride, alum or zeolite as a coagulant -Pre-coagulation /sedimentation before the MBR -Adding particular activated carbon as an adsorption agents -Addition of granular sludge - Addition of cationic polymer-based compounds

2.4 BIOFILM-MBRS

Another option for increased fouling control is to combine the membrane to a BF system. The available literature on BF-MBRs is still limited and no real-size plants exist. There are however prospects of several improvements by conducting BF in MBRs:

- Prospects of increased fouling control due to less SS [20]

- Higher biomass concentration resulting in improved organic removal efficiency, relatively shorter HRT, and/or reduced volume of the reactor [37]
- Improved oxygen transfer rates [37]
- Higher nitrification rates [37]

The literature reports however varying results regarding fouling in the BF system. There are naturally differences in the biomass characteristics in AS- and BF-MBRs, while almost all the knowledge about MBR fouling and operation is conducted from AS MBRs. The membrane fouling characteristic, design criteria, and optimized operations may therefore not be suitable for the BF-MBR, and a number of issues need to be investigated in order to optimize the BF-MBR process. [38]

2.4.1 THE BF-MBR PILOTS

Most of the available pilot studies apply the MBBR process or similar suspended BF systems due to their high tolerance of particulate and organic loadings [13]. Many of these pilot studies are from NTNU in Trondheim, and have generally illustrated high and consistent effluent quality, irrespectively of loading rates and membrane operation mode. However, the membrane performance has varied and seems to depend on the wastewater quality and submicron fraction of SS [20]. The different configurations and operating conditions varies to a great extent between pilots and may affect the results. It is therefore difficult to present the results in a general matter without describing the circumstances they were obtained from. A summary of the literature employ here on BF-MBRs are therefore enclosed in appendix 1. Their results regarding biomass characteristics, operating parameters and membrane will be discussed here.

2.4.2 BIOMASS CHARACTERIZATION AND FOULING

The BF-MBR produces biomass with a different composition and characterization which may encourage other fouling mechanisms than the AS-MBRs. [20]

PARTICLE SIZE DISTRIBUTION

Several of the contributions focuses on PSD, and it seems to be without doubt that the submicron fraction is a major foulant in BF-MBRs. [6, 13, 20, 37-42], Four studies are directly comparing AS- and BF-MBR. All demonstrate increased amounts of smaller particles in the BF reactor. [37, 43-44]

SUSPENDED SOLID

The SS concentration is one of the driving forces for applying BF in MBRs. All the BF pilots have applied different SS concentrations, and some of them may be seen as more hybrid AS/BF systems (IFAS). It seems however to be a contradictory in results on the impact from SS on fouling.

Sombatsompop et al. operated a BF-MBR at increasing SS concentrations. The fouling rates are shown in figure 2.14. The fouling was low at 5 and 10 g/l but increased a significantly when the SS expanded to 15 g/l. [37]

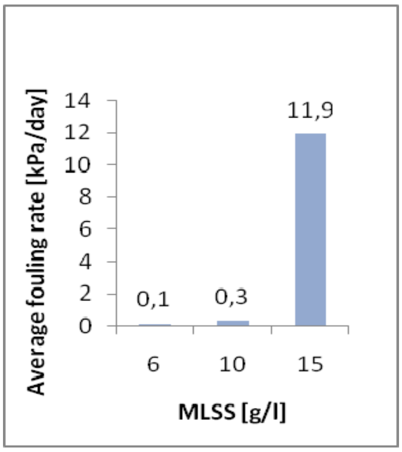


FIGURE 2.14- THE AVERAGE FOULING RATES FOR AN AS- AND BF-MBR OPERATED WITH THE SAME CONDITIONS AND THREE DIFFERENT SS CONCENTRATIONS [MODIFIED FROM [37]]

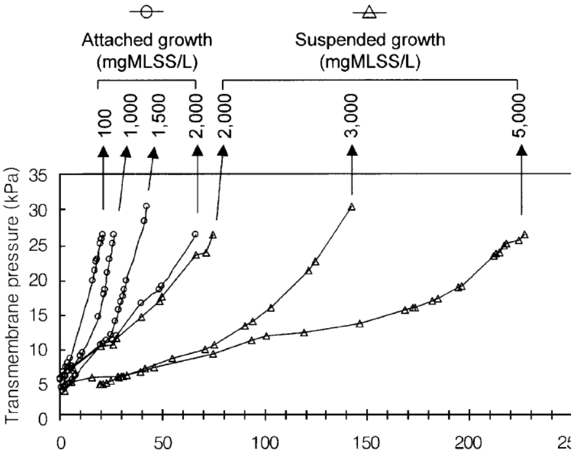


FIGURE 2.15 THE TMP DVELOPMENT FOR THE AS AND BF MBR AT DIFFERENT SS CONCENTRATIONS [44]

J. Lee et al. compared an integrated AS-MBR and a fixed BF-MBR. AS illustrated significantly better fouling properties and the SS concentrations were increased in both reactors in order to evaluate the impact. These results are shown in figure 2.15. The performances of the BF membrane improved with increased SS concentrations within the tested range. The fouling at the same SS concentration was however similar for both reactors. [44]

These results coincide with the literature from AS-MBR which found the existence of an optimum SS concentration. The theory is that too low concentrations prevent formation of a dynamic protecting layer and/or aggregation of submicron particles, while a too high concentration causes increased viscosity and fouling due to the thickness of the cake layer and other side effects such as simultaneously increased SMP production. [16]

EPS/SMP

Incompatible results are also found related to ESP/SMP. Only three of the studies analyzed EPS and SMP directly [4, 37, 44]. Two of these demonstrated that the composition and amounts of EPS and SMP were quite similar in an AS and BF-MBR. This indicates that it is the difference in PSD that caused the different observed membrane performance. [37, 44] Sombatsompop found however slightly smaller amounts of both EPS and SMP in the suspended BF-system. The composition of EPS/SMP also varied between the AS-system and suspended BF-system, with higher protein over carbohydrate ratio in the EPS and lower in the SMP from the suspended BF-reactor. The fouling potential was despite this larger in the BF system, which further support that the submicron particles caused the observed excessive fouling in the BF-MBRs. [4]

Leiknes et al. found however no clear correlation between fouling and SS nor COD. However, a correlation between FCOD below 1.2 µm and the permeability decline was found. This correlation is illustrated in figure 2.16, and suggests that the fraction of organic matter below 1.2µm is an important foulant in BF-MBRs. Indications that COD fraction below 0.45µm had greatest impact were also obtained, which implies that SMP is a major foulant. [6]

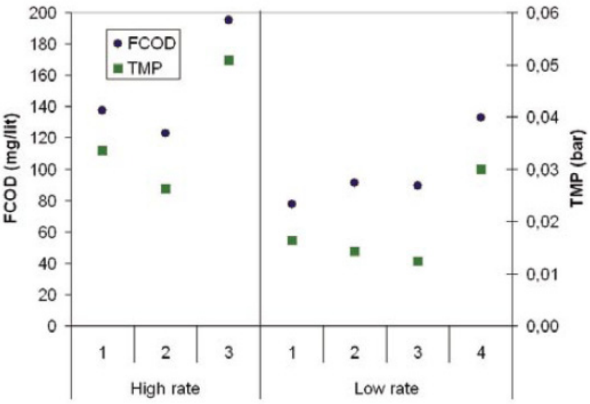


FIGURE 2.16 THE CORRELATION FOUND BETWEEN FCOD (1.2UM) AND TMP FOR BOTH A HIGH RATE AND LOW RATER BF-MBR [6]

2.4.2.1 NITROGEN REMOVAL

The compactness of the MBBR opens an opportunity of nitrogen removal in the same space as a COD-removing AS-reactor. Yang et al. examined the potential of simultaneously nitrification and denitrification in aerated BF-MBR and AS-MBR. One of the advantages with MBRs is that they can operate with high biomass concentrations and provide better retention of slow-growing bacteria such as the nitrifiers. The problem in AS-MBRs is however to make anaerobic areas for the nitrification process within the aeration tank. The potential of anaerobic micro-zones is higher in BF-processes due to the biofilm thickness. The results also illustrated adequate nitrogen removal in the BF-MBR, which increased with increasing thickness of the biofilm. The nitrogen removal was in addition less influenced by variations in the COD/TN-ratio. [43]

2.4.3 OPERATIONAL PARAMETERS AND FOULING

All the pilots from the literature apply cross-flow operation with submerged HF membranes. The membranes are submerged into an external membrane reactor, in a separate space in the reactor, or directly into the BF-reactor. They are operated with constant flux driven by pressure, with or without relaxation and/or backwashing. And the pore sizes ranged from 0.04 - 0.1 µm. Most of the systems treat pre-settled municipal wastewater, while four of them applied synthetic wastewater. [6, 9, 13, 20, 37-45]

EXTERNAL VERSUS INTEGRATED MEMBRANE REACTOR

The membrane reactor may be either integrated or separated. Separation of the membrane unit offers a great advantage since both reactors can be optimized for its purpose regarding flow pattern, turbulence, aeration, and SS. One advantage by integrating the membrane is however prospects of a more compact system. [20] The pilots from NTNU all applied external membrane reactors and generally reported of adequate membrane performances. Some of the experiments in the literature apply however integrated membrane reactors. Four of these compared AS-MBR to BF-MBR, and three of them reported that the AS-MBR was significantly more efficient [4, 43-44]. Comparing these results is difficult, but some of the good performance in the Norwegian pilots could be due to increased fouling control in external membrane reactors.

W. Lee et al. submerged the membrane directly into the carriers in the bioreactor without any protection. The collisions between the carriers and the membrane had a significant positive effect on fouling due to rubbing of the cake layer, and the membrane was hardly damage by the collisions. [9]

THE BF-MEDIA

Most of the pilots applied the MBBR carriers. Four of the studies did however apply another type of suspended plastic carriers at smaller filling fractions (i.e. 5 – 30 %) in addition to larger amounts of AS (i.e. 1.5 - 5 g SS/l) [4, 9, 37, 43], while two pilots applied a looped cord BF-media [4, 44]. Inconsistence in results is however also demonstrated in these studies.

Sombatsompop evaluated the differences in EPS production, and COD- and total Kjeldal nitrogen (TKN) removal in 5 different batch BF-media reactors. This was done to evaluate which BF that was best suited for BF-MBRs. The different BF-medias tested were PE beads (PB), PE granule (PG), PE sheets (PS), cylindrical PP (CP), and PE sponges (S). All the BFs gave good removals of both COD and TKN. Figure 2.17 illustrates the EPS content when EPS was related to the surface area of the different BFs. The PS media had the lowest surface area and hence the largest EPS production. S on the other hand had the largest surface area and therefore the lowest production. This is due to the fact that larger surface areas bind more bacteria cells to the surface, and hence less EPS are in the water phase. The low lifetime and weak physical strength of the sponges made however the author to prefer the second best alternative which was the cylinder shaped PE. This system had the second lowest EPS production per surface area in addition to advantages like good floating and mixing properties, still high surface area, and a non biodegradable nature.

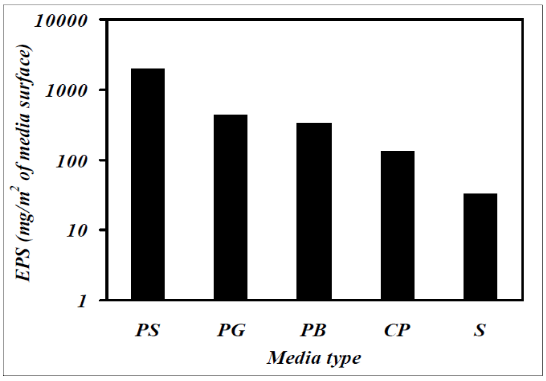


FIGURE 2.17 THE SPESIFIC EPS PRODUCTION PER BF-SURFACE AREA FOR THE DIFFERENT MEDIAS. [4]

Sombatsompop also operated an AS-MBR, a fixed BF-MBR, and a suspended BF-MBR in parallel in order to compare the systems. It can be found from these results that the suspended BF caused slightly better COD- and TKN removal. The suspended BF-media also had less EPS/SMP for all tested HRTs. The fouling potential and cake layer resistance were nevertheless significantly higher in the suspended BF reactor, and the CST revealed worse dewatering properties which corresponded to the smaller mean particles found. This supports that PSD, rather than EPS, plays the major role in BF-MBR fouling and that the movement of suspended carriers may counteract the positive effects of this BF-media. [4]

THE AERATION

An external membrane reactor can give an advantage, as the membrane aeration needs to be optimized for membrane scouring alone. Ivanovic et al. examined the impact of five different aeration rates for membrane scouring. They found that different aeration rates did not impact the effluent quality, but affected the membrane performance. Higher aeration rates improved the performance up to a system specific limit, and less significant enhancement was observed above 3.37 Nm^3_{air}/m^2h. This supports findings from AS-MBRs where increased aeration improves the membrane performance up to a limit where deflocculation counteracts the affect of increased sheer stress. An approach for finding the optimum aeration rate for membrane scouring of a specific BF-MBR was also suggested. The procedure was to change the aeration from high to low with one day steps, while constantly measuring the TMP and daily measure the PSD. The intersection point between the overall fouling rate and the PSD (size at max number percentage) as functions of SAD_m would then indicate the optimum aeration rate for the given system. [40]

HRT

Much of the literature deals with high rate versus low-rate MBBR-MBRs, where the high rates (45 min – 1h) only treat soluble organics whereas full nitrification is achieved in the low rate operations (4h) [4, 6, 13, 20, 38-39]. A significant decrease in the membrane fouling is generally observed at longer HRTs, due to changes in SS characteristic and PSD. Leiknes et al. reached the TMP limit after 1 - 3 days in the high-rate mode and after 12 - 17 days in the low-rate mode under otherwise equal conditions [6]. The generally observed changes at longer HRTs are listed below;

- Larger particles (volumetric %) [4, 6, 13, 36]
- Smaller amount of submicron particles around 0.1µm (relative fraction %) [4, 6, 13]
- Improved dewatering properties shown as shorter CST [4, 39]
- Reduced cake layer resistance [4]
- Reduced amounts of EPS and SMP [4]
- Reduced protein/carbohydrate ratio in the EPS. [4]
- Reduced sludge production [39]
- Improved settling of the sludge [39]

The change towards larger particles (i.e. the volumetric percentage) with increasing HRT may be attributed to increased hydrolysis of colloids or improved flocculation. The trend towards larger particles also indicates that stronger aggregates are produced at longer HRTs, which are not broken by the aeration of the membrane. The trend towards smaller amounts of submicron particles indicates that also these particles are incorporated into the flocks. [20] Result from sludge analysis of high-rate/low-rate investigations also illustrated that the low-rate operation produced 10 % less sludge with improved settling properties, dewatering properties, and filterability. This was probably due to reduced amounts of colloidal matter, soluble organic matter, filamentous bacteria, and more compact particles. [39] A slightly better removal of COD has also been observed in low-rate MBBR-MBRs, probably due to increased hydrolysis of particular COD. [6, 13]

Melin et al. did on the other hand not find any consistent difference in fouling rates when a high load and a low-load pilot were operated in parallel. There were nevertheless large differences in the settling of the sludge into the sludge pocket in the membrane reactors causing less SS around the membrane in the low-rate reactor. [38] An explanation may be that decreased amounts off SS in the membrane reactor caused a smaller protective cake layer and/or reduced aggregation of colloids which counteracted the benefit from a decreased fraction of submicron particles from the bioreactor.

FLUXES

The pilots are operated with fluxes in a range from 1.8 to 60 LMH [4, 45]. Most fluxes in the pure BF-MBRs ranged from 25-52 LMH [6, 13, 39-42], while the fluxes in the more hybrid systems were below 25 LMH [37, 43-44]. One of the lowest reported fluxes was from a study where the sustainable flux was found from a step-test to be only 5 - 6 LMH [38]. The configuration and other operating conditions were approximately similar to the operating conditions in the other complete BF-MBR pilots and it is difficult to evaluate what affected the sustainable flux. Another contribution reports of sustainable operation with relatively low fouling around 60 LMH, and concludes that the MBBR-MBR has a potential of treating 2 - 8 kg COD/m^{3}d with HRTs up to 4h, and a sustainable flux of 50 LMH. The AS-MBR on the other hand have typical operating conditions of 1-3 kg COD/m^{3}d with HRT of 4 - 10 h and a sustainable flux of 15 - 25 LMH. [20, 45] This is a very high flux at high loadings and may indicate the potential of MBBR-MBR under the right circumstances.

CLEANING PROCEDURES

Constant flux, backwashing, relaxation, and chemical cleaning were all utilized in the studies. One research tested both continuously filtration and backwashing, with and without aeration for scouring. It demonstrates that backwashing with continuously air-scoring gives the best membrane performance. [20] Results of fouling from three tests with backwashing and no air scouring, air scouring in pulses, and constant air scoring supports this. These fouling developments are shown in figure 2.18 and clearly indicate that backwashing with continuously air scouring is favorable [45].

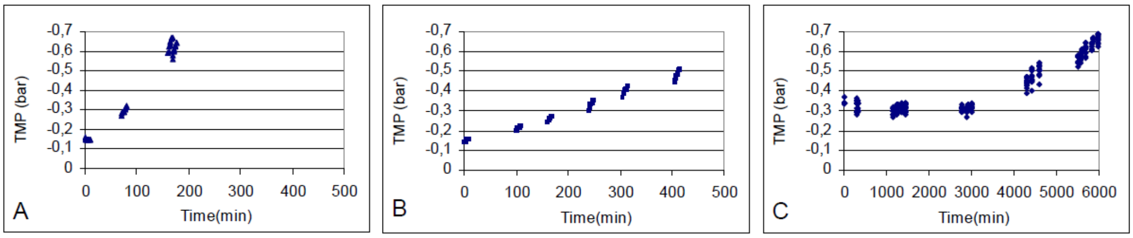


FIGURE 2.18 REPRESENTATION OF FOULING DEVELOPMENT OVER TIME WHEN A) NOR AIR SCOURING, B) AIR SCOURING IN CYCLUS, AND C) CONTINOUSLY AIR SCOURING ARE APPLIED [45]

2.4.4 THE MEMBRANE AND FOULING

All the pilots in the literature applied HF membranes. There is therefore no basis of comparison of different membrane configurations. The pore sizes of the membranes were either 0.04 µm or 0.1 µm, which may affect the impact of submicron particles. [4, 6, 9, 13, 20, 37-44]

2.4.5 FOULING CONTROL

There are several actions that can be done to improve the membrane performance if the submicron particles are the major foulant.

