Hydrodynamical Optimisation of Membrane Bioreactors

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HYDRODYNAMICAL OPTIMISATION OF MEMBRANE BIOREACTORS

BY
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AALBORG UNIVERSITY
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PREFACE

This Thesis has been made as a part of my PhD study on Aalborg University during the period from 2016 to 2018. The study is partly funded by Alfa Laval and partly by Aalborg University. The project has been done in the process of redesigning the flat sheet membrane bioreactor module from Alfa Laval. The study has been supervised by Associate Professor Thomas Ruby Bentzen. The study has been made in collaboration with Alfa Laval who has contributed to present issues for active treatment plants.

First, I would like to thank my supervisor Thomas Ruby Bentzen, for the professional discussions and guidance during this period.

Furthermore, I would like to thank the team from Alfa Laval for being the part of the project and a special thanks to Nicolas Heinen, who has contributed to many good discussions with his great knowledge about what is going on in the field of commercial MBR.

I would also like to thank Kristian Skov who was a part of the preliminary studies in the laboratory for the excellent collaboration and always being patient with me when needed.

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Finally, I would like to thank the entire staff at the Department, who has contributed to a good workplace and making the last couple of years a good period of my life.

Lasse Sørensen

Aalborg University, 2018

ENGLISH SUMMARY

This project is concerned with the fluid dynamics in membrane bioreactors (MBR). MBR has the ability to treat wastewater to a higher effluent quality than what is seen in conventional activated sludge treatment plants. Due to the high effluent quality, MBR is often seen as the method of the future for wastewater treatment. The high effluent quality is secured by filtration through membranes for the separation instead of sedimentation which is the classical method. By use of membranes for separation, the effluent quality can be controlled more directly by the pore size of the membranes. For typical MBR this includes removal of bacterias while viruses are not removed. With this pore size is it also possible to achieve almost complete removal of microplastic as it is larger than the pores.

One of the reasons why MBR only plays a minor role compared the conventional activated sludge treatment plants is due to the high energy consumption making them too expensive. The issues with the high energy consumption shape the basis of this project, where the aim has been to optimise existing systems lower the energy consumption. The main challenge with using membranes for separation of the sludge is the fouling of the membranes, which lower the permeability of the membranes. The lower permeability leads to an increase in energy needed to maintain the flux through the membranes. It has been shown in several studies that the fluid dynamics can be used to mitigate the fouling of the membranes and thereby maintaining the flux through the membranes. The knowledge of how optimal flows are achieved in the systems is still limited. This work covers some the issues with the fluid dynamics in full-scale MBR. It includes an evaluation of the optimal methods for modelling the fluid dynamics. The flow in these systems is very complex in nature with a fluid composition of organic materials, particles and often also with air in the systems. This study relates to two different types of MBR where one of them have rotating membranes while the other one is a flat sheet MBR from Alfa Lava, where the membranes are mounted on these flat hollow sheets.

Different strengths and weaknesses of the existing methods for modelling the fluid dynamics are found and described in this thesis. Besides the evaluation of the methods for modelling the fluid dynamics, the methods have been used to evaluate the flow of the different types of MBRs. It has been found that the geometry and operation has a significant impact on the effectivity for rotating membranes. Furthermore, have some general flow patterns been identified in the FS MBR system and it has been shown that the use of deflectors can be used to increase the volume fraction of air in the system whereby it might be possible to reduce the air flow and thereby also energy consumption.

DANSK RESUME

Dette projekt omhandler strømninger i membran bioreaktorer (MBR). MBR har evnen til at rense spildevand til en meget bedre vandkvalitet end hvad der er kendt fra konventionelle renseanlæg og derfor er det også af mange anset som fremtiden indenfor spildevandsrensning. Den gode vandkvalitet er sikret ved at vandet filtreres gennem membraner i stedet for sedimentationstanke som er den konventionelle metode. Ved at rense vandet på denne metode kan kvaliteten af det rensede vand styres direkte ud fra porestørrelsen for membranen. Ved typiske porrestørrelser renses vandet til en grad hvor selv bakterier fjernes, mens vira dog ikke fjernes. Ved denne porrestørrelse er det også muligt at opnå en nærmest komplet fjernelse af mikroplastik som for tiden er et meget diskuteret område, hvis påvirkning på recipienter stadig er usikker.