FLOCCULATION

The membrane performance can be improved by flocculation if the submicron colloids are responsible for much of the fouling. Two studies added a flocculation device below the membrane in the external membrane reactor and compared the results to parallel reactors without flocculation. Both experiments found similar results, with decreasing amounts of submicron particles and significantly improved fouling in the flocculating reactors. The sludge also settled better and had better filterability characteristic, which caused significantly less SS near the membrane. The improved membrane performance could however not be directly related to SS or COD/FCOD, but the PSD analyze revealed that flocculation do occur and that submicron particles are being aggregated. These studies therefore support that the submicron colloidal fraction is a significant foulant in BF-MBR. [41-42]

COAGULATION

Adding coagulation to a separate membrane reactor can cause reduced amount of submicron colloids around the membrane, and hence improve the membrane performance. Such systems give the potential for extremely compact wastewater treatment plants with increased fouling control. However, no studies have yet been reported on this matter. [45]

2.5 AS-MBR VERSUS BF-MBRS

The processes of AS and BF-MBR will here be compared.

2.5.1 STUDIES DIRECTLY COMPARING THE AS- AND BF-MBR

Four of the studies made a direct comparison between AS-MBRs and BF-MBRs. Although some of these results are mentioned previously, a short overview of the experiences will be given here.

Yang et al. investigated the potential for simultaneously nitrification and denitrification in an AS- and BF-MBR. The SS concentration did however increase during the experiment, and the BF system ended up more like an IFAS. The two rectors also had different sizes and were operated with different fluxes. Both reactors showed high organic removal, while the fouling in the BF systems was much more severe. This was explained by a denser cake layer caused by deposition of fiber shaped bacteria. The filamentous bacteria further acted as a framework and attracted membrane foulants. [43]

J. Lee et al. studied a submerged membrane operated with and without a looped cord BF media to evaluate the fouling differences. The BF system fouled 7 times faster under the given conditions, even though both systems contained similar amounts and composition of EPS and SMP. The SS concentrations were therefore changed in both reactors in order to evaluate the impact on fouling. These results are discussed under "suspended solid" in chapter 2.4. The PSD revealed smaller particles in the BF system. The improved membrane properties for the AS reactor was explained by the formation of a dynamic layer that kept submicron particles from adsorbing directly to the membrane. The article also separated the total fouling into membrane resistance, cake layer resistance, and resistance due to adsorption and clogging. These results illustrate that the BF reactor gave increased irreversible fouling while the cake layer formation was reduced. The sludge from the AS was also more compressible and created a rougher and looser cake layer with increased amount of channels. [44]

Sombatsompop did two separated experiments on BF-MBRs. The first found higher fouling potential in the BF reactor while the other found reduced fouling in the BF-MBR. The first one evaluated the effect of HRT on an AS-MBR, a suspended media BF-MBR, and a fixed media BF-MBR. The second part evaluated the effect of three different SS concentrations. All the experiments were conducted with equal SS concentration in the AS and BF reactors. The measurements of the fixed BF system generally gave results between the AS and suspended BF-MBR. The results found regarding the suspended BF system in the first part gave slightly better COD removal at low HRTs, slightly lower EPS and SMP concentrations independent of HRT, significantly smaller mean particle size independent of HRT, hence significantly longer CST, significantly higher cake layer resistance, and higher fouling potential for all HRTs. The floc structure, shape, size, and type of microorganisms also differ widely, with dense matrix flocs with smaller sizes and a more irregular shape in the BF reactor. The second part demonstrates nevertheless that the AS-MBR fouled significantly faster than the BF for all tested SS concentrations. These findings included similar amount and composition of EPS and SMP in the two reactors, while a higher relative amount of submicron particles were observed in the BF for all the SS concentrations. The relative amount of submicron particles also increased with the SS in the BF reactors. Less cake layer formation was however observed. The improved fouling in the BF system were explained by the movement of the carriers that produced smaller particles which formed a more porous and thinner cake layer. This is however not in agreement with the other studies. [4] The relative amount of the largest submicron fraction was below 1.5 % for all the BF operations in this experiment while 7 % was at ≈ 25 kDA in J. Lee's [44]. This could indicate that the operation of this BF-pilot encourage less submicron particles which cause the improved performance when compared to the AS-MBR. It might be the large amounts of SS which aggregates the smaller particles and forms of a dynamic cake layer. The latter contribution proves however that the BF-MBR can perform better under certain conditions.

2.5.2 AN EVALUATION OF THE POSSIBLE DIFFERENCES

It seems to be two main wings within the BF-MBR field. (1) The NTNU studies where the BF-MBRs generally seem to have a greater potential than the conventional AS-MBR, but where a directly comparisons not yet had been carried out, and (2) direct comparisons that have been applied several places in Asia, and mostly demonstrate significantly better performance in the AS reactor. Differences in biomass and less SS in the BF-MBR cause a different composition of feed water. This further result in different fouling mechanisms hence different optimized operations and configurations. There is therefore a gap of knowledge before the possibly potential benefits of the BF-MBR can be utilized practically. It is also important to stress that the results within AS-MBR research highly varies, while there are very limited studies evaluating the BF-MBR.

BIOMASS CHARACTERISTICS AND FOULING

The SS concentration is generally significantly lower in BF-MBRs, while the amount and deposition of EPS generally are found to be similar in the two reactors. The amount of submicron particles seems however to be significantly smaller. Hence reduced sludge dewatering and settling properties have been observed. It seems reasonably clear that these small particles are a main foulant in BF-MBRs, while EPS and SMP seem to play a larger role in the AS systems. Increased amounts of filamentous bacteria and less equally shaped flocks have however also been observed in BF-MBRs and could contribute to larger permeability declines. The BF studies indicate that that it exist an optimum SS concentration and that excessive fouling will be caused by concentrations above 10 - 15 g/l. This coincide with studies of the AS-MBRs that illustrate an upper limit around 10 - 15 g SS/l due to the viscosity of the feed, and a lower limit where the fouling increases due to lack of a protective cake layer. The decreased SS concentration could also cause reduced aggregation of submicron particles which further leads to increased amount of this fraction. The anticipated reduce of protective cake layer would then allow increased interaction between the small particles and the membrane. The smaller particles could however also be caused by flock breakups of the moving media.

OPERATING CONDITIONS

It seems like the BF-MBRs can handle higher fluxes under the right circumstances. It can also operate with significantly shorter HRTs, hence provide a more compact reactors. The bio aeration of the reactor may be carried out by larger air bubbles and possible decreased aeration rates, which would contribute to reduced energy cost. The fouling seems however to be more of an irreversible kind, and increased chemical requirements for cleaning could be necessary. It also seems like separated bioreactor and membrane reactor could be a greater advantage in BF-MBR as these reactors generally have improved performances.

A short summery of what seems to be the advantages and disadvantages with the BF-MBR are presented in table 2.6.

TABLE 2.5 POSSIBLE ADVANOUGEST AND DISADVANOUGES OF THE SUSPENDED BF-MBR COMPARED TO AS-MBR [20, 37][43]

ADVANTAGES	DISADVANTAGES
• Prospect of increased fouling control under the right circumstances, due to less SS concentrations. • Prospect of being more energy efficient • Prospect of handling greater organic loadings, or applying higher operating rates • Possibility of more compact reactors • Prospect of increased simultaneously nitrification and denitrification • The MBBR reactor has shown to be more robust against toxic or hydraulic shock loads.	• May increase the need for chemical enhanced backwashing • Possible more filamentous bacteria which causes poorer filtration properties • More research need to be done in order to evaluate the optimum conditions/less knowledge available • Increased amounts of submicron particles which need to be handled to avoid excessive fouling • Decreased sludge settling- and dewatering properties

3 CHAPTER 3 -METHOD

Two pilot plants were operated in parallel to compare the performance and fouling properties of an AS-MBR and a BF-MBR under as equal conditions as possible. Figure 3.1 shows the pilots during the experiment, while figure 3.2 and 3.3 illustrate the different compounds and sample locations in the pilots.

FIGURE 3.1 A-THE AS-MBR PILOT, B- THE MBBR-MBR PILOT

3.1 THE PILOT SYSTEMS

The reactors were made of Plexiglas and were separated into a bioreactor and a semi-integrated membrane reactor by a vertical hold baffle plate. The baffle wall had a screen in the upper part were water could pass and get into the membrane reactor. The total volumes of the reactors were 13 l. The system specifications are listed in table 3.1.

AS-MBR PILOT

The AS-MBR was assumed to be completely mixed and 300 ml sludge was removed daily. Biomass from retentate of another BF-MBR pilot was inoculated in the beginning to accelerate the stabilization phase.

BF-MBR PILOT

The biofilm reactor was an MBBR system using K1 carrier at 67 % filling. This equals a theoretical growth area of 14.7 m^2. The settling was planned to take place in a room separated with a screen in the bottom of the reactor. This did however not work properly and increasingly SS concentrations were observed. The problem was partly solved by introducing an extern 1 L settling tank. A pump pumped 40 mL/min (later reduced to 20 mL/min) into the middle of the tank while an overflow returned the water from the top back into the reactor. 300 mL/d of sludge was then removed from the settling tank..

TABLE 3.1THE GENERAL SYSTEM SPESIFICATIONS

SYSTEM SPESIFICATIONS	
Volum$_{Total}$ [l]	13
Volume$_{Membrane\ reactor}$ [l]	1.6
Volume $_{bioreactor}$ [l]	11.4
Flux [LMH]	10.3
Sludge removal [l/d]	0.3
Membrane type	FS
Membrane area [cm^2]	1160
Membrane pore size [µm]	0.4
Aeration$_{bio\text{-}growth}$ [L/min]	4
Aeration$_{membrane\ scouring}$ [L/min]	4
AS	
SS [g/l]	4.7
SRT [d]	43
MBBR	
SS [g/l]	0.8
Carrier	K1
Area$_{Specific\ growth}$[m^2/m^3]	335

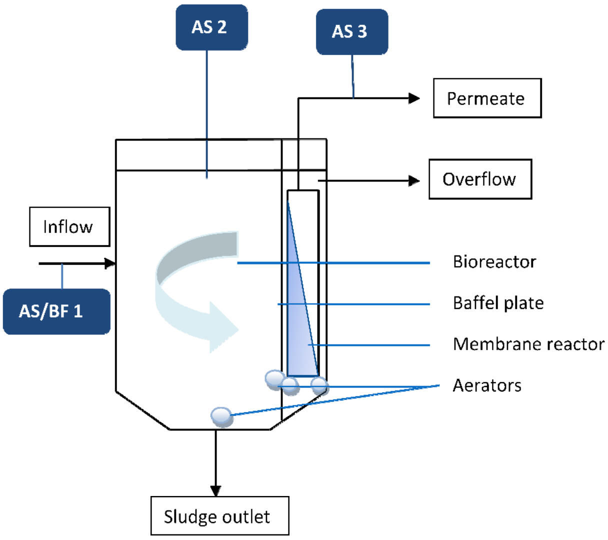


FIGURE 3.2 THE SETUP AND SAMPLE POINTS OF THE AS-MBR PILOT

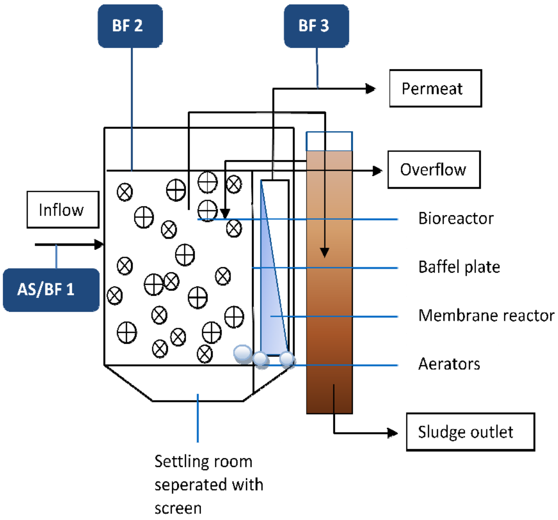


FIGURE 3.3 THE SETUP AN SAMPLE POINTS OF THE BF-MBR PILOT

THE PILOT DESIGNS

The two pilots had equal volume and aeration rates in order to have as similar conditions and costs as possible. A simplified evaluation of the required space and air for secondary treatment was however performed and is attached in appendix D. This was based on the total chemical oxygen demand (TCOD) levels in the raw water the past 6 months and Norwegian guidelines [7] for CAS and MBBR design. The estimated required volumes indicated that the BF pilot has more than enough space while the AS needs a larger pilot for organic removal. The large difference in required space may seem unlikely, but nevertheless illustrates that the BF requires significantly less space. The oxygen demand also revealed a significantly larger aeration demand for the AS pilot. It should however be emphasized that the guidelines neither are made for pilot scales nor MBRs.

THE FEED WATER

The experiments were conducted on semi-synthetic wastewater. The available combined wastewater had a COD concentration below 100 mg/l and ammonia content of 5 - 9 mg/l. As these concentrations are not sufficient to achieve the required biological activity, a synthetic solution was added. The recipe for the solution is listed in table 3.2. The wastewater was passed through a small sedimentation-tank before addition of the synthetic waste. The water was further pumped into the pilots. Table 3.3 lists the average raw water quality together with the standard deviation in the period of the experiment. The values have relatively high standard deviation (stdev.) and the natural variations and variations caused by season/weather may impact on the permeability decline.

TABLE 3.2 THE RECIPI FOR THE CYNTETIC WASTEWATER ADDED

RECIPE
2.9 kg Molasses
480g NH_4Cl
13 g $MgSO_4$
13 g K_2HPO_4
180 g Na_2CO_3
295 g Salmon-peptone
0.7 g Iron sulfate

TABLE 3.3 THE AVERAGE WATER QUALITY AND STANDARD DEVIATION DURING THE EXPERIMENT.

RAW WATER QUALITY											
Parameter	TC	TIC	TOC	TCOD	PCOD	FCOD	SS	NH_4-N	PO_4	TN	pH
Average	120.8	30.1	105.8	458.2	86.6	364.3	74.0	32.1	9.9	42.3	6.7
Stdev.	41.8	18.6	34.7	134.3	39.1	107.8	38.1	11.6	4.0	12.6	0.13

TC denotes total carbon, TIC is the total inorganic carbon and TOC is the total organic carbon. TCOD is the total COD, while PCOD is the particular COD. NH_4-N is the nitrogen content of ammonia while PO_4 is the phosphate concentration, and TN is total nitrogen. All values except pH are given in mg/l.

AERATION

The same air rate and distribution were obtained throughout the whole experiment by using four Dwyer aeration pumps. The membranes were aerated from both sides with a three holed tube for coarse bubble aeration. The holes in the middle were 2 mm (i.e. diameter) large while the two on the sides were 1.4 mm. The total membrane aeration rate was 4 l/min. Both bioreactors were also aerated by 4 l/min, but unequally distributed. The BF-MBR was aerated by a similar tube in the bioreactor, while the AS-MBR had additional aeration in the bottom of the tank to keep the sludge from settling. The holes for bio-aeration were 1 mm large in diameter.

MEMBRANE

The membranes applied were 0.4 µm FS Kubota with a filtration area of 1160 cm^2. The submerged membrane is illustrated in figure 3.4. The scouring by the aeration can also be seen in the illustration. This membrane stands out from the rest of the BF-MBR pilots as only HF membranes with significantly smaller pore sizes have been applied.

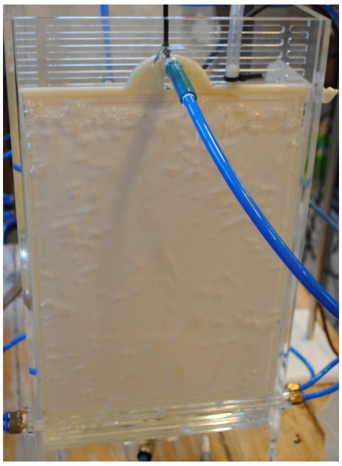


FIGURE 3.4 THE KUBOTA FS MEMBRANE SUBMERGED INTO THE MEMBRANE ROOM IN THE REACTOR

FLUX, HRT AND SRT

The flux was generally kept around 10 LMH, the HRT around 10 h, and the SRT (AS-MBR) around 43 days. The flux and SRT were in the middle of the normal operating range for Kubota membrane, while the HRT was slightly below. This HRT was however long when compared to many of the BF-MBR pilots in similar studies. The long SRT may be of a great advantage for the AS-MBR as decreased fouling is observed for SRT up to 30 days.

PERMEATE

The effluents were extracted through the membrane with constant flux by Master flex L/S suction pumps. The suction heads were Easy-load II and the pumps were connected to a computer and WinLin2_0 software for programming the relaxation. The pumps were operated constantly and with relaxation in different periods of the experiment. The tubes positions were changed weekly in order to eliminate the effect of reduced pumping caused by fatigued tubes.

THE CLEANING PROCEDURE

Air scouring was conducted in the first part of the experiment, while relaxation was added after a while. The chemical cleaning of the membrane between the different experiments were performed by 0.5 % NaOCl and 1 % Oxalic acid. The membranes were soaked into the different solutions for about 24 hours and cleaned with water in between.

3.2 THE ANALYSIS

All analyses were performed according to Norwegian standards. Table 3.4 lists the general frequency of the different samples while the blue marks in figure 3.2 and 3.3 illustrate the sample points. The frequencies varied due to assumed problems with stabilization in the pilots. Instant samples were taken. The reactors were assumed to be completely mixed and samples taken here represent the water from both the bioreactor and the membrane case.