En af grundene til at MBR kun spiller en begrænset rolle i forhold til de konventionelle renseanlæg er at de stadig er dyrere i drift. Det er den problemstilling som har skabt basis for denne Ph.d.-afhandling, hvor det søges at optimere de nuværende systemer til at gøre dem mere energieffektive og dermed konkurrencedygtige. Den største udfordring ved at anvende membraner til separering af slammet er tendensen til tilstopning af membranerne som mindsker deres permeabilitet. Derved skal der bruges mere energi på at presse vandet gennem membranerne og det kan ende med en total tilstopning af membranerne. Det er vist i adskillige studier at strømningsdynamikken kan bruges til at undgå tilstopningen på oversiden af membranerne hvorved de bedre bibeholder deres permeabilitet. Der mangler dog stadig viden om hvordan optimale strømningsfold i MBR anlæg opnås. Det er i det område hvor denne afhandlinger afdækker nogle eksisterende problemstillinger. Det indebærer et studie af hvilke metoder der er optimale til modellering af strømningerne i sådanne systemer, som ofte er meget komplekse med slam der indeholder organisk som påvirker reologien af væsken samt partikler og i mange systemer også luftbobler, hvilket tilsammen giver et utroligt komplekst system. Studiet forholder sig til to specifikke typer af MBR anlæg hvor det ene har roterende membraner og den andet er et såkaldt flat sheet MBR anlæg fra Alfa Laval hvor membranerne er monteret på nogle hule plader. Der er fundet forskellige forcer ved metoderne til strømningsmodelleringen som er beskrevet i afhandlingen.

Udover en evaluering af hvordan modelleringen af sådanne systemer bedst foretages er modellerne anvendt i praksis til at studere eksisterende systemer med henblik på at kunne optimere strømningsforholdene til at få mest muligt ud af den energi der anvendes til at hindre tilstopningen af membranerne. Det er vist at der er store energioptimeringer at hente ved at optimere geometrien og styringen af roterende membraner. Derudover er der vist nogle af de mønstre der observeres i flat sheet systemer og det er påvist at deflektorer kan anvendes til at øge udnyttelsen af beluftningen til at opnå et højere luftindhold i systemet.

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ABBREVIATIONS

1.1. ABBREVIATIONS

AS	Activated sludge
CAS	Conventional activated sludge
CAPEX	Capital expenditures
CFD	Computational fluid dynamics
CICSAM	Capturing Scheme for Arbitrary Meshes
CIP	Cleaning in place
CMC	Carboxymethyl Cellulose
EDM	Electrodiffusion method
FS	Flat sheet
HF	Hollow fibre
HRIC	High resolution interface capturing scheme
LDA	Laser Doppler anemometer
MBR	Membrane bioreactor
MF	Microfiltration
OPEX	Operating expenditures
TMP	Transmembrane pressure
TSS	Total suspended solids

1.2. NOMENCLATURE

A	Area
A_{ij}^{D}	Linearized drag coefficient for phase j acting on phase i
$C_{L,effective}$	Effective lift coefficient
$\boldsymbol{F}_{ij}^{D}$	Drag force vector for phase j acting on phase i
$\boldsymbol{F}^{L}$	Lift force vector
$\boldsymbol{g}$	Gravity vector
h	Height
k	Consistency factor
M	Moment
$\boldsymbol{M}$	Interphase momentum transfer vector
n	Flow behaviour index
p	Pressure
r	Radius
R_b	Radius bob
R_c	Radius cup
t	Time
V	Volume
$\boldsymbol{v}_c$	Velocity vector continuous phase
$\boldsymbol{v_i}$	Velocity vector phase i
$\boldsymbol{v_j}$	Velocity vector phase j
$\boldsymbol{v_r}$	Relative velocity vector

v	Velocity
α	Gap ratio
α_i	Volume fraction of phase i
α_d	Volume fraction dispersed phase
$\dot{\gamma}$	Shear rate
μ	Viscosity
μ_{app}	Apparent viscosity
ω	Rotational velocity
ρ_c	Density continuous phase
ρ_d	Density dispersed phase
τ	Shear stress
τ_i	Shear stress phase i
τ_y	Yield shear stress

CHAPTER 2. INTRODUCTION

The harmfulness of wastewater has been known for many years, and the first systems for transporting the wastewater out of the cities is known to go all the way back to the ancient Greeks in 300 BC (Henze 2008). Since then a lot has happened, and the focus is now also on the water quality of the receiving water bodies, increasing the focus on sources of influencing the water quality including effluent from wastewater treatments plants. The increased focus is present in Europe where the water framework directive sets increased criteria for the quality of the effluent to the receiving water bodies (European Union) and the clean water act (USA) and is a global trend.