TABLE 3.4 THE DIFFERENT SAMPLES AND FREQUENCY

ANALYZE	SAMPLE	FREQUENCY
SS	AS/BF 1, AS 2, BF 2	3 times pr. week
COD/FCOD	AS/BF 1, AS 2, BF2, AS3, BF3	3 times pr. week (AS/BF 1 –1)
NH_4-N	AS/BF 1, AS 3, BF 3	1 time pr. week
CST	AS 2, BF 2, (BF sludge)	3 times pr. week
Color, UV-absorbance	AS 3, BF 3	3 times pr. week
PSD	AS 2, BF 2, (BF sludge)	3 times pr. week
TMP	AS 2, BF 2	Constantly
Temperature	AS 2	Constantly
DO	AS 2, BF 2	
pH	AS 2, BF 2	

FOULING MEASURES

The overall performance of the membrane process and membrane fouling was determined by logging the TMP measures every minute. Two online pressure meters (Genspec GP 4200) were connected to a pressure transducer (Field Point, FP100 with FP-AI-110 analogue input) and connected to a LabVIEW data acquisition and analysis program. The water temperature was logged continuously with a temperature transducer to normalize the TMP. The membrane was chemically cleaned when the TMP reached -0.35 bars. The fouling was further evaluated based on TMP or daily TMP declines as the flux was held reasonable stabile. The TMP used for further analysis were the average daily value of the hourly 10 % percentile, after the TMP was temperature corrected for the viscosity changes. The daily TMP decline was the three days average difference between the daily TMPs. Two days averages were however applied when the third day was assumed unrepresentative due to membrane change or change of fouling phase.

SUSPENDED SOLID

SS was analyzed according to NS 4733. Suspended solid is here classified as the particles that are retained by a 1.2 µm fiber glass filter. The filter utilized was Whatman GF/C glass micro filter and 10 ml samples from the reactors were filtrated by suction. The SS concentration was calculated by eq. 3.1.

$$X = \frac{1000\,(b-a+c)}{V} \tag{3.1}$$

Where *a* is the weight of the filter before the filtration, *b* is the weight after filtration, *c* is the value from a blind test estimating the average weight loss when 150ml distilled water is being filtrated, and V is the volume of the sample being filtrated. [46]

CHEMICAL OXYGEN DEMAND

COD is an indicator for SMP [25][43] while comparing the COD in the inlet and the effluent gives an indication for the treatment efficiency of the system. The inert amount of COD in the feed is previously found to be around 30 - 40mg O/l. Concentrations near this in the effluent indicates therefore complete removal of biodegradable COD [13]. The COD removal of the BF-MBR is expected to increase over time [43]. The COD was measures with Dr. Lange LCK 314 cuvette tests. COD is here the consumption of dichromate consumed by suspended and dissolved compounds under given circumstances. The COD found can be seen as the amount of oxygen needed to oxidize all the organic material into inorganic end products. The quality of this measurement mainly depends on the extent of the oxidation. What actually happens is that the oxidizable substances in the sample react with sulphuric acid – potassium dichromate in the presence of silver sulphate as a catalyst. Mercury sulphate is added to prevent chloride from impacting the results, and the chloride ions will bind to mercury-chloride-complexes instead. The COD is then found from evaluation of the reduction of the yellow coloration Cr^{6+} with Dr. Lange Lasa 20. This method can be used where the chloride concentration is below 1500 mg/l. [47][48]

FILTRATED CHEMICAL OXYGEN DEMAND

FCOD is found the same way as COD, but with filtrated samples. The filters applied were a 0.45 µm cellulose nitrate filter from Sartonius Stedim Biotech, and a Whatman 1.2 µm GF/C glass microfiber filter. Both these FCOD fractions were measured in order to evaluate which fraction that had the greatest impact.

PARTICLE SIZE DISTRIBUTION

PSD was analyzed by a coulter LS 230. The instrument applies the principle of laser diffraction to measure the particle distribution. A sample was placed in distilled water and circulated through a sample cell. A beam of laser light shined through the cell and got diffracted by the particles in the sample. The diffracted light was then collected by a series of sensors, and the size distribution could be calculated due to the distribution of the diffracted light. Particles from 0.4 – 2000 µm can be measured by this method. Most particles below

0.5 µm will however give a similar flux pattern in the PSD, and smaller particles (i.e. down to 0.1 µm) may be measured by including a second method; PIDS (polarization intensity differential scattering). This method includes light with three wavelengths in both horizontal and vertical direction to catch smaller particles. There are however several problems with this measurements. The sample will change characteristic when it is stored, hence the samples should not be stored for more than 30 minutes. The dilution and circulation of the sample may also break up or flocculate the samples and change the PSD. A pump speed of 30 was utilized in this experiment in order to avoid break-ups of the flocks. A third possible error is that the Fraunhofer model was utilized, which is less accurate for particles below 10 µm, but the refraction index for wastewater is unknown and there is therefore no other option. The model also assumes spherical particles, while little is known about the particle shapes in wastewater. Each sample was measured three times for 120 s with 3 s break in between. [49] There were however problems with the PIDS measures in the PSD meter during the period of this experiment, and particles below 0.4µm were not included in several of the measurements.

COLOR

This test was preformed according to NS 4748 with a Hitachi U-3000 Spectrometer. The color is defines as the optic property which causes changes in the composition of the visible light passing through light. The color is here given as the corresponding reference solution of platinum-cobalt in distilled water. The color normally origins from humus and metal compounds such as iron, and this test is only valuable for colored water within the humus scale. The sample has to be filtrated trough 0.45 µm to remove colored particles, which here is done by the membranes in the pilots. The samples are moved into glass cuvettes and the real color made by the colloids is decided at 410 nm in a spectrometer. The pH of the water may impact on the results, and the samples should be analyzed as soon as possible after they are taken. [50] Most of the effluent colors were outside the range of machines calibrations, and the values had to be extrapolated. The calibration curve utilized is the same as the one applied in the software, and shown in eq. 3.2.

$$C = 354.55 * abs - 0.4740 \tag{3.2}$$

UV-ABSORBANCE

The UV-absorbance was found according to NS 9462 and Hitachi U-3000 Spectrometer. The UV-absorbance is here defined as the optic property that diminishes the intensity of the UV energy of UV light at 254 nm going through the sample. The UV-absorbance is mostly affected by dissolved organic matter, rather than dissolved minerals and suspended matter. The value is therefore closely related to color and TOC. The samples are analyzed in quartz cuvettes. [51]

CAPILLARY SUCTION TIME (CST)

The CST values were used to evaluate the dewatering properties of the sludge. This was done by Triton WPPL type 92/1 and Triton CST papers. Values below 100 illustrated good dewatering characteristics [6]. The machine was however out of order for a longer time during the experiments.

DO

The dissolved oxygen was measured by DO-meter (Hanna HI 9146) according to NS 4765. This is an electrochemical method that works well for crass water such as sewage. An electrochemical cell is separated from the water by a selective membrane. Oxygen passes through the membrane and produces a galvanic effect. The current produced is further correlated to the temperature and the DO concentration in the water can be found. [52]

PH

pH was measured according to NS 4720, by a pH-meter (Mettler Toledo Sevengo pH). This is a meter that measures the voltage between hydrogen ions in the water and in an electrochemical cell. [53]

AMMONIA

NH_4–N was measured in the effluent to evaluate the treatment efficiency of the biomass/biofilm. The ammonia concentrations were evaluated by Dr. Lange cuvette tests, LCK 304. Ammonium ions react at pH 12.6 with hypochlorite ions and salicylate ions in the presence of sodium nitroprusside, and blue indophenols is formed [54]. The ammonia concentration may further be evaluated by absorption of 630 nm light in Dr. Lange Lasa 20 spectrometer [55].

4 CHAPTER 4 - RESULTS AND DISCUSSION

The AS-MBR generally performed significantly better than the BF-MBR with the applied experimental setup. This chapter will first evaluate the differences between the pilots performance before the fouling in the AS- and BF-MBR will be evaluated separately.

4.1 THE PROCEDURE OF THE EXPERIMENT

The pilots were operated for two months before the experiments started. This was to stabilize the biomass as well as initial operating problems. There were also several problems the first month of the experiment due to aeration failure, shock load, and sedimentation problems. Figure 4.1 illustrates the TMP during the whole period. The numbers explains the procedure.

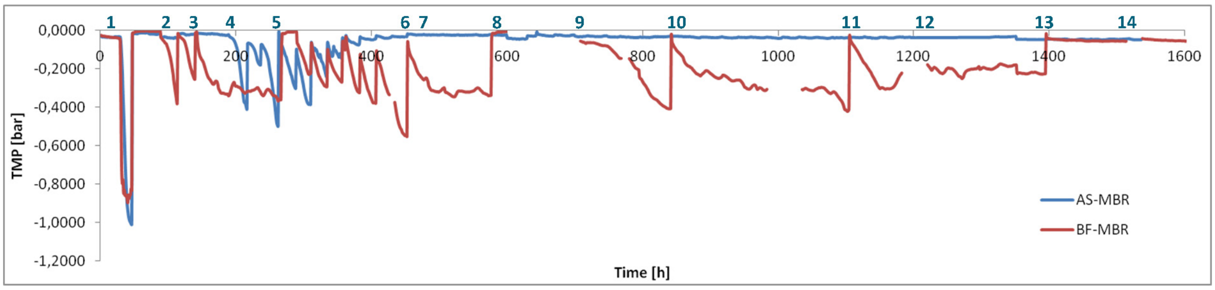


FIGURE 4.1 THE TMP DEVELOPMENT IN THE PILOTS FROM THE TWO EVELUATED MONTHS OF THE EXPERIMENT

1. The aerators stopped working for 15 hours. The flux was 12.5 LMH.
2. The BF started to foul, and the membrane had to be changed two days in a row. Decreased SS together with increase in CST and decreased size of max number percentage were observed.
3. The flux in the BF was reduced to 11.5 LMH, while it was increased to 13.5 LMH in the AS.
4. Shock load from the raw water. The BF reactor seemed unaffected while the AS performance decreased significantly. The AS was operated with relaxation for 20min/day in 11 days, and the fluxes were reduced to 10.5LMH for both reactors.
5. New membranes and 20 min/day relaxation in both reactors.
6. New BF membrane and relaxation for 2min/h in both reactors. A huge population of red worms had grown up in the BF reactor, and high FCOD levels and CSTs were observed.
7. Reduced the BF settling pump flow from 40 to 20mL/h hoping this would improve the settling of smaller particles. The BF pilot stabilized before -0.4bar was reached.
8. The BF reactor was emptied and cleaned as high FCOD and CST measures were thought to be due to the red worms. The aeration was stopped for 24 hours when this didn't help, and a few days were utilized to regain the stability in the reactor. This period is left out of the graph.
9. New membrane in the BF reactor. The SS was very low due to the cleaning of the pilot.
10. New membrane in the BF reactor. The missing spot is a time where the flow had increased with 1LMH. This period is therefore not representative and left out of the evaluation.
11. New membrane in the BF reactor.
12. The flow had increased about 0.5LMH, the TMP went back down again when this was corrected.
13. New membrane and higher SS concentration in the BF system.
14. Final experiment, with new membrane in both reactors, increased SS, and flux (15LMH)

4.2 TREATMENT PROPERTIES

The average effluent qualities and their standard deviations are given in table 4.1.

TABLE 4.1 THE AVERAGE EFFLUENT QUALITY

PARAMETERS	AS-MBR		BF-MBR	
	Value	Stdev.	Value	Stdev
COD –removal [%]	88.9 %	2.6 %	87.3 %	3.1 %
Av. COD levels in effluent [mg O/l]	44.7	7.2	51.4	8.0
NH_4-N removal [%]	99.7 %	0.2 %	98.7 %	1.5 %
Color [-]	118	14.0	130	17.4
UV_{254} [abs]	0.500	0.061	0.525	0.064

Table 4.1 illustrates that the AS-MBR produced higher effluent quality regardless of parameter. The AS also seemed to remove all the biodegradable organics as the inert COD level in the effluent has been illustrated to be around 40 - 50 mg O/l.

4.3 THE PERMEABILITY DECLINES

It can be seen from figure 4.1 that the AS membrane generally performed significantly better, which also coincides with similar documented studies. The average TMPs were respectively 0.20 and 0.58 bar in the AS and BF reactor, even though the BF membrane was changed and chemically rinsed seven times against one for the AS membrane. Microscopic pictures of the membrane feeds are illustrated in figure 4.2 and 4.3. These are taken between point 9 and 10 in Figure 4.1, and should be reasonably representative for the whole experiment. The pictures are magnified ten times.

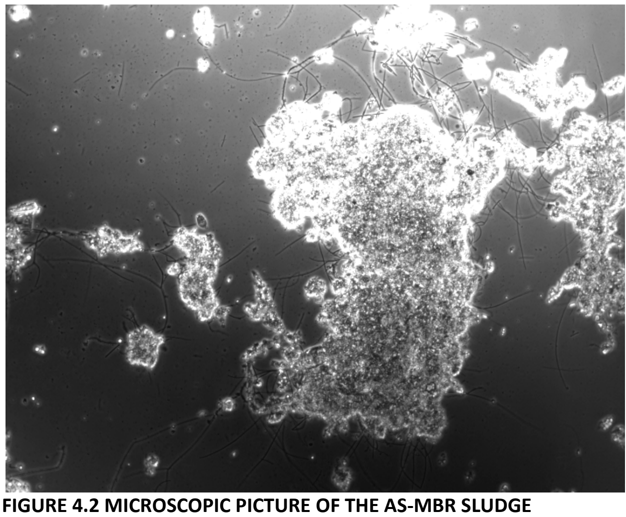


FIGURE 4.2 MICROSCOPIC PICTURE OF THE AS-MBR SLUDGE

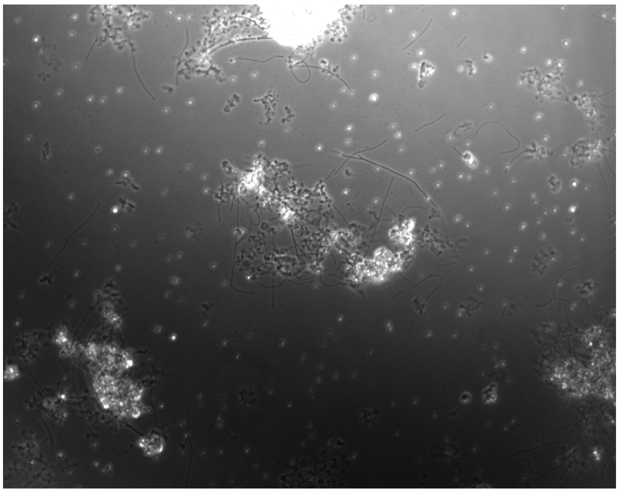


FIGURE 4.3 MICROSCOPIC PICTURE OF THE BF-MBR SLUDGE

The pictures reveals significantly larger flocks in the AS reactor. The amounts of filamentous bacteria seem to be similar in both reactor, but this is difficult to quantify.

4.3.1 THE MEMBRANE FEED CHARACTERISTICS

Table 4.2 lists the average membrane feed characteristics from the two reactors.

TABLE 4.2 THE AVERAGE MEMBRANE FEED WATER CHARACTERISTICS FROM 22.02.10 TO 28.05.10

PARAMETERS		AS-MBR		BF-MBR	
		Average	Stdev.	Average	Stdev.
SS	[g/l]	5.0	0.6	0.7	0.5
FCOD (1.2um)	[mgO/l]	60	18	93	29
FCOD (0.45um)	[mg O/l]	47	21	74	27
Permeate COD	[mg O/l]	45	7	51	8
CST [s]	[s]	18	6	44	43
DO	[mg O/l]	4.5	0.6	4.7	0.5
pH [-]	[-]	6.55	0.3	6.60	0.2
PSD	Av. num % [%]	8.3		8.3	
	Size [µm]	0.079		0.138	
	Av. vol % [%]	3.6		4.3	
	Size [µm]	98		78	

The stdev for the SS concentration in the BF-MBR is large due to evaluation of the performance at increasing concentrations. Significantly larger amounts of FCOD were generally observed in the BF-MBR. The CST was also significantly longer for the BF suspension. Both DO and pH was generally higher in the BF pilot. They were also quite stabile in both reactors, and within the recommended range. The average PSD values revealed smaller particle of the max volume percentage in the BF pilot, together with larger size of the submicron particles at max number percentage. Figure 4.4 shows a representative PSD of the volume distributions for both reactors, which confirm the average values. The figure further confirms that the AS generally had a wider range of particles. Two similar peaks were also often observed around 80 µm and 167 µm. Figure 4.5 illustrates however a representative distribution of the relatively number percentage in the two system, and provides a slightly different impression than the average values. This number distribution reveals approximately the same size of max number percentage, but with higher relatively amounts in the AS membrane feed.