The legislation influences a massive amount of wastewater treatment plants as the countries of the EU alone had a total installed capacity for wastewater treatment of 780 million population equivalents in 2017 (European commission 2017).

The traditional method for wastewater treatment is conventional activated sludge (CAS) treatment plants. This method goes more than 100 years back (Ardern, Lockett 1914). The method uses biological treatment for the digesting organic matter in the wastewater. The separation of the of the sludge and the water takes place in settling tanks where the sludge flocs settle and separate the water phase from the sludge. The classic treatment methods have some issues due to the method for the separation of the sludge from the water as it can be difficult to obtain satisfactory water quality needed to obey the water quality demands.

The need for treatment methods for better water quality has led to increased development and implementation of MBR. In the MBR plants, the separation of the sludge and the water is achieved with membranes rather than by sedimentation. The filtration gives much better control of the effluent quality as the selectivity from the membranes is controlled directly by the pore size. The pore sizes for commercial MBR systems are generally in the range of 0.03 to 0.4 µm (Judd 2016). The small pores secure a high quality of the effluent (Judd, Judd 2011). With pore sizes of 0.4 µm which is some of the largest pores sizes used, a 9 log reduction of coliform bacteria is shown (Gander et al. 2000). The removal of coliform bacteria is of importance for the bathing water quality and Escherichia coli used is one of the parameters used for classifying bathing water quality in the EU (European commission 2006).

The different advantage makes MBRs an interesting method for wastewater treatment as it helps the minimize the stress on the receiving water bodies. Currently, another big focus area of for the water bodies is microplastic. With the use of membranes, the removal of the microplastic can also be controlled by the pore size which only allows particles smaller than the pores to pass.

MBR typical operates at sludge concentrations in the range of 8 to 18 g/L (Drews 2010) where CAS typically operate at concentrations around 5 g/L to sustain the settling (Ho, Zydney 2006). Some MBR treatment methods can even go as high as 30+ g/L. The higher sludge concentrations have several positive effects compared to CAS. Combined with the fact that there is no need for settling tanks with the need of high retention times it leads to the possibility of smaller treatment plants. Another positive effect of the high sludge concentration is the lower volume of sludge produced per volume of treated wastewater which lowers the cost of sludge disposal. The higher sludge concentration does also make it more feasible for biogas production, which can be an economic gain.

The growing interest for MBR is well reflected in the installation of MBR treatment plants. In 2006 The first MBR plant larger than 10000 m^3/d in China was installed, while the number of treatment plants of this size in 2014 reached 130 (Xiao et al. 2014). The same trend is seen other places in the world with a global yearly increase of 10.5% in the number of installed MBR treatment plants (Meng et al. 2012).

Despite the increasing number of installed plants using MBR, there are still some drawbacks. It is generally agreed that MBR is more expensive than CAS when evaluating both the capital expenditures (CAPEX) and the operational expenditures (OPEX). There have been made some work where it has been shown that MBR is cost-competitive to CAS if a high effluent quality is needed (Iglesias et al. 2017; Brepols et al. 2010). It does though still leave MBR at a stage where it in most cases is not economically feasible compared to CAS, and further development is needed.

Fouling of membranes is the largest issue for widespread application of MBR, and the fouling of membranes is limiting the application of widespread MBR (Le-Clech et al. 2006).

It has been found that fouling in some degree can be controlled by the hydrodynamics the MBRs. (Böhm et al. 2012). It has led to several studies of the fluid dynamics in MBRs, but due to the complex nature of the systems, it is an area that is still not fully understood. It is though generally agreed that shear on the surface helps to mitigate fouling. This can, e.g. be achieved by rotating membranes or with aeration which generates a scouring effect on the surface of the membranes. For such aerated systems, there have been found an increasing interest in avoiding uneven aeration. In surveys from 2010, 2012 and 2015 there have been found an increase in the interest in uneven aeration where more than 5 % answered that uneven aeration was the main issue in 2015 (Judd 2016). One of the largest issues was membrane surface fouling with more than 15 % in both 2010, 2012 and 2015 (Judd 2016). It is believed that this problem with fouling might also to some degree be a consequence of the uneven aeration.