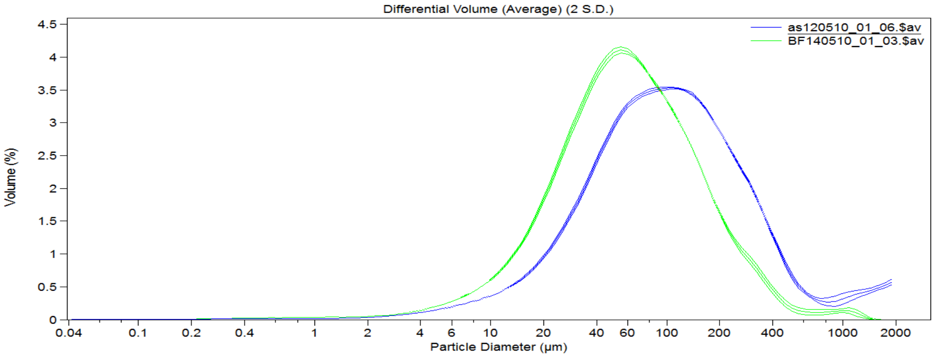


FIGURE 4.4 A REPRESENTATIVE DISTRIBUTION OF RELATIV VOLUME PERCENTAGE IN THE TWO PILOT REACTORS

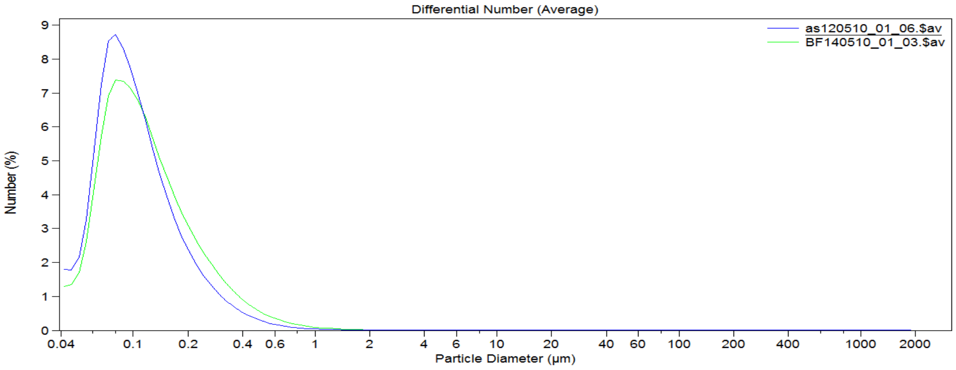


FIGURE 4.5 A REPRESENTATIVE DISTRIBUTION OF RELATIV NUMBER PERCENTAGE IN THE TWO PILOT REACTORS

The significantly larger amount of FCOD in the BF system reveals larger amounts of submicron organic material, and hence a greater fouling potential for irreversibly fouling. This partly coincides with similar studies as increased amounts of submicron particles consistently have been observed in BF-MBRs. FCOD is however also an indicator of SMP, while similar amounts of EPS/SMP generally has been found in these two systems. The CST measures support finding of increased fouling in the BF system. The higher DO level also coincides with the expectations, as less viscous water and higher oxygen transfer rates are observed in MBBR reactors. The PSD measures are however harder to evaluate due to the changing results. The observed increased amount of relative submicron particles in the AS reactor is also in great contrast with the expectations. The extent of SS could however faster create a ticker protective cake layer, which partly would prevent the submicron particles from adsorbing directly to the membrane. The wider distribution of the larger particles in the AS could also form a more porous cake layer, where larger amounts of submicron particles could be adsorbed. The AS pilot therefore posses a greater potential for handling these submicron particles. The observed fouling differences, together with the microscopic pictures of the sludge, and reports from similar literature may however suggest that the PSD measures of the submicron particles are misleading. Higher FCOD in the BF system greatly supports this suspicion. The longer CST illustrates poorer dewatering properties, which also indicates larger amounts of colloidal matter. The increased color and UV absorbance in the BF-effluent further suggest that the number of particles smaller than the pore size/porosity of the cake layer is higher in this system. Observations of significantly poorer settling properties for the BF water are jet another indication of higher amounts of colloidal matter. The following analyzes of fouling compounds and permeability decline neither revealed any correlations between the submicron fraction and fouling, which may be hard to accept as FCOD was found to be a foulant. Problems occurred however with the PSD machine during the experiment, resulting in several measurements where PIDS measures not were included (the measure of submicron particles). The reliability of the remaining PIDS measurements should therefore be questioned. Hence it will further be assumed that higher amounts of submicron particles do occur in the BF reactor, even as this not can be proved. It therefore seems to be significantly higher amounts of irreversibly foulants in the BF-MBR, while the AS-MBR has a greater potential for cake layer fouling.

4.3.2 CRITICAL FLUX –STEP TESTING

The critical flux was evaluated the day before the experiment started. This was done by increasing the flux stepwise for 30 minutes after changing to clean membranes. Seven steps between 7 to 17LMH were applied. The SS concentration was 3.8 g/l in the AS reactor which were quite low and could. The SS in the BF was 0.7. Figure 4.6 and 4.7 illustrates the TMP development, where the red lines illustrate the flux as the experiment took place.

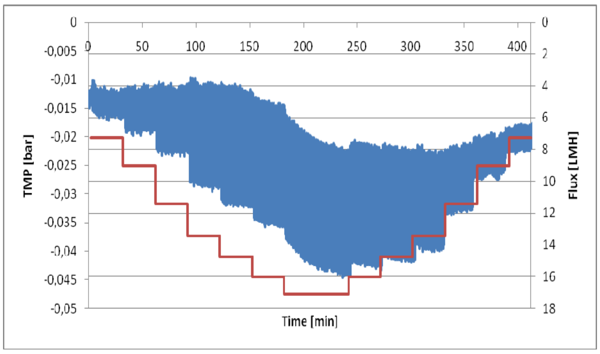


FIGURE 4.6 THE TMP DEVELOPMENT IN THE AS-MBR

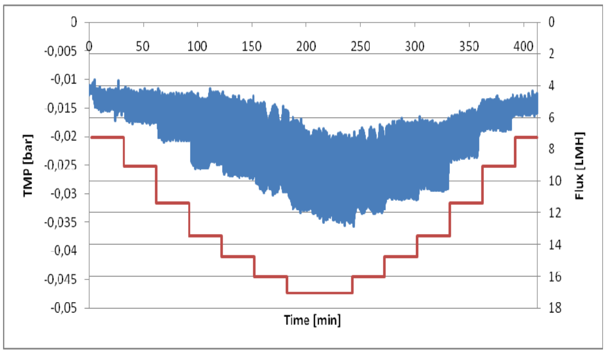


FIGURE 4.7 THE TMP DEVELOPMENT IN THE BF-MBR

The fouling in the AS-MBR stabilized at higher TMP levels up to 16LMH, where the critical flux seems to be reached. It's harder to evaluate the level for the BF-MBR, but the critical flux was certainly reached for both reactors within the next and final step. The flux decline further indicates that the critical flux for the AS actually was lower than 16LMH. The BF regained its initial TMP in the end of the experiment, while the AS stabilized at a lower level illustrating irreversibly deposition. This further supports the findings of a lower critical flux in the AS-MBR.

The sustainable fluxes were not systematically tested. The AS was however operated with 20LMH for two days and seemed reasonable stabile under similar conditions. The BF on the other hand showed unstable conditions at 10 LHM under similar conditions.

The long-term experiment illustrated the opposite as the step-testing, when the BF had significantly greater fouling. The step-testing mainly measures fouling caused by suspended solids, while adsorption and clogging by colloidal matter might be of greater importance in the BF-MBR. This test may therefore not be adaptable for comparing these systems due to assumed different fouling natures. There is neither any report to be found about critical flux testing of BF-MBRs. The instability of the TMP within the steps could further support that the test is less adaptable to BF systems. These results illustrate many of the issues with the short-term flux test, such as the results from short term experiments may not be applicable in real situations, the fouling rate is generally significantly lower in real situations for AS-MBR, and subjective opinions have to be applied when the exact critical flux is evaluated.

4.4 FOULING MECHANISMS IN THE AS-MBR

The fouling in each system will further be evaluated separately in order to investigate the impact from the different fouling mechanisms. Figure 4.8 illustrates the TMP development in the AS system in a stabile period. The period starts at point six and lasts until slightly before point 13 in figure 4.1. This period is chosen to evaluate the fouling mechanisms in the AS-system as the flux is kept stabile, the relaxation procedure is constant, and there are numerous of equally distributed measurements within the period. The missing spot in the graph represents two days where the flux was doubled in order to evaluate the sustainable flux.

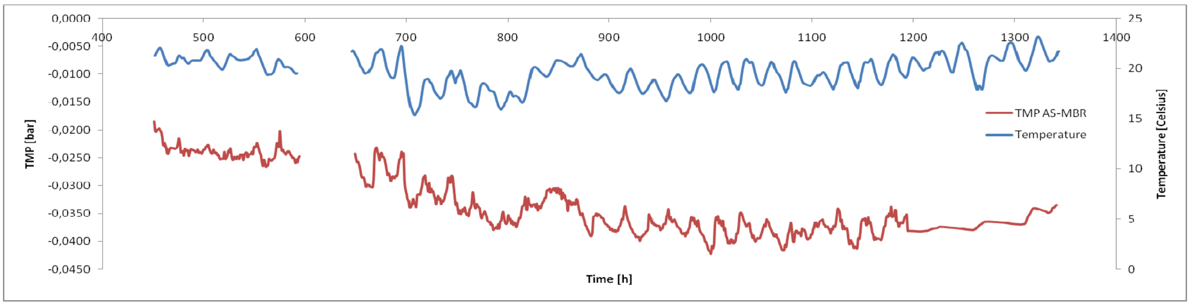


FIGURE 4.8 THE TMP DELEVELPOMENT FOR THE AS-MBR IN AN STABILE PERIOD TOGETHER WITH THE CORRESPONDING TEMPERATURE

The oscillating nature of the TMP measures together with the relatively insignificant TMP development, made it difficult to apply fouling rates to evaluate the fouling mechanisms. The oscillations are probably a function of temperature changes even after the viscosities are temperature corrected. One oscillation is typically 24 hours which confirm the impact of the temperature. The blue line in figure 4.8 also illustrates the corresponding temperatures and further confirms the correlation between temperature and TMP. The TMP increases however with time even though the temperature also increases. Daily average TMPs of the hourly 10% percentile are therefore applied as an indicator of fouling in this system.

A correlation between SS and TMP was found and is illustrated in figure 4.9. Figure 4.10 shows a more modest logarithmical correlation between TMP and the effluent COD. This was further confirmed by logarithmical correlations between TMP and both FCOD fractions (0.45µm - R^2=0.33 and 1.2µm - R^2=0.25, appendix C). A trend of reduced effluent quality at lower TMP was also observed, and a logarithmical correlation between UV-absorbance and the TMP is illustrated in figure 4.11. A weaker correlation suggests the same trend between the TMP and color. No correlations between TMP and PSD were found. The size and relative number of submicron particles measurements were quite stabile during the period, while quantification of the size and number of max volume percentage was hard, due to a wide range of particles often with two similar peaks. Correlations between PSD and fouling can therefore not be eliminated.

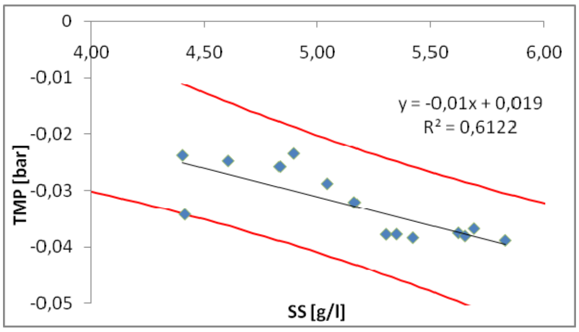


FIGURE 4.9 CORRELATION BETWEEN TMP AND SS. RED LINES ILLUSTRATES THE 95% CONFIDENCE INTERVAL

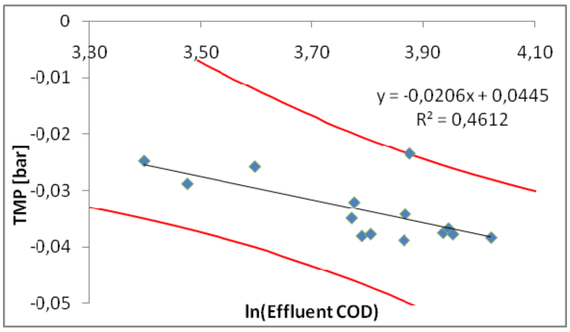


FIGURE 4.10 CORRELATION BETWEEN TMP AND EFFLUENT COD RED LINES ILLUSTRATES THE 95% CONFIDENCE INTERVAL

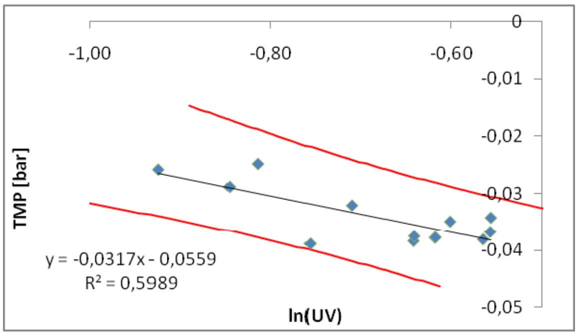


FIGURE 4.11 CORRELATION BETWEEN TMP AND UV, RED LINES ILLUSTRATES THE 95% CONFIDENCE INTERVAL

The flow was measure to be between 10.5 and 11LMH in the evaluated period. This is small changes but could be a source of error. All the TMP correlations were therefore further tested against three days average TMPs. This gave similar correlations, and increased the certainty of the results. The CST was further evaluated as a fouling indicator for the extended period. This increased the amount of measurements and was done in order to further enhance the value of the implications. A discreet correlation between CST and SS were observed (R^2=0.47). A slightly stronger logarithmical correlation between 0.45 FCOD and CST was also found (R^2=0.51), and confirmed by a weaker correlation between 1.2 FCOD and CST (R^2=0.37). All these figures are to be found in appendix D. No correlations were found with the PSD measures.

The 95 % confidence intervals are wide, but there are reasonable indications that SS, hence reversibly fouling is a large fouling mechanism in the AS-MBR pilot. It could however appear that simultaneously changes in the membrane feed characteristic caused the TMP decline. No significant correlations between SS and FCOD or PSD were however found. The correlations between TMP/CST and FCOD are more modest, but suggest that also irreversibly fouling occur. The improved correlation at tighter filtrations (1.2µm, 0.45µm, 0.4µm) could also suggest that especially the FCOD fraction below the pore size of the membrane is a foulant. The increased treatment at lower TMP is in contrast to the idea of a tighter cake layer at higher TMPs. The TMP is however quite stabile and modest through the entire period, and different retention properties within the cake layer may therefore not be of any significance. The impact from the PSD seems trifling, but cannot be excluded.

4.5 FOULING IN THE BF-MBR

The fouling in the BF-MBR was more thorough investigated in order to evaluate how the performance could be improved.

4.5.1 THE TMP DEVELOPMENT

A rapid fouling period after membrane maintenance by chemical cleaning or extensive relaxation for 20 minutes was consistently observed. There were however five times were the TMP stabilized at acceptable levels and the pilot was kept in operation. Three of these phases ended in a rapid second TMP increase, while the final two was stopped before this occurred. The periods are illustrated in figure 4.13, and starts at point 3, 6, 10, 11, and 13 in figure 4.1. The fouling seems to stabilize some before 48 hours in four of the cases, while the fifth run only required a couple of hours to stabilize.

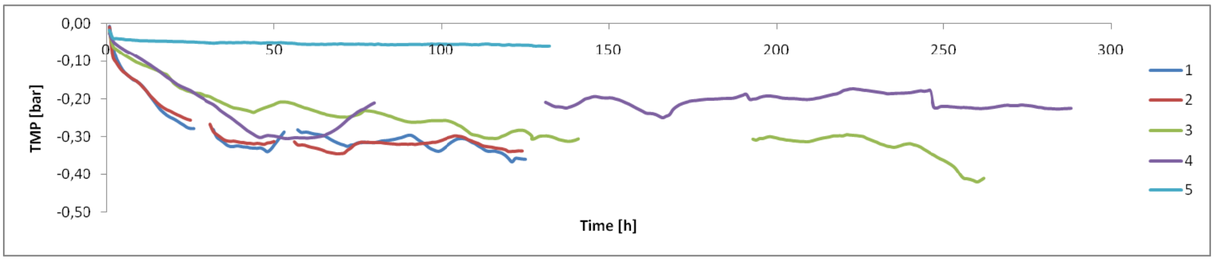


FIGURE 4.12 THE FIVE PERIODS WHERE THE FOUING STABLIZED AT AN ACCEPTEBLE TMP

This pattern could be a variation of the observed fouling pattern from AS-MBR operated with constant flux. The initial fouling would then be the "conditioning period" where irreversible fouling takes place. This phase is however significantly smaller in AS-MBR, which further supports earlier suggestion of extensive irreversible fouling in the BF-system. It should however be noted that much of this fouling was reversed when 20min relaxation was applied. This indicates that also reversible fouling occurs in the initial fouling. The stabile phase would then be the "slow fouling phase". The cake layer would prior to this phase be formed and balanced by the air scouring, and further fouling would mainly be caused by increasing density of the cake layer. The second permeability decline would then be the "TMP jump" where the tightness of the cake layer has increased to an extent where local fluxes exceed the critical flux, hence a rapid fouling occurs.

Both initial and stabile fouling rates together with average feed water characteristics and effluent qualities for the five phases are presented in table 4.3. The level of stabilization increases significantly and is more than six times higher in the fifth run. The initial fouling rate also decreases significantly with time, while the length of the slow fouling stage increases. It can therefore be concluded that the fouling in both the initial and stabile fouling phase decreases a lot from the first to the final period. This is further supported by the decrease in average CST.

TABLE 4.3- FOULING , MEMBRANE FEED CHARACTERISTICS, AND EFFLUENT QUALITY IN THE FIVE PERIODS OF TMP STABILIZATION,.

	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
Flux [LMH]	11.7	10.9	10.8	10.4	10.4
Fouling					
Av. initial fouling rate [bar/h]	-0,008	-0,007	-0,004	-0,004	-0,0001
Av. TMP after stabilization [bar]	-0.32	-0.32	-0.29	-0.22	-0.05
AV. fouling rate after stab. [bar/h]	-0,00047	-0,00006	-0,00046	0,00029	-0,00008
Feed water characteristic					
SS [g/l]	~0.1	0.34	0.91	1.21	1.29
CST [s]		79	34.2	26.5	23.8
PSD -Size at max number [um]	0.097	0.073	0.088	0.094	0.300
PSD - Size at max volume [um]	60.5	48.0	83.3	64.7	92.2
FCOD-1.2um [mg O/l]		122.0	87.9	75.8	
FCOD-0.45um [mg O/l]		92.1	87.9	65.6	
Effluent quality					
COD –effluent [mg O/l]		62.4	52.8	52.0	
COD removal [%]		85.5 %	87.7 %	90.0 %	
Color [mg Pt/l]		117.03	126.92	144.16	
UV_{254} [abs]		0.434	0.547	0.565	

The average feed water qualities are included in the table in order to explain the improved membrane performance. There are mainly two developments that could cause the improved permeability; The SS increases significantly from period to period, while the amounts of FCOD are reduced. The size of the colloidal particles also seems to increase. Increased SS concentration could cause a protective cake layer as well as aggregation of smaller particles. The changes in FCOD and particle size could therefore be a function of increased SS. The decreased FCOD could also be due to improved organic removal properties as the biomass gets more mature.