The conclusion of this is that MBR as technique is making its entry on the scene for wastewater treatment, but also the fact that there are still issues with fouling mitigation where proper fluid dynamics play a significant role. The fluid dynamics can be studied both experimentally and numerically.

The experimental study of fluid dynamics is the classical method where experiments are conducted, and the properties of interest are measured. This approach is useful in many cases as the properties of interest are measured directly or sometimes indirectly. It does though have some shortcomings. Some properties might not be directly measurable, the experiments are expensive, the measurement device influences the property of interest, and it can be very time-consuming. This makes computational fluid dynamics a useful alternative for experimental fluid dynamics.

CFD is a well-recognised tool as it has been used for many years for studying fluid dynamics. It was first proposed as early as 1922 for weather forecasts (Richardson 1922). Since then much development has happened and both with the methods used for CFD but also with the entry of modern computers which allows the computation of a high number of coupled differential equations. CFD is today used in a wide variety of setups ranging from the aerodynamics of Formula 1 cars and space rockets to the optimisation of pumping systems in the oil industry and many other places. With the use by these billion-dollar industries as well as in many other areas, there is much ongoing research in the optimisation of algorithms for CFD. This development has led to the development of a vast variety of algorithms which also allows the study of complex multiphase systems with moving parts as the case is for some MBR setups. CFD has been used within the area of wastewater treatment and more specifically within the area of MBR for both rotating systems, flat sheet systems, and hollow fibre systems (Ratkovich et al. 2012; Ndinisa et al. 2006b; Ratkovich, Bentzen 2013; Wang et al. 2010). In these studies, it has been found useful for comparison between different types of setups and energy optimisation of existing systems. The CFD has been used in this work to optimise the fluid dynamics in different kinds of MBRs.

CHAPTER 3. STATE OF THE ART

State of the art covers all the different areas of this work. This state of the art includes MBR, fluid dynamics, and rheology.

3.1. MEMBRANE BIORECATORS

The principle of MBR is filtration of the sludge with membranes. Different types of membranes bioreactors exist, with various advantages. In general, the filtration unit can be subdivided into two main groups being dead-end filtration or cross-flow filtration. The dead-end filtration is where the flow direction is normal to the membrane surface where the retention will lead to a build-up of the retentate on the surface of the membrane (Li, Li 2015). The other method is the cross-flow filtration where a flow parallel to the membranes is present resulting in a removal of the retentate from the surface of the membrane. The cross-flow method is the method used for industrial MBR plants and is also the focal point for this work. This method can further be subdivided into side-stream MBR, and submerged MBR systems also called immersed MBR. The immersed system was introduced in Yamamoto et al. (1988) with a hollow fibre system. Immersed systems include hollow fibre systems and flat sheet systems. The side-stream systems include the multitube configuration and also rotating membranes. The focus in this work has been on one setup of immersed systems with flat sheet (FS) membranes. The other system is a side-stream system with rotating membranes. A principle sketch of different treatment types is illustrated in Figure 3-1. The figure shows the CAS setup where the separation takes place with sedimentation after the biological treatment. For the immersed setup is the membranes submerged into the tank where also the aeration and biological processes take place. This principle can both be the flat sheet membranes and hollow fibre membranes. The side-stream is illustrated with the membranes outside the tank and work more like the well-known CAS treatment plants, where the difference is separation by filtration rather than sedimentation.

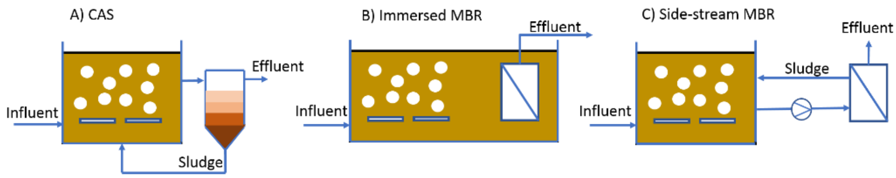

Figure 3-1: Principal setups for A) CAS, B) submerged MBR and C) side-stream MBR.

3.1.1. FLAT SHEET MEMBRANES

For the flat sheet setups, the membranes are submerged into the biological tank where the aeration also takes place. The aeration is used to facilitate the biological processes but also to generate a lift resulting in a recirculating flow and thereby apply shear on the surface of the membranes. A picture of the setup is shown in Figure 3-2. The flat sheets with the membranes are mounted inside the module, with an aerator underneath, generating the recirculating flow. This an illustration of a single filtration module of which there can be several placed in the tank, dependent on the needed capacity. The transparent sheets are used to force the air to flow up between the membranes rather than outside the module. The sheets with the membranes are in this setup is mounted with a gap of 7 mm between them.