The effluent quality illustrates a divided development as the organic removal improves at the same time as the effluent color and UV absorbance increases. The increased COD removal could however be explained by improved organic treatment properties by a more mature biomass, which is expected in young MBBR systems. The simultaneously decrease in color and UV could further be explained by reduced filtration due to a less dens cake layer at higher TMPs.

These findings suggest that FCOD, hence irreversibly fouling, is the major fouling mechanism. It's further suggested that the suspended solid is important for BF-MBR fouling, but with the opposite influence as for the AS-MBR. This coincides with the literature where the BF-MBR fouling potential is found to decrease with increasing amounts of suspended solids within this range. Further investigation of the fouling phases separately may however strengthen the indications and provide increased insight into the system.

4.5.2 THE INITIAL FOULING STAGE

Figure 4.14 illustrates the fouling in the initial fouling phases. These are all immediately after extensive membrane relaxation or chemical cleaning. The missing spots are places where pilot maintenance effected the measurements, and are therefore neglected. The average fouling rate for each phase is estimated as the slope from linear regression. These slopes together with the average measurements for each phase are to be found in appendix D. The data from especially the first phases are limited, and the parameters are only based on 1-3 values each. A few data is weighted between two values within the phase to increase their representativeness, and a few of the PSD value is assumed equal as the day before. The flux in the two first periods is about 12.4 LMH while it is 10.5LMH with a standard derivation 0.3 in the remaining 12 phases.

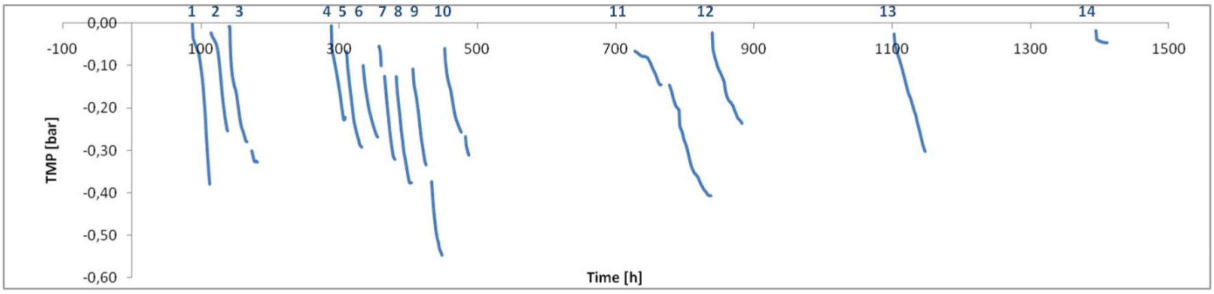


FIGURE 4.13 THE INITIAL FOULING STAGES

The effluent quality and fouling rates were not compared as the cake layer is formed during the phase, end the measurement are taken at varying times of the phase. Two correlations were however found between the feed water characteristic and the fouling rates. These are given in figure 4.15 and 4.16. The first figure is based on eight phases and illustrates a correlation between SS and the initial fouling rate. There are only four phases were FCOD were measured, which is assumed to be too few phases to make any statement of correlation. Figure 4.16 illustrates however a correlation between the effluents COD and the fouling rates. No good correlations between PSD and the fouling rate were to be found.

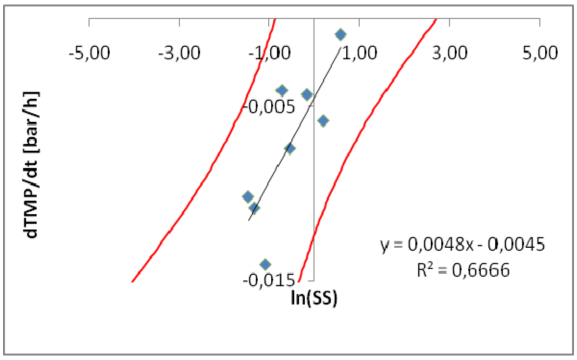


FIGURE 4.14 LOGARITMICAL CORRELATION BETWEEN SS AND FOULING RATES IN THE INITIAL FOULING. THE RED LINES ARE THE 95% CONFIDENCE INTERVAL

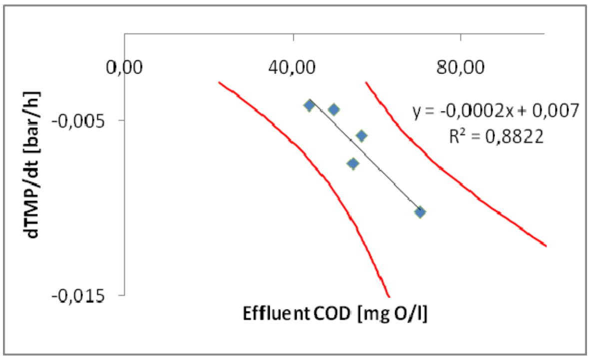


FIGURE 4.15 CORRELATION BETWEEN EFFLUENT COD AND THE FOULING RATE IN THE INITIAL PHASE. THE RED LINES ARE THE 95% CONFIDENCE INTERVAL

These findings illustrates that increased SS is important for fouling control in the initial fouling phase. The correlation is however logarithmical which could indicate that further increase in SS has a limited effect. The second correlation implies that increased amounts of FCOD below 0.4µm would increase the fouling. Increased SS may reduce the initial irreversible fouling by quicker formation of a dynamic and protective cake layer. An affect of increased aggregation may also occur.

4.5.3 THE SLOW FOULING STAGE

There are mainly five different phases, shown in figure 4.17, where the fouling somewhat stabilizes at reasonable TMPs and the system is kept operating. These are the stabile parts of the phases evaluated in chapter 4.5.1. The missing spots are places were improved performance were cause by increases in the flux. The intervals start right after a rapid fouling phase end lasts until the membranes are changed; the assumed TMP jump is therefore included in some of the periods.

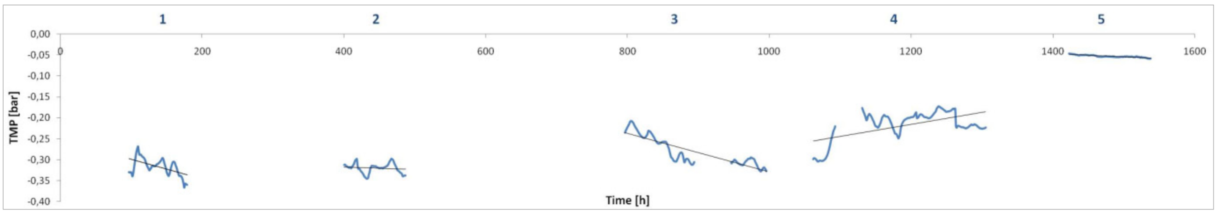


FIGURE 4.16 THE SLOW FOULING PHASE IN THE FIVE STABILIZED PERIODS

Table 4.4 gives the average data from these phases. The third, fourth and fifth period are based on several measurements, while there are fewer measurements in the second phase, and non in the first. The SS in phase one is therefore assumed equal as three days earlier. A great impact on the correlations was however not caused by this point. The slope from linear regression is applied as the average fouling rate in order to compare the phases. The feed water characteristic in the stabile phases will further be compared to the three days average fouling rates in order to increase the number of points for correlation. The average dTMP/dt is applied in order to eliminate the impact of smaller changes caused by alterations in temperature and flow.

TABLE 4.4 THE AVERAGE FOULING RATE, TMP, AND FEED WATER CHARACTERISTICS IN THE FIVE PHASES

PARAMETERS	PHASE 1	PHASE 2	PHASE 3	PHASE 4	PHASE 5
Fouling rate [bar/h]	-0,00047	-0,00006	-0,00046	0,00029	-0,00008
Stabilized TMP	-0,317	-0,320	-0,278	-0,217	-0,053
SS [g/l]	0.3	0.34	0.91	1.36	1.5
FCOD -1.2um [mg O/l]		122	114	76	
FCOD -0.45 um [mg O/l]		92	105	61,85	
PSD Num% [um]		0.073	0.079	0.086	0.116
PSD Vol % [um]		48	82	57	92

No correlation between the fouling rates in the stabile periods, and neither the stabilized TMP levels nor the initial fouling rates were found. A correlation between the stabilized TMP level and SS concentrations was however found and is illustrated in figure 4.17. This was further confirmed by a correlations between the square of SS and the daily TMP averages in figure 4.18. Only a weak correlation was found between the slow fouling rates and the SS (R^2=0.34) indicating decreased fouling at higher SS. The PSD was measured for four of the phases but no correlation was found. The FCOD was only measures for three of the phases, there was however a clear correlation between the square of 0.45-FCOD and the fouling rate (R^2=0.95), suggesting reduced fouling rates with decreasing FCOD. This could also be seen in the 1.2 FCOD fraction (R^2=0.51), but there were not enough points to make any statement. Figure 4.19 and 4.20 therefore illustrates the correlations with the three days average fouling rates and FCOD. No correlations were found between the daily fouling rates and neither PSD nor SS.

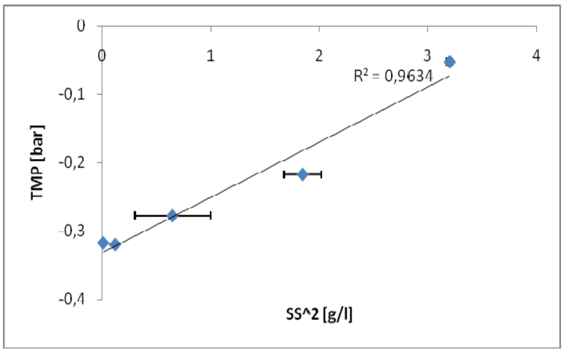


FIGURE 4.17 TCORRELATION BETWEEN THE SQUARE SS AND THE AVERAGE TMP IN THE STABILIZED PHASES, WITH ERROR BARS (THE FIRST MEASURE IS BASED ON ONE VALUE)

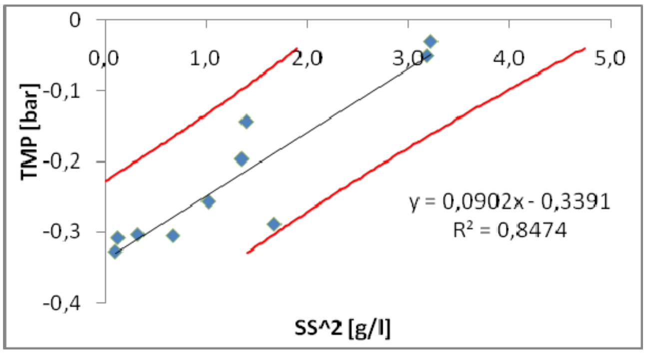


FIGURE 4.18 THE SQUEARE OF SS AND THE DAILY TMP MEASURES IN THE TABILE PERIODS. THE RED LINES ILLUSTRATE THE 95% CONFIDENCE INTERVAL

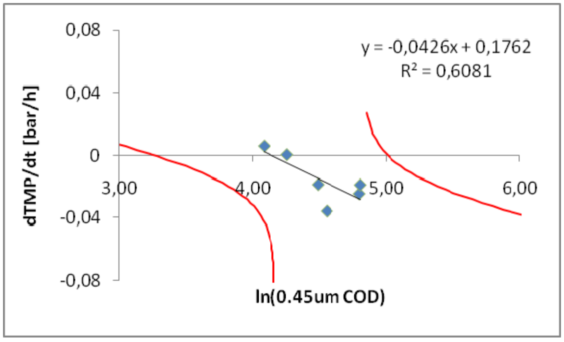


FIGURE 4.19 THE CORRELATIONS BETWEEN 2-3 DAYS AVERAGE FOULING RATES AND LN(FCOD) BELOW 0.45UM. THE RED LINES ILLUSTRATE THE 95% CONFIDENCE INTERVAL

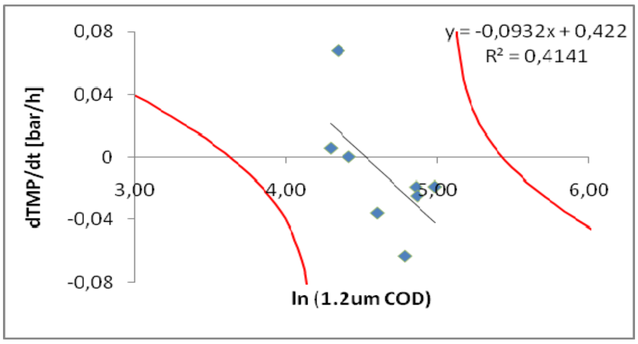


FIGURE 4.20 THE CORRELATIONS BETWEEN 2-3 DAYS AVERAGE FOULING RATES AND LN(FCOD) BELOW 1.2UM. THE RED LINES ILLUSTRATE THE 95% CONFIDENCE INTERVAL

The lack of correlation between slow fouling rate and stabilized TMP level and initial fouling rate supports that different fouling mechanisms occur in the two stages. The SS correlations further implies that high amounts of SS causes lower stabilized TMP, while the affect on the fouling is reduced once the cake layer is stabile. The FCOD correlations further suggests that especially the fraction below 0.45µm is the main foulant also in this phase, even though the 95% confidence interval is large. The main fouling mechanisms in this phase could therefore be adsorption within the cake layer and hence decreased porosity.

The affect of increased SS may be divided; A protective cake layer could be formed at a higher rate causing a more rapidly protection between the adsorbents and the membrane surface, hence decrease the potential for initial conditioning by absorbance. This would further decrease the length of the initial fouling as well as the TMP for stabilization. A ticker cake layer will also be formed at higher SS, causing increased adsorption potential. This could further keep the membrane running for a longer time in the slow fouling phase. Increased SS could also aggregate the submicron particles prior to deposition on the membrane and/or increase the relative range and size of particles at max volume percentage. Such development may further cause a more porous cake layer, hence reduce the resistance.

4.5.4 THE IMPACT OF SS ON THE OTHER PARAMETERS

The correlation between SS and the feed water characteristics could be interesting to evaluate in order to find out if simultaneously changes in the water characteristic may have an impact on the results.

SS AND COD

No correlation between SS and neither the permeate COD nor the FCOD fraction were found. This could indicate that the affect of aggregation of foulants may be less considerable. A correlation between the COD removal and the SS concentration in the BF reactor was however found and is illustrated in figure 4.21. This indicates that the BF reactor have better treatment performance at increased SS, which could indicate increased biological performance at higher SS, or be a product of higher SS as the biomass matured in the experiment.

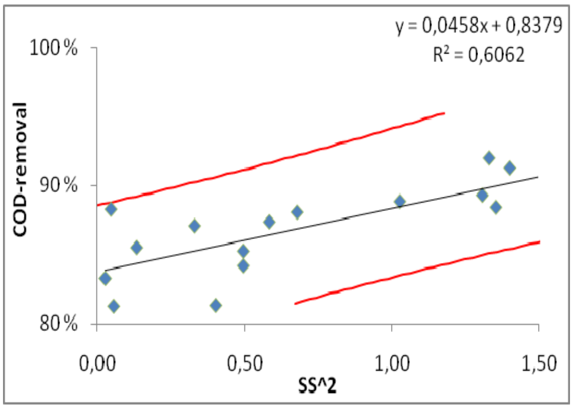


FIGURE 4.21 CORRELATION BETWEEN THE COD REMOVAL AND THE SQUARE OF SS. THE RED LINES ILLUSTRATE THE 95% CONFIDENCE INTERVAL

SS AND CST

No significant correlation was found between CST and SS in the BF-reactor. This is however probably due to few measurements as the machine broke down. The measurements that were taken are also concentrated around the period with red worms.

SS AND UV_{254} AND COLOR

A modest logarithmical correlation between SS and UV-absorbance was found for the BF permeate, and is illustrated in figure 4.22. This supports that a denser cake layer is created at lower SS, which retain more humic substances. An even weaker correlation between the permeate color and SS (R^2=0.19) may further support these indications.

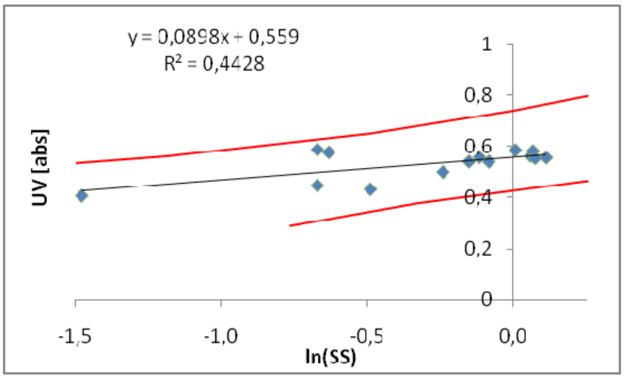


FIGURE 4.22 CORRELATION BETWEEN UV-ABSORBANCE AND LOG SS, THE RED LINES ILLUSTRATE THE 95% CONFIDENCE INTERVAL

SS AND PSD

Figure 4.24 illustrates the correlation between the sizes at max volume and the square of SS. This correlation is not strong but could indicate that an aggregation of large particles takes place at higher SS concentrations.

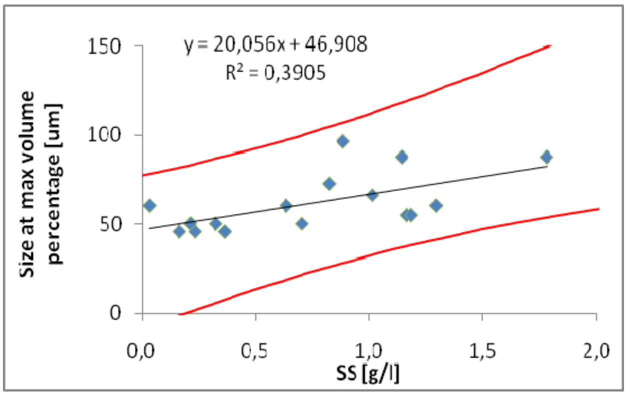


FIGURE 4.23 THE CORRELATION BETWEEN SIZE AT MAX VOLUME PERCENTAGE AND SS

The lack of correlation between FCOD and SS suggests that it is creation of a protective cake layer rather than aggregation of submicron particles that causes the change. Increased sizes of the larger particles are nevertheless observed and may contribute to increased permeability by forming a more porous cake layer at higher concentrations of suspended solid.

4.5.5 INCREASED FLUX AND SS

A final experiment was executed in order to strengthen the indications of the impact from suspended solids. The SS was therefore increased to an average of 1.7 g/l in the BF-pilot and kept at 5.8 g/l in the AS-MBR. The filling fraction of the BF-MBR was further reduced to 50%. This was done when troubles of keeping the carriers in suspension at such high SS levels earlier had been observed. The settling tank was also eliminated when high SS had caused issues with the sedimentation unit. Both membranes were changed before the experiment started, and the flux was increased to 15LMH in order to speed up the process. Figure 4.25 illustrates the observed TMP development. The BF fouled less than the AS for the first time under stabile conditions, due to significantly reduction of initial fouling.

These results strongly support that increased SS concentrations cause improved BF-MBR performance. The wastewater was however shut down the second day, and the system was kept alive by only the synthetic part of the raw water. This could have affected the performance, but the systems had already stabilized before this occurred. It should also be mentioned that the AS had a slightly higher SS concentration than normally, which may have influenced on the performance of this membrane in a bad direction.

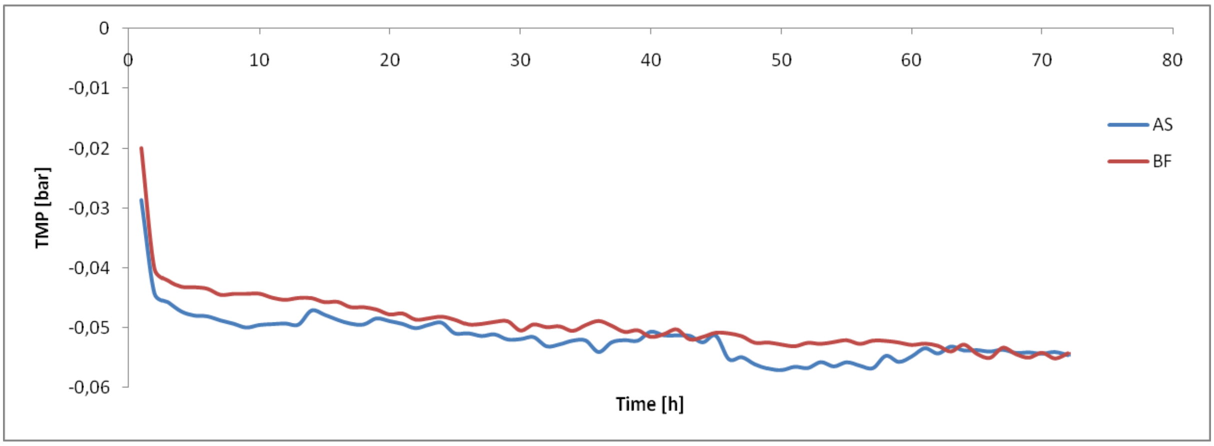


FIGURE 4.24 THE TMP DECLINE IN THE TO PILOTS AFTER THE SS WAS INCREASED TO 1.7 IN THE BF REACTOR

4.6 OPERATIONAL PROBLEMS

There have been observed several operational problems during the experiment. These will further be discussed here in order to make a full comparing of the MBRs.

THE REACTION TO FAILURE IN THE AERATION SUPPLY

The aeration ceased for almost 18 hours due to failures in the aeration system at point 1 in figure 4.1. This gave an opportunity to observe the systems reactions to such operating issues. Figure 4.25 illustrates the TMP increase when the membrane scouring was cut off, and equals point 1 in figure 4.1. It can be seen that the BF reacted instantly but stabilized after a short period. The AS fouled however at a slower rate but constantly until the aeration was turned back on. These results are hard to generalize. But the BF may have a more severe reaction to smaller breaks in the aeration system, which probably is caused by a denser cake layer. The eventually higher TMP in the AS could however be due to compaction of a ticker cake layer caused by larger amount of suspended solid.

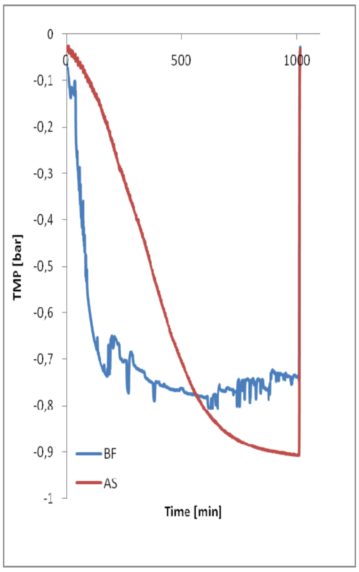


FIGURE 4.25 THE TMP DECLINE IN THE TWO PILOTS WHEN THE AERATION WAS CEASED

THE REACTION TO SHOCK LOADS

There was presumably something in the raw water which highly affected the performance of the AS-MBR after about 200h (point 2 in figure 4.1). The following TMP increase is shown in figure 4.26. The AS-MBR was further operated with relaxation for 20 min/day until the initial good performance was regained, which took about ten days. The existence of the shock load was confirmed by other pilots, but the BF-MBR seemed to be unaffected. This is in line with the literature where more robust properties against both organic and toxic shock loads are illustrated in MBBR system.

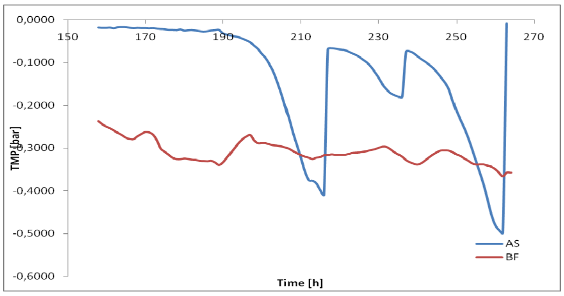


FIGURE 4.26 THE TMP DECLINE AFTER A SHOCK LOAD

A huge population of red worms seemed however to grow up in the BF pilot soon after the happening. Microscopic pictures of these are showed in figure 4.27. This could indicate that the shock load affecting the AS consisted of very low amounts of organics together with high levels of DO. Extensive populations of red worms should normally not be a problem in MBBR systems due to turbulence and motion of the carriers. The carriers are however made for real size plants and are large in the small pilot, which may have given the worms an opportunity to graze on the biofilm after all. The reactor was cleaned and the water was changed in order to handle the problem. The worms did however not disappear until the aeration was shut down for 24h. There were few measurements in this period due to Easter vacation, but measurements in the last part of the period revealed extreme CST values of 165s together with higher colored effluent (165) and poor COD removal (81.3%). The system improved however previously to the elimination of the worms and it's therefore hard to evaluate the impact of the worms.

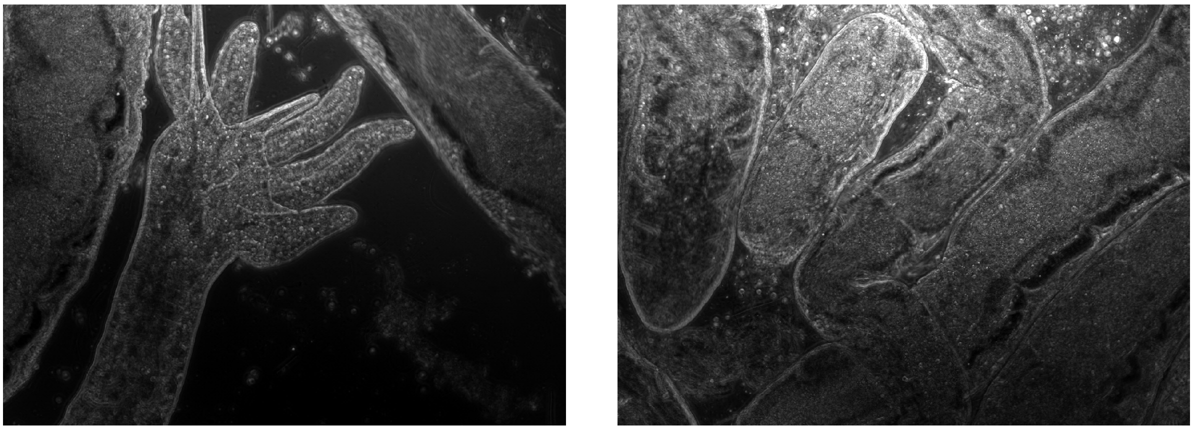


FIGURE 4.27 MICROSCOPIC PICTURES OF THE RED WORMS MAGNIFIED 10 TIMES.

This indicates that both rectors may have been affected by the shock load in its own way. The AS reacted however immediately and with increased effect. The red worms may also not have been a problem in a full scale reactor.

AERATION

Another issue with aeration was increased tendency of aeration hole clogging the in the BF-system, which may have reduced the effect of membrane scouring. This was also a problem for the biomass aeration at high levels of SS, and could support the indications of smaller particles in this reactor.

SEDIMENTATION

Sedimentation was a huge issue in the BF-pilot. There was a small protected room in the bottom of the BF reactor for sedimentation. This did however not work properly due to erosion caused by circulation of flow and carriers, and the SS in the pilot kept building up. An external cylindrical sedimentation tank of 1L was therefore installed, and 40 mL/min was pumped into the middle of the tank, while the water on the top went back into the reactor tough a tube. This decreased the speed of sludge accumulation and worked reasonably well the first time. The initial bad performance of the pilot was however thought to be due to accumulation of small particles. The theory was that only the large particles had enough time to sink to the bottom.. The sedimentation flow was therefore reduced to 20 mL/min. This might have worked as the TMP stabilized immediately after. The sludge properties kept however changing as the SS increased. And the sedimentation went from phase A to B in figure 4.28, where some sludge floated to the top while some sank to the bottom. The sludge kept changing, and moved temporarily into stage C in the final period of the experiments. This lasted however only for a couple of days before the overflow tube was plugged.

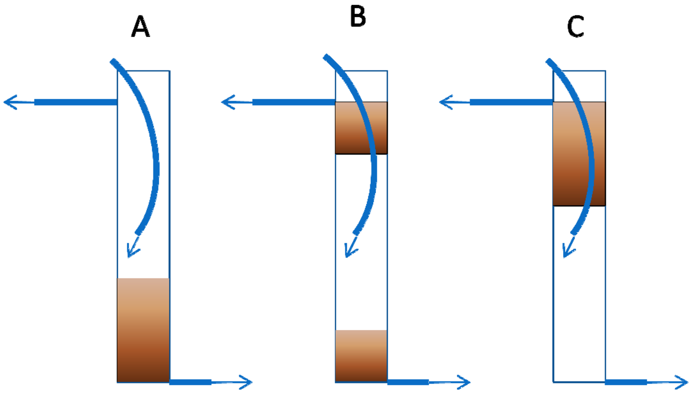


FIGURE 4.28 THE DIFFERENT STAGES OF THE SEDIMENTATION PROPERTIES

Increased flocculation of submicron particles could have taken place in the sedimentation tank, hence reduced the fouling potential. A divided effect of the floating sludge could also occur; it could cause increased sludge in the reactor as only limited sedimentation took place, but it could also work as a sludge blanket and keep smaller particles from returning. The settling tank was however eliminated after the tube got plugged and prior to the increased flux/SS operation, but the membrane performance kept improving significantly. This suggests that the possibly impact on the PSD from the settling tank not was of a major influence.

The sludge handling remains however a problem in the BF system. And a small flotation unit could have been a better choice than the sedimentation tank. A larger and more protected space integrated in the membrane reactor may also have solved the problem.

RELAXATION CONTRA CONSTANT FLUX

Both systems have been operated with constant flux, relaxation for 20min/day, and relaxation for 2min/h. The conditions were however somewhat different in the different operations, and no statements can be made. It may however seem like daily removal of the cake layer by extensive relaxation not worked well for the BF membrane.

4.7 ASSESSMENT OF THE EXPERIMENT

There are a several different sources of errors relating to both the experiment and the analysis. The increased tendency of clogging in BF-MBR aerators might have decreased the scouring effect, hence increased the fouling in this reactor. Introduction of the external sedimentation tank in the BF-MBR lowers the comparable basis as the tank provided an extra volume and hence increased HRT. It could also affect the system by increased flocculation, even though no such effect could be quantified. Temporarily anaerobic conditions could also occur in the initial sludge pocket as this only was emptied weekly. Such changes from aerobic to anaerobic conditions are anticipated to produce excessive amounts of EPS, and thus may have affected the reactor in an undesired direction. Errors in the CST, DO, and PSD measurements could also have occurred, as all of these meters broken down for parts of the experiment period.

The AS-MBR illustrated nevertheless a significantly better membrane performance in this experiment. Improved effluent quality was observed simultaneously. This seems to be due to less foulants such as SMP and possibly submicron particles. The AS-MBR may also have increased potential for handling these foulants, respectively through increased membrane protection, adoration, and/or flocculation caused by the extensive SS. The prospect of a more compact, stabile, and energy economical unit maintain however the desire of exploring adequate approaches for common BF-MBR issues. An approach may be to explore how the fouling can be stabilized at an acceptable level and kept here for longer periods. Increased capital cost for obtaining this may be justified by reduced operational costs due to increased oxygen transfer and reduced space requirements. Introducing extra membrane surfaces to decrease flux can therefore be a feasible option. The results in this thesis suggest however that increased amounts of SS easily could improve the performance of the BF-MBR system. This could be obtained by operating the BF-MBR as a hybrid AS/BF system, but many of the advantages with the BF-MBR would then be reduced. Another option may therefore be to operate the BF-MBR with an external membrane reactor where higher amounts of suspended solids are present. The poor settling property of the sludge is another issue that needs to be taken care of. These issues may however be smaller in larger treatment pilots, or reduced by introducing IFAS or external membrane reactor with increased SS. Appliance of a small flotation unit or utilization of a sludge blanket separation could also be further explored and may solve both the settling problem as well as reducing the amount of submicron particles. Energy for pumping would however reduce the prospects of decreased operational cost.

The anticipated fouling by the submicron particles should further be confirmed and the prospects of an optimum SS concentration should be assessed. The effect of the aggregation tendency versus the protective cake layer could also be investigating in order to obtain improved understanding of the influence from SS. Evaluate the prospects of IFAS versus external membrane reactor with higher amounts of suspended solid would also be interesting in order to optimize the BF-MBR. It took about 20 years to find an appropriate configuration and operation for the AS-MBR. The fouling in the BF-MBR seems however to be of a different nature, hence have different optimum conditions. It may therefore take some research before the potential of the BF-MBR can be applicable.

5 CONCLUSION

This study concludes that the AS-MBR performed significantly better with respect to both fouling and treatment efficiency when compared to the BF-MBR. However, results also showed that the BF-MBR could have similar performance at increased contents of SS. The main differences in the membrane feeds were significantly less SS and larger amounts of FCOD in the BF system. Several indications also suggest increased amounts of submicron particles in the BF reactor, though this was not confirmed by the PSD measures. A wider distribution of larger particles at maximal volume percentage was however observed in the AS system.

These results can potentially influence the membrane performance in several ways. Increased amounts of FCOD in the BF system can lead to increased amounts of irreversible foulants. The reduced amount of SS can further increase the effect of the irreversible foulants in two ways; by reducing the protective cake layer which prevents the irreversible foulants from adsorbing directly to the membrane, and by reducing the extent of adsorption/flocculation of irreversible foulants prior to deposition. The cake layer formation seemed however to be of largest influence in this study. The wider distribution with larger particles in the AS-MBR could further contribute to the improved performance by forming a more porous cake layer with increased porosity and adsorption potential. It should however be stressed that several of the correlations are modest. The SS followed by FCOD seemed to be the main foulants in the AS-MBR; hence both reversibly and irreversibly fouling occurred. The permeability decline in the BF-MBR illustrated a three phase development, where FCOD was found to be the main foulant, and SS had a positive effect within the tested range;

1. An initial rapid fouling phase was observed. The fouling rate decreased with increasing SS up to an assumed threshold limit.
2. A slow fouling phase further succeeded. The amounts of SS affected the level of stabilization, but did not have a great impact on the further fouling.
3. A second rapid fouling phase was observed several times.

This pattern may be caused by extensive irreversible fouling in the start up phase, prior to formation of a stabile, dynamic, and protective cake layer. Condensing of the dynamic cake layer may than occur in the slow fouling phase and the length of this phase could depend of the available amounts of irreversible foulants, and the adsorption potential within the cake layer. The third stage would then occur when the density of the cake layer exceeds a specific value and the local fluxes exceed the critical flux. The prospect of a more compact, stabile, and energy economical unit maintain the desires of detecting the solution of fouling control in the BF-MBR. These results confirm that the membrane performance in BF-MBR could be competitive with the AS-MBR. Recommendations based on these findings are therefore to further investigate the prospect of increased SS, preferably in an external membrane reactor.