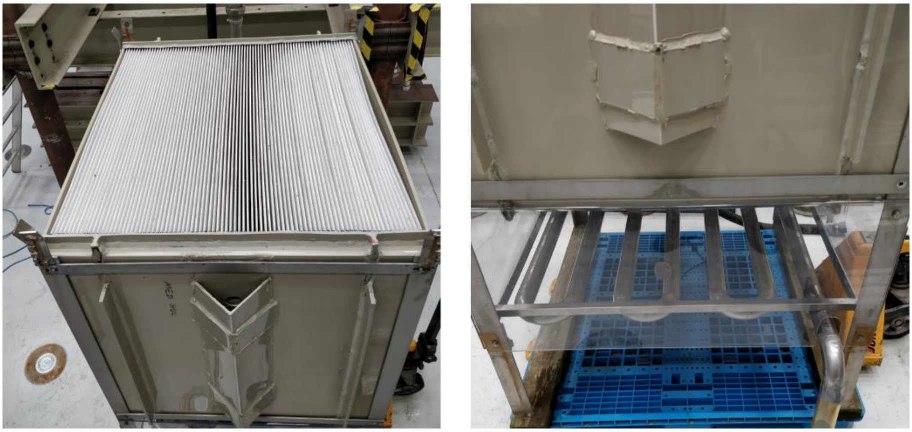

Figure 3-2: Setup of the module with flat sheet membranes.

In a wastewater treatment plant, the modules will typically be located in both series and parallel as illustrated in Figure 3-3.

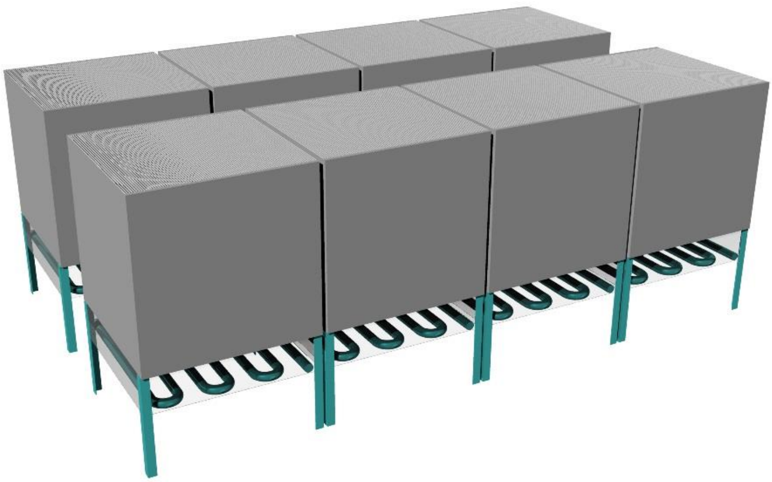

Figure 3-3: Example of the FS MBRs with their internal location.

The membranes are mounted on hollow sheets with internal channels to allow the flow of the permeate as illustrated in Figure 3-4. By applying suction to these channels, the TMP creates a flow through the membranes. For the immersed systems the TMP is mainly driven by the hydraulic head and operates with a TMP in the range of 0.1-0.8 mH_2O (Ho, Zydney 2006). This low pressure gives a lower flux through the membranes, but this also gives a lower fouling rate as the permeation drag is lower (Koustrup Jørgensen 2014). The drag of the particle increases with the velocity of the fluid relative to the particle and does furthermore depend on the shape of the particle (Haider, Levenspiel 1989). The flat sheet membranes still have issues with fouling as other types of MBR. The fouling control is accomplished with the flow from the induced air where an example of an aerator is shown in Figure 3-4. There have been conducted various experiments to study the effect of the aeration. This includes the effect of gap size between membranes, bubbles size and air flow rate. The higher aeration, the better fouling mitigation (Ducom et al. 2002; Ndinisa et al. 2006a) For membranes located with 20 mm distance there is a positive effect of larger bubbles until a threshold at a bubble size of 60 mL (Zhang et al. 2009).For the distance between the membranes, a positive effect has been found with smaller distance with gaps in the range of 3-7 mm (Prieske et al. 2012). All these studies show that the hydrodynamic conditions are crucial for optimal operating conditions.

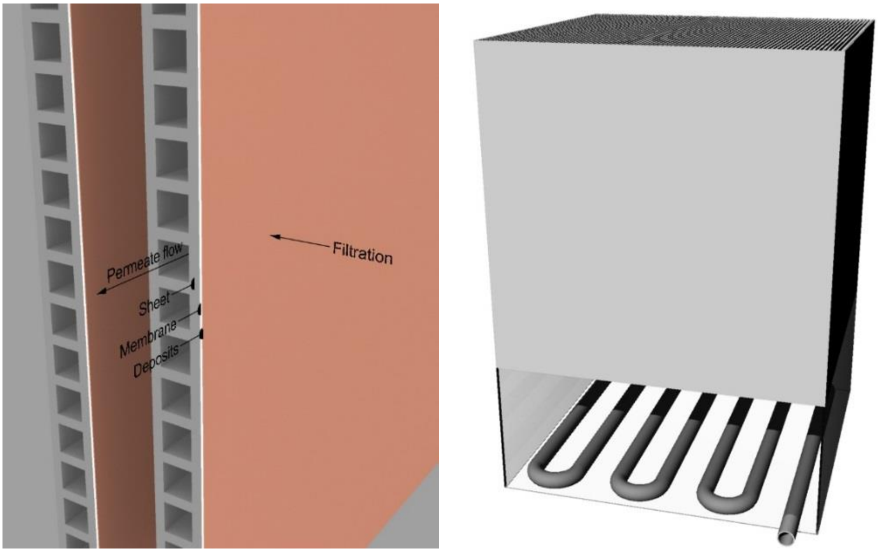

Figure 3-4: Principal illustration of two flat sheets, with the channels for permeate flow, the membrane, deposits on the membranes and the sludge flow towards the membrane and a simplified full-scale module.

3.1.2. ROTATING MEMBRANES

The side-stream MBR has the biological treatment and the filtration separated in two different tanks. There is one tank for the biological treatments from where the sludge it led into the filtration unit. In this case, the separation is in cylindrical containers with rotating membranes inside. An example of such systems is the Alfa BioBooster, which is used at Herlev Hospital to secure a good effluent quality of the wastewater from the hospital which contains pharmaceuticals, antibiotic resistant bacteria.

Figure 3-5: Illustration of a single unit with rotating membranes.

The rotation of the membranes is used to generate shear on the membrane surface for fouling mitigation. The setup of this system is illustrated in Figure 3-6; these units are then serially connected were the concentration of the sludge increases through the system. Furthermore, they will typically be parallel connected to achieve the needed

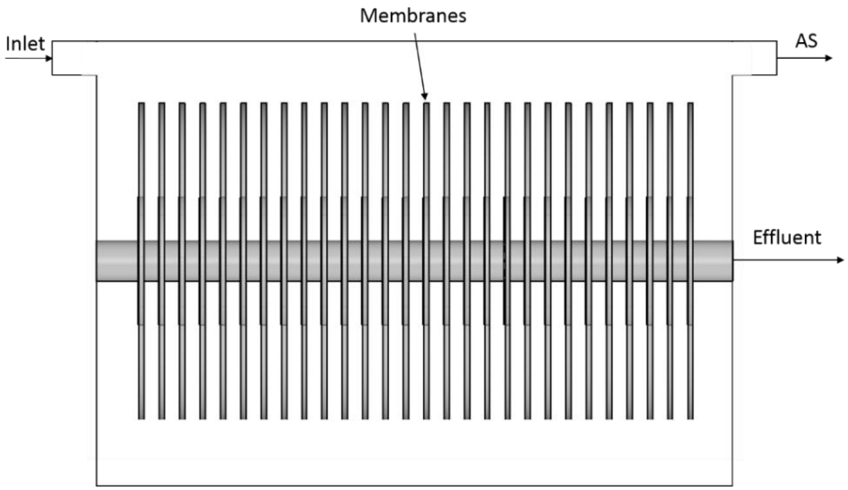

Figure 3-6: Setup for rotating membranes in a side-stream MBR.

capacity. Side-stream MBR is typically operated with TMP in the range of 0.1-0.5 MPa, which is significantly higher than for the immersed systems.

With the shear generated by the rotating membranes, it is possible to achieve high shear as the rotation rate can be controlled directly. This entails that the system can work at higher pressures as the limiting flux is controlled by the shear stress (Jørgensen et al. 2014). The high energy input for shear also entails that the system can work at sludge concentrations as high as 40 gTSS/L (Ratkovich, Bentzen 2013). It gives some advantages compared to other systems, as it produces much less sludge for disposal and it also means that the treatment plants can be more compact.

The higher shear stresses and the higher pressure does though demand higher energy and is making this method more energy consuming than the submerged flat sheets.

The rotating membrane systems do not in general use aeration in the same unit. This simplifies the evaluation of the flows as the multiphase flows are of high complexity. This has in a higher degree allowed the study of wall shear stress in these systems, as they are easier to measure and model. Constant wall shear stress can control the limiting flux through the membranes of rotating membranes (Jørgensen et al. 2014). With other rotating systems the fouling mitigation has also been shown to be related to the fluctuations of the wall shear stresses (Chan et al. 2011).

3.1.3. FOULING MITIGATION OF MEMBRANES

Much work has been put into understanding fouling, and different classifications are used. The fouling of the membranes can be divided into different stages, with different causes and different cures. The principle of the membranes is to retain organic matter and particles in the sludge. As the permeate goes through the membrane, the retentate is retained on the membrane surface. This retentate creates the fouling of the membranes which be divided into the three steps (Judd, Judd 2011).

1. Conditioning fouling
2. Slow fouling
3. Trans Membrane Pressure (TMP) jump

The conditioning fouling takes place immediately and is primarily irreversible fouling (Judd, Judd 2011). This initial fouling is almost independent of shear applied to the membranes (Ognier et al. 2002).

The slow fouling step takes place during operation. This is from a hydrodynamic view the most interesting part of the fouling as it can be reduced with optimal hydrodynamic conditions.

The third part is where a sudden jump in the TMP is observed. This jump is thought to be due to unevenly distributed fouling, resulting in increased flux in the less fouled areas of the membrane which have shown to at some point give a sudden increase in TMP (Le Clech et al. 2003).

The last step in the fouling is irreversible fouling where chemical cleaning or even replacement of the membranes is needed (Drews 2010)

The fouling of the membranes is a big issue for MBR. No simple model describing the fouling of the membranes exists. This is due to the complex nature of the systems with many parameters influencing the fouling of the membranes. For the shear stresses it has been shown that fluctuations in shear with long duration and high peak values are positive for fouling mitigation (Chan et al. 2011). In addition to the average wall shear stress does higher amplitudes in the fluctuation of the wall shear stress enhance fouling mitigation (Ducom et al. 2002). A higher standard deviation of the wall shear stress has been shown to reduce the TMP in a hollow fibre membrane system (Yang et al. 2016). The maximum value of the shear rate on the surface of the membranes has also shown to increase the permeate flux through the membranes (Akoum et al. 2002).

There are other parameters influencing the fouling of the membranes as the composition of the sludge, temperature and more. This work is though focused on the use of fluid dynamics for fouling mitigation. Regarding the fluid dynamics in MBR a few essential points can be made based on state of the art.

- The higher shear, the better fouling mitigation
- The larger temporal variations in the shear stress, the better
- The smaller spatial variations in the shear stress, the better

The positive effect of shear on fouling corresponds well with the fact that a higher shear rate increases the lift of the particles (Saffman 1965). This leads to a force acting in the normal direction away from the surface. It is from the above-mentioned points not totally clear if the fouling mitigation is due to shear stress or shear rate, and from eqn. (1) it is clear that they are intercorrelated and that an increase in one of the will also lead to an increase in the other. The exact effect which of the parameters have on fouling is a full study itself, and here is it just used that increased shear stress leads to increased fouling mitigation.

It is though also important to note that there is a threshold where the increase of shear stresses does not have a positive effect and might even have an adverse effect, which is likely due to the break-up of the sludge particles (Böhm et al. 2012).

The shear stress is described with eqn. (1). As the wall shear stresses depend on the viscosity and the shear rate, these parameters are of importance. This relationship shows that both the fluid dynamics of the system and the rheology which influences the fluid dynamics is essential.

$$\tau = \dot{\gamma}\ \mu_{app} \qquad (1)$$

τ	Shear stress
$\dot{\gamma}$	Shear rate
μ_{app}	Apparent viscosity

The influence of fluid dynamics fosters the basis for the evaluation of the systems where it is sought to model fluid dynamics in setups with rotating membranes and FS membranes to optimise the distribution of wall shear stresses while minimising the energy consumption for fouling mitigation. There have already been made some work influence of optimised fluid dynamics for where a modification of geometry under the sheets increased the air flow rate with 30–50% with the same aeration rate (Prieske et al. 2012). This energy demand shows the potential for energy optimisation by enhancing fluid dynamics.