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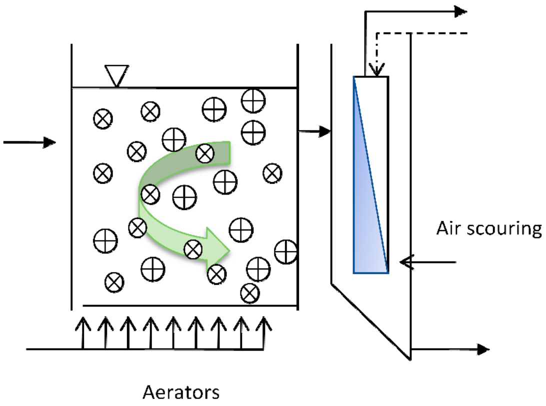
APPENDIXES

The measurements and raw data are attached in the electronic attachment

A -AN OVERVIEW OF BF-MBR STUDIES

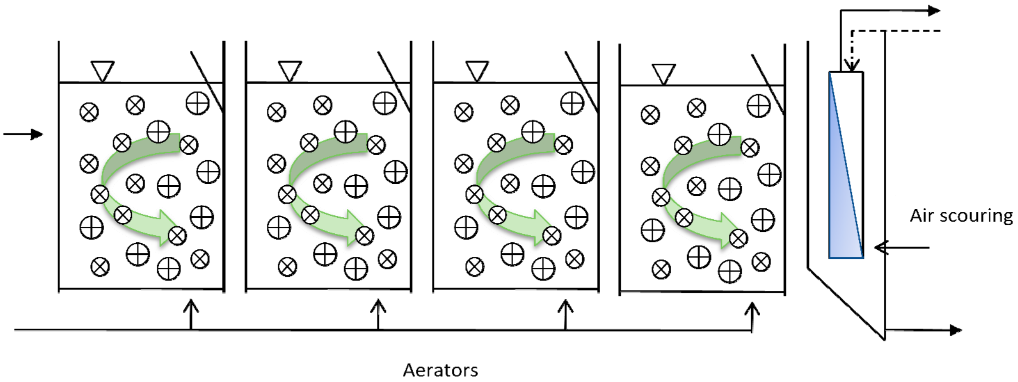
THE DEVELOPMENT OF A BIOFILM MEMBRANE REACTOR, NORWAY 2005 [20]



Configuration and operational conditions;
This pilot have separated bioreactor and membrane reactor and the membrane is submerged into the water. The system is fed by municipal wastewater from a combined sewage system. The reactor is filled to 70% with BF-carrier K1. The membrane reactor was operated with both constant filtrations and by periodic backwashing (9.5min on/0.5 min backwashing), and both operations were tested with and without air scouring. The fluxes varied from 20-60 LHM. This report is however a summary of the results from first MBBR-MBR pilots that was applied at NTNU in Trondheim, and the pilot configuration may have varied some from the figure.

The results;
Continuously air-scoring in combination with backwashing gave the best fouling control here. And the pilot could operate with sustainable fluxes at 50 LHM with a relatively low fouling rate. The treatment efficiency was high and more or less independent of the changing operating conditions. It was found that the biodegradable compounds were removed in the bioreactor while the particular matter was removed in the membrane reactor, and each compartment could therefore be optimized individually. The organic loadings were also varied between low and high-rate which gave similar effluent quality but different membrane performance. And larger particles were found at lower loadings (differential %volume), which may be explained by hydrolysis of colloidal organic particles or an enhanced effect of flocculation mechanisms. A relative increase in the sub-micron particles were however found at higher HRTs (differential number %), which may be due to a redistribution of the numbers of particles in the various size fractions as a function of particle aggregation in the larger particle size range, giving an only relative increase in the sub-micron particles. The average Zeta potential for several of the experiments/operational conditions were found to be around 15-20 mV, indicating relative stable colloids. There were also found indications that the submicron particles were aggregated into stronger fnocs at lower loadings, which prevented break-up due to scouring. All of this indicates that the submicron colloid particles are a major foulant.

- **A) INVESTIGATING THE EFFECT OF COLLOIDS ON THE PERFORMANCE OF A BF-MBR FOR TREATMENT OF MUNICIPAL WASTEWATER, NORWAY, 2006 [6]**
- **B) INFLUENCE ON LOADING RATES ON PRODUCTION AND CHARACTERISTICS OF RETENTATE FROM BIOFILM MEMBRANE REACTOR (BF-MBR), NORWAY, 2006 [39]**
- **C) TRACKING PARTICLE SIZE DISTRIBUTION IN A MOVING BED BIOFILM MEMBRANE REACTOR FOR TREATMENT OF MUNICIPAL WASTEWATER, NORWAY, 2006 [13]**
- **D) IMPACT OF AERATION RATES ON PARTICLE COLLOIDAL FRACTION IN THE BF-MBR. NORWAY, 2007 [40]**



Configurations and operational conditions;
4 bioreactors with 65 l each were applied in series treating municipal wastewater. The membrane media applied was K1 at 67% filling. The HRT varied between 1 h and 4 h in A, B, and C, and between 45 min and 180 min was 4h in D, Only one of the reactors was applied in the high rate mode (1h/45 min). A Zenon HF submerged membrane with 0.04µm pores was placed in an external reactor of 27l (A,B,C) 33 l(D). The membrane was operated with backflushing (9.5 min/0.5 min (A, B, C), 4.75min/0.25 min(D)). And the flux applied was 50 LMH (A, B, C) and 52 LMH (D). Constant aeration with varying SAD_m rates for scouring from 0.85 to 6.75 $Nm^3/(m^2*h)$ was applied in research D.

The results;
A)
This pilot was driven with no nitrification in the high-rate mode (HRT 1 h), and complete nitrification in the low-rate mode (HRT 4h). A slightly better removal efficiency of organics was shown in the low-rate condition. This was probably due to less hydrolysis of particular COD. The composition and characteristic of the SS in the reactor varied however a lot with the organic loadings, and the membrane performance changed as well. The high-rate mode experiments reached the TMP limit after about 1-3 days while the low-rate modes lasted for about 12-17 days under the same conditions. The only significant difference between the operations was CST and FCOD, and a correlation was found between TMP and FCOD for both modes, indicating that the colloidal organic fraction below 1.2µm is one of the main fouling contributors in BF-MBRs. The PSD also revealed significantly larger particles in the low-rate operation, especially for the sub-micron particles. The PSD for the concentrate in the low-rate operation also indicated an aggregation of the sub-micron colloids which resulted in less colloids around the membrane, which may explain the better membrane performance for the low-rate. The smaller amount of colloids in this concentrate may also explain the improved CST and filterability properties. Three different FCODs were also measured in order to indicate which COD fraction below 1.2µm that contributed most to the fouling. This

suggested that the colloidal fraction below 0.45μm and not below 0.1μm had the largest impact, but colloids of non-organic nature and the composition of EPS/SMP was not taken into account.

B)

This article discussed the retentate properties of the same experiment. It was found that the low rate (4h HRT) produced 10% less sludge compared to the high rate (1h). They also found that the high-rate retentate gave poorer dewatering properties and filtering characteristics, with higher amounts of submicron particles, more soluble organic matter, more filamentous bacteria, and less compact particles.

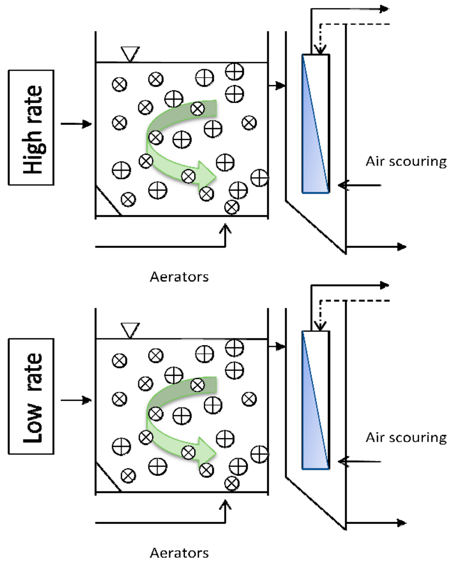
C)

A low rate and a high rate operation were being compared under otherwise similar conditions in order to evaluate differences regarding submicron colloidal fractions and fouling. The system with high-rate conditions fouled faster than the low-rate system, in addition to some poorer removal of COD. The PSD was found to vary as a function of loading-rates. The overall PSD changes in the system showed a shift towards larger particles at increasing HRT due to aggregation. The low-rate had a smaller relative amount of submicron particles around 0.1 μm in the membrane reactor, which indicated a better flocculation here, and may explain the different fouling properties on the assumption that the submicron particles are the major foulant. The low-rate operation also showed better settling properties, probably due to the improved aggregation of larger particles.

D)

The permeate quality was stabile and not affected by changing aeration rates. The membrane performance was however affected, with lower fouling-rates with increased aeration. Aeration rates above 3.37 $Nm^3/(m^2*h)$ did however not improve the performance significantly. This aeration limit is however a function of the membrane reactor and the module design and is therefore system dependent. The PSD illustrated a clear increase in amount of smaller particles (especially the fraction below 0.1μm) with increasing aeration, in addition to decreased size of the particles. This supports the theory that increased aeration breaks up the flocks, at the same time as it increases the shear forces and remove the fouling composition. To find the optimum aeration rate is important in order to minimize the fouling, and an optimum aeration rate may therefore be found where these effects are balanced.

MOVING BED BIOFILM MEMBRANE REACTOR CHARACTERISTIC AND POTENTIALS OF HYBRID PROCESS DESIGN FOR COMPACT WASTEWATER TREATMENT PLANTS [45]



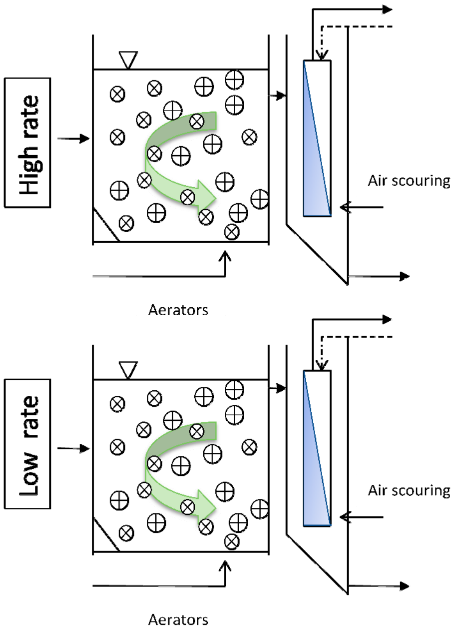
Configuration and operating conditions;

Two MBBR-MBRs operated in parallel were filled 60-70% of carriers and treating pre-settled raw municipal wastewater. The HRT varied from 18-380 minutes, and an external HF membrane was applied. A backwashing cycle of 1 min (9.5/0.5) was also applied in addition to no air scoring, air scouring in pulse (2 min on/off), and constant air scouring.

Results;

The results regarding HRT and COD removal indicates that degradation of soluble COD is rapid while hydrolysis of particular COD takes place if the HRT is significantly longer. An average permeate flux of 60 LMH was maintained for all tests. They also found that backwashing in combination constant scouring gave significantly better fouling control.

EFFECT OF ORGANIC LOADING RATES ON A WASTEWATER TREATMENT PROCESS COMBINING MOVING BED BIOFILM AND MEMBRANE REACTORS, NORWAY [38]



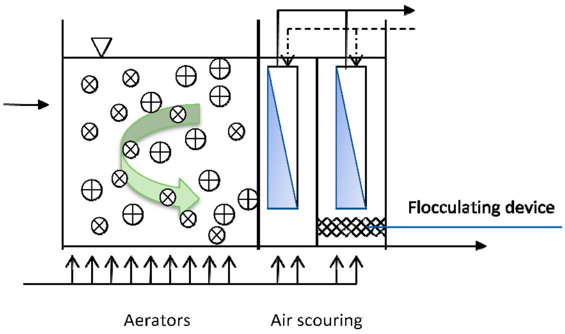
Configuration and operating conditions;

Two BF-MBRs with different HRTs were operated in parallel in order to make a complete comparing of the systems. Submerged HF membranes with MWCO of 30 kDa were applied in an external reactor containing 1.8l, where backwashing was applied. (9.5 min on/0.5 min backpulse). Fluxes ranged from 3.3-5.6 LMH were applied. The low-rate pilots consisted of a 60l reactor separated into three compartments, with an initial HRT of 3h, later changed to 4h. The high rate reactor was a one-unit 30l large tank with an initial HRT of 1h and later decreased to 45 min. Both reactor were filled by 70% of K1 carriers, and treated pre-settled municipal wastewater from the combined swage system, mixed with sodium acetate. The DO in the reactor varied from 2.7-6.3 mg/l.

Results;

There was observed a clear shift toward larger particles at longer HRTs, and the low-rate reactor produced more sedimentarable sludge in the membrane reactor, which caused less SS around the membrane. No consistent difference in fouling rate was however observed, except from the operation with the largest flux close to sustainable flux. The loading rate did however not have dramatic effects on the COD removal. And different FCOD fractions compared to the MWCO indicated that the choice of membrane pore size has little effect on the COD removal.

ASSESSMENT OF MEMBRANE REACTOR DESIGN IN THE PERFORMANCE OF A HYBRID BIOFILM MEMBRANE REACTOR, NORWAY, 2006 [41]



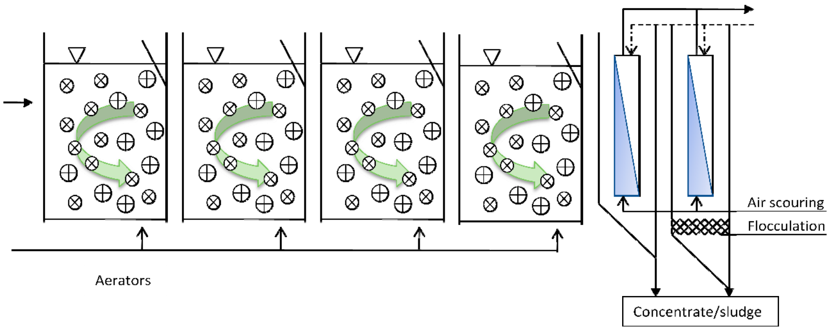
Configuration and operating conditions;

Two external membrane reactors are operated in parallel where a flocculation device is integrated in one of them. The reactor is fed by municipal wastewater. The flux was held constant around 40 LHM while the organic loading varied. The biodegradation took place in the BF-reactor while the separation took place in the membrane reactor; it is therefore assumed that the membrane reactor is external.

The results;

They revealed that the variations in the wastewater quality had a significant impact on the membrane fouling, and found EPS and MLSS concentrations, in particular the submicron fraction, to be the largest foulants. A correlation between PSD and membrane performance was found, where the fouling increased with increasing amounts of submicron particles (differential number percentage). The deviser with the flocculation device fouled less and had a smaller amount of submicron particles. This device also had better settling characteristic and lower experienced SS near the membrane.

FOULING CONTROL BY REDUCTION OF SUBMICRON PARTICLES IN A BF-MBR WITH AN INTEGRATED FLOCCULATION ZONE IN THE MEMBRANE REACTOR, NORWAY, 2008 [42]



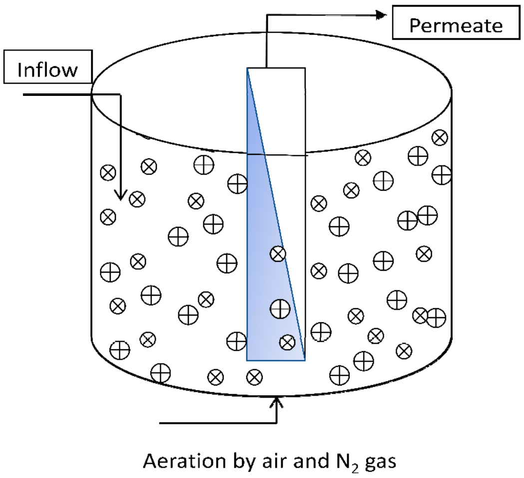
Configuration and operating conditions;

This pilot treated municipal wastewater and utilized 4 MBBR reactors in series, each at 65 l. Full nitrification was achieved and the HRT in the bioreactors was 4 h. The flux was 50 LHM and an operating cyclic of 114 s on/6 s backwashing was utilized. Two different membrane reactors were applied in series; one with and one without flocculation zone. The reactor with flocculation had a volume of 33 l, while the one without was 25 l. A submerged Zenon HF membrane with 0.04µm was used together with continuously air- scouring.

The results;

Significantly better separation of MLSS was achieved in the membrane with flocculation, resulting in 48% less MLSS around the membrane. The sludge in this reactor also showed better filterability characteristics, and is probably easier to treat. The SVI was lower for the flocculated operation, but still higher for both operations than for conventional AS-MBRs. The PSD in the membrane reactors revealed that flocculation do occur in the flocculating reactor and that submicron particles are being aggregated. The theory was that decreased amounts of colloidal in the membrane reactor would increase the membrane performance. The membrane with flocculation fouled after 16 days, while the other one fouled after only 12 days, which showed that the reduction of SS and submicron particles did improve the fouling, and confirmed that the submicron colloidal is a large foulant.

FACTORS AFFECTING FILTRATION CHARACTERISTICS IN MEMBRANE-COUPLED MOVING BED BIOFILM REACTOR, SOUTH KOREA, 2006 [9]

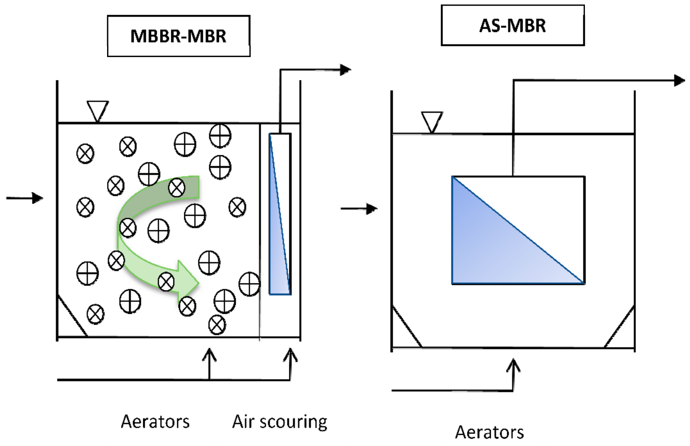


Configuration and operating conditions;

A HF membrane with 0.1µm pores was immersed into a BF-MBR. The flux in the pilot was kept at 30 LMH and no relaxation/backwashing was applied. The HRT in the system was 10h, while SRT of the sludge was 10 days. The BF-media applied was polyurethane cubes (1.3 cm) coated with activated carbon. The airflow and filling fraction was varied. BF fillings of 5-20% was utilized in addition to 5000 mg/l activates sludge, which made the system a hybrid AS/BF system. The DO was kept around 5 mg/l, and addition of N_2 gas was utilized in order to increase the aeration without affecting the DO. The membrane was in direct contact with the carriers. A protected membrane was tested as well, in order to evaluate the impact of carriers rubbing the membrane.