3.2. FLUID DYNAMICS IN MBR

The fluid dynamics in MBR is a complex area of science. The sludge is a non-Newtonian fluid (Rosenberger et al. 2002; Eshtiaghi et al. 2013) which also contains particulate matter and flocs (Ratkovich et al. 2013). For aerated systems, the liquid gas interaction makes the fluid dynamics even more complicated.

The study of fluid dynamics can be done with either experimental fluid dynamics or computational fluid dynamics. The two methods do also often work hand in hand as both methods have their limitations.

In MBR the wall shear stresses are of huge interest as they are used to control fouling mitigation. The most used experimental method for measuring wall shear stresses is the electrodiffusion method (EDM). The application of the method is described in Böhm et al. (2014). The theory of the method is outside the scope of this work but should be highlighted that the method is not directly measuring the wall shear stress but rather the electric current between a cathode and an anode mounted on the wall where the shear rate is determined from the convection and the diffusion. With the use of the electric circuit, it sets high demands for the used electrolytic solutions. These requirements complicate the use of AS as a liquid. The method has successfully aerated FS systems with both water and surrogates for sludge (Zhang et al. 2009; Böhm, Kraume 2015). The method is though very time consuming and difficult to apply on full-scale solutions, making it difficult to use for full-scale optimisation.

The general flow patterns are also of interest in MBR system as it can be used to optimise the fouling mitigation. A non-invasive method for measuring the fluid velocity is with a laser Doppler anemometer (LDA). In its most advanced versions, it can measure all the velocity component on a very low timescale. The equipment does though have its limitation as the laser beams must be able to reach the point of interest. This can be problematic as the measurement area is shielded by the geometry which will either make the measurements impossible or result in modified geometries to be able to conduct the measurements. The fact that the fluid has a low transmittance and a large content of particulate matter is also a limiting factor which means that a surrogate for AS is often used. The method has been used to validate models for setups with water which have been used for modelling of fluids with sludge properties (Bentzen et al. 2012).

The limitations or at least challenges when using experimental fluid dynamics for studying fluid dynamics in MBR gives the initiative to use CFD.

3.3. CFD IN MBR

CFD has been used in MBR for both setups with rotating membrane systems and flat sheet membrane setups. Different methods exist for CFD, well-known is Navier-Stokes equation which uses the finite volume approach. There does also exist meshless discrete element methods as smoothed particle hydrodynamics (SPH). SPH has been successfully used for modelling stirrers in sludge tanks for wastewater treatment (Meister et al. 2017). The amount of literature concerning this area is still limited, and the development of the methods is not at the same stage as for the Finite volume method for Navier Stokes equation which is used in this study. This method allows modelling of rotating parts and bubbly flows. CFD very complex area with implementation of solution schemes and solvers used to solve the differential equations for the physics. The implementation of these is outside the scope of this work, where the commercial software STAR CCM+ has been used for all the modelling. In the following is a short description of some of the physic models which have been used and validated in this study.

3.3.1. MODELLING OF MOVING PARTS

For modelling moving parts two methods exist. The methods are the moving reference frame and the moving mesh. The moving reference frame is a computationally light model where the moving parts do not actually move. This method gives the possibility to give the geometry a velocity from which the energy is transported to the fluid, but the location of the geometry relative to each other will remain the same. The method has been used within the area of rotating membranes (Bentzen et al. 2012).

The other method is the moving mesh method, where the moving part has its mesh which can move relative to the rest of the geometry. For both the methods an interface is made between the moving and the stationary region where the transfer from the transport equations can take place, this method has successfully been used for rotating parts in MBR (Ratkovich et al. 2012). The two methods both allow the modelling of rotating membranes.

3.3.2. MODELLING OF NARROW GAP MULTIPHASE SYSTEMS

For the flat sheet membranes, the modelling of the multiphase interaction is a crucial point. There exist different methods for multiphase modelling. In this work, they have been grouped into three different methods being the VOF method, the Eulerian multiphase method, and the Euler-Lagrange method. The full equations for the different methods will not be given here as it is out of the scope of this work and they can be found elsewhere.

The Euler-Lagrange method has the classic Eulerian method described with the finite volume