The results;
This research wanted to investigate the rubbing effect between BF-carriers and an unprotected membrane. Both increased airflow (9l/min) and increased filling-fraction (20%) decreased the fouling, but also the particle size was decreased which normally would have caused increased fouling instead. The increased fouling was probably due to increased turbulence and collision frequency between the carriers and membrane, which exceeded the effect from reduced floc size. The composition and characteristic of bound EPS did not change much between the experiments, and biomass characteristics were concluded not to impact the different results. An additional protected membrane with an iron net was then introduced to the system in order to illuminate the possibility that increased amounts of detached BF caused the reduced fouling. The filling fraction was now 20% and the aeration 5 mg/l, and the flux was doubled to 60 LMH. The unprotected membrane was hardly damages by the collisions with the carriers and fouled 5 times slower than the protected membrane. This indicated that is actually was the collisions between the carriers and membrane that improved the performance, hence a ticker cake layer with less roughness was observed at the protected membrane.

COMPARISON BETWEEN A MBBR-MBR AND A CONVENTIONAL MBR ON ORGANIC CARBON AND NITROGEN REMOVAL, CHINA, 2008 [43]



Configuration and operational conditions;
An AS-MBR was operated under similar conditions as a MBBR-MBR. The results were compared and has much similarities to the experiment conducted in this thesis. Both reactor used HF membranes with 0.1µm pores, and operated with relaxation (10min on/2 min off). The reactors were fed with synthetic wastewater and the HRT was 12 h and SRT 60 days.

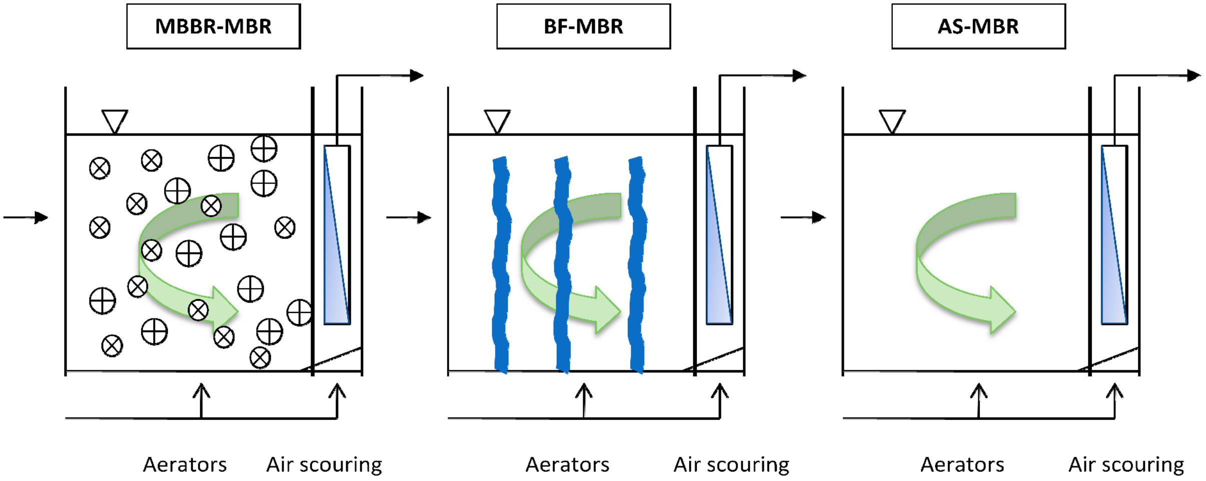
<u>MBBR-MBR:</u> The reactor volume was 30 l. The membrane area was 0.4 m^2. A clapboard with bores divided the reactor into a bioreactor and a membrane reactor with volumetric relationship of 4:1. A new kind of nonwoven carriers with a surface of $900m^2/m^3$ was added to 30% filling, which gives slightly less bio-growth area than K1. The density of these carriers was 0.27 g/cm^3. The flux was kept at 6.25 LHM, while the aeration was 7.5 l/min (with 2/3 in the bio-reactor). There were no sludge outlet here, and the MLSS concentrations increased with time in both reactors, and the MBBR-MBR became a hybrid AS/BF process as time went by.

AS-MBR: The reactor volume was 10 l, and the membrane filtration area was 0.2 m^2. The flux was kept at 4.17 LHM, while the aeration was 2.5 l/min.

The results;

The main goal of this research was to investigate the achievability of simultaneously nitrification and denitrification (SND) in constantly aerated MBRs. The MBBR-MBR showed good performance on nitrogen removal for several COD/TN-ratios, while the SND was more affected by the COD/TN variations in the AS-MBR. Both reactors showed a good removal of organic substances, the removal of organics increased however with time in the MBBR-MBR, indicating that a combined AS/BF-MBR may have a higher ability of removing organic carbon and handling organic shock loads than conventional AS-MBRs. The sludge from the two systems varied in both color and composition, and had a more varied composition of bacteria in the MBBR-MBR. This research found a significantly higher fouling rate for the MBBR-MBR, the cake-layer from this reactor was also ticker and denser due to deposition of filamentous bacteria and other materials. It may however be noticed that the reactors were quite different and that the MBBR-MBR was operated with much higher flux.

MEMBRANE FOULING STUDIES IN SUSPENDED AND ATTACHED GROWTH MEMBRANE BIOREACTOR SYSTEMS, THAILAND, 2007 [4]



The object of this study was parted into three parts; 1; to evaluate different materials for the plastic carriers, 2; to evaluate the impact on HRT on three pilots; one AS-MBR, one BF-MBR with fixed media, and one BF-MBR with suspended carriers, the third experiment was to evaluate the impact of different MLSS concentration between the AS-MBR and the suspended BF-MBR.

The configuration and operational conditions;

The reactors were separated into to compartments by a holed baffle wall and had a working volume of 5 l. The membranes applied were HF Mitsubishi membranes with 0.1µm pores. The system was fed with synthetic wastewater. The suspended BF-MBR utilized a 24% filling of plastic cylinder carriers with 4mm in diameter.

A) A comparison between EPS production, COD and TKN removal of different suspended and attached growth systems with varying media was conducted. PE bead, PE granule, PE sheet, cylindrical PE, and PE sponge were examined together with an AS system in batch reactors. The SRT was kept at 10 days, and the MLSS at 4000 mg/l.

B) HRTs of 2, 4, 6 and 8h were evaluated with a fixed SRT of 20 days. The CP carrier was applied at 24% filling in the MBBR-MBR reactor, while the BF media in the attached BF was poluvinylidine chloride fibers with 7.33 m^2/m fixed media which equals 5 % of the reactor volume. The increase of HRT also caused decreased MLSS which could influence the sludge characteristics. The flux was also varied from 1.8 – 7.1 LMH, where 1.8 corresponded to 8h HRT and 7.1 to 2h.

C) The systems used relaxation with 10/1 min cylices and had HRTs of 2 h and a flux of 7 LHM. The aeration conducted was $0.6m^3/h$. Only the AS and the suspended BF-MBR was operated here.

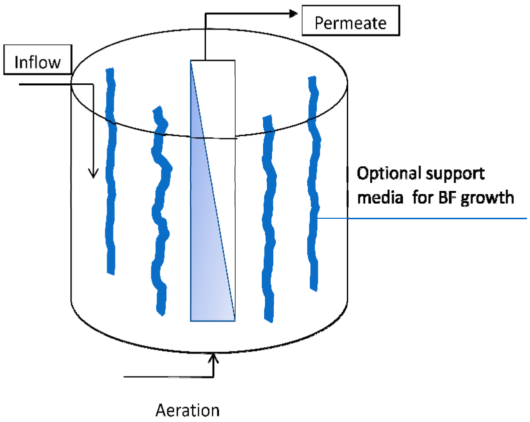
Results;

A) No significant difference in the COD removal was observed for the different BFs or the AS, while the nitrogen removal was improved in the BF systems, where the granular showed best results. The EPS and biofilm production was affected by the shape and size of the applied media, and the sponge media reduced the EPS content due to the greatest surface area. The low lifetime due to weaker physical strength of the sponges made the researcher choose the second best alternative anyway. This was the cylinder shaped PE which had the second lowest EPS production and advantages like better floating and mixing properties, higher surface area, and a non biodegradable nature.

B) The difference HRTs did not affect the bound EPS, while the soluble EPS increased at shorter HRTs, which was caused by increased utilization of bound EPS in the floc together with increased cell lysis. It was also found that the CST in the MBBR reactor was the highest, probably due to movements of the carriers, and that the CST increased with increasing HRT. The floc shape, size, and types of microorganisms also varied a lot in the three reactors.

C) The AS-MBR fouled much faster for all MLSS concentrations, and a more rapid acceleration of the fouling was observed. A higher fouling rate was also illustrated at increasing MLSS due to increased cake resistance at increasing viscosity. The different fouling properties were due to a much thicker and denser cake layer formation on the AS membrane which gave more than twice as large cake layer resistance. This was explained by the difference in PSD, as the amounts and composition of EPS and SMP were quite similar, indicating no change in biological characteristics. The amount of bound EPS increased with MLSS, and contained of almost 70% proteins, which gives a hydrophobic sludge easily adsorbed, while the SMP mainly consisted of carbohydrates. Significantly smaller particles were produced by the biomass in the BF-system and the system had much more colloidal particles. This caused a longer CST (which increased with the MLSS), but was also used to explain the better fouling performance. BF-MBR will require less maintenance and have longer lifetime, hence a lower operational cost, based on these results.

COMPARISON OF THE FILTRATION CHARACTERISTICS BETWEEN ATTACHED AND SUSPENDED GROWTH MICROORGANISMS IN SUBMERGED MEMBRANE BIOREACTOR, SOUTH KOREA [44]



Configurations and operational conditions;

An HF membrane was immersed into a 5l large bio-reactor. The membrane was a HF Mitsubishi MF-membrane with 0.1µm. Aerations at the bottom supplied air for both membrane scouring and biomass growth. No relaxation was applied and a constant flux of 25 LMH was applied for both reactors. The systems were fed by synthetic wastewater. The only difference in the two systems was the biofilm media, which was a 4.37m^2 looped cord media, and the MLSS in the BF-reactor was about 100 mg/l. The MLSS in the AS was kept at 3000 mg/l. The aeration was 2.5 l/min in both reactor, which gave a DO around 6 mg O2/l. The HRT in the systems was 8 h. [18]

The results;

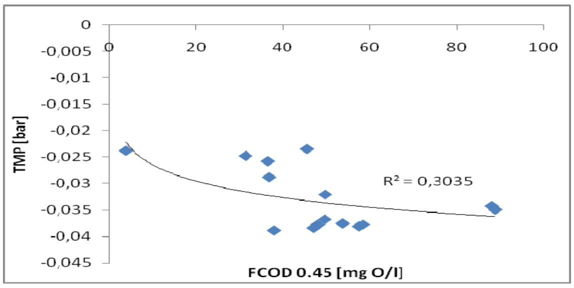
The increase rate of the TMP was 7 times higher in the BF system, even though the AS-reactor had 30 times higher MLSS concentration. Both reactors had similar EPS amounts and composition, and the quantitative and qualitative characterization of the soluble organic fraction was about the same. So it seemed to be the suspended solid that made the difference after all. The MLSS was increased for both reactors in order to see the impact, and both reactor fouled slower with increasing MLSS up to 2000 mg/l for BF and 5000 mg/l for AS. This indicates that the MLSS forms a dynamic protective layer on the membrane surface which protects the membrane from sub micron colloids and soluble organic compounds. SEM and AFM pictures of the two membranes supported this theory. This was further supported by resistance analysis, where the resistance from the adsorption was much higher for the BF system and the cake layer resistance was much smaller. The MLSS was also more compressible in the AS system and the specific cake layer resistance was one order of magnitude smaller. Both systems showed good treatment efficiencies, but the AS-MBR had a slightly better treatment efficiency regarding COD, and a bit poorer regarding ammonia.

B -THE DESIGN OF THE SYSTEMS PILOTS AS A CAS AND A REGULAR MBBR

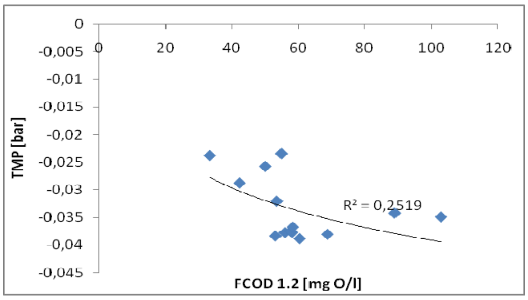
REQUIRED SPACE AND OXYGEN IN THE PILOTS			
Q_{dim} [ml/min]	20	=> Q_{dim} [l/h]	1.2
$TCOD_{dim}$ [mgO/l]	600	=> BOD_5 [mgO/l]	90
AS		MBBR	
SS/BOD_5 [mg SS/mg BOD_5]	1.4	Org. Areal load g BOD_5/m^2*d]	<8
SRT [d]	43	Required growth area [m^2]	0.3
MLSS [g/l]	4.9	Specific growth area [m^2/m^3]	335
Sludge production [g SS/g BOD_5]	1.03	V_T [l]	1.0
V_T [l]	23.6	Oxygen demand [g O_2/d]	2.6
Oxygen demand [g O_2/d]	3.4		

Q_{dim} is the flow of the outlet pump, TCOD is the 85 % percentile of the total organic carbon in the raw water, V_T is the total required volume, and the oxygen demand is the required oxygenation excluded membrane scouring. It is also assumed that COD equals 30% of the TCOD, and that BOF_5 equals 50% of the COD [3]. The calculating is further based on Norwegian guidelines for conventional active sludge and MBBR design[7]. It’s here assumed a temperature of 10 °C, which is lower than the real temperature.

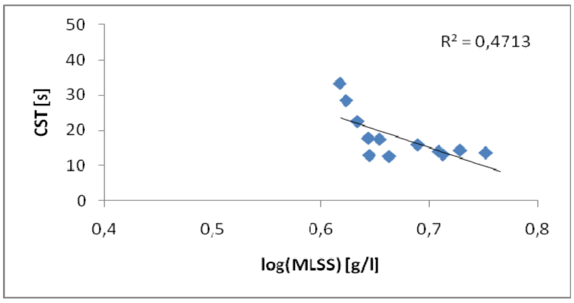
C – CORRELATIONS IN THE AS-REACTOR



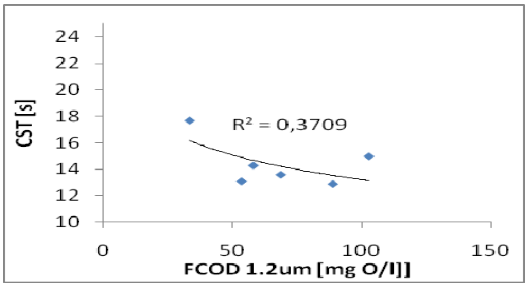
FIGUR 1 CORRELATION BETWEEN FCOD (0.45UM) AND TMP IN THE AS REACTOR



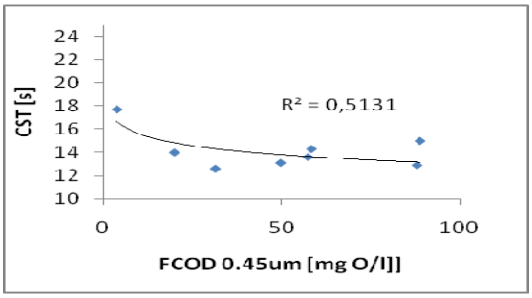
FIGUR 2 CORRELATION BETWEEN FCOD (1.2UM) AND TMP IN THE AS REACTOR



FIGUR 3 – THE CORRELATION BETWEEN CST AND SS IN THE AS REACTOR



FIGUR 4 THE CORRELATION BETWEEN CST AND FCOD (1.2) IN THE AS REACTOR



FIGUR 5 – THE CORRELATIO BETWEEN CST AND FCOD IN THE AS REACTOR. THE LINE ILLUSTRATES THE LOGATITHMICAL COORELATION

D - FOULING AND MEMBRANE FEED WATER CHARACTERISTICS IN THE INITIAL FOULING PHASE IN THE BF-MBR

Average measurements vaules in the given periods														
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Slope [bar/h]	-0,014	-0,011	-0,008	-0,010	-0,010	-0,008	-0,013	-0,011	-0,010	-0,007	-0,004	-0,004	-0,006	-0,001
SS [g/l]	0,34	0,27							0,23	0,58	0,49	0,85	1,22	1,79
PSD -Size at num. % [um]	0,097	0,097		0,0805	0,0805					0,073		0,074	0,089	0,115
PSD -Size at vol. % [um]	60,5	60,5		245,2	245,2				45,75	45,75	50,22	69,65	74,2	92,195
PSD -Num. % [%]	6,6	6,6		7,8	7,8					5,8		8,45	6,56	9,9425
PSD -Vol. % [%]	4,2	4,2		4,5	4,5				4,6	6,4	4,7	4,55	4,05	4,45
FCOD(1.2) [mgO/l]										120	98,8	103	76,35	
FCOD(0.45) [mgO/l]									34,1		76,85	95,2	68,7	
COD removal [%]									81 %	86 %	88 %	87 %	90 %	
COD perm. [mgO/l]									70,3	54,4	44,05	49,85	56,4	
Color [-]		102	102						165		137	125	141	
UV [abs]									0,58		0,57	0,56	0,56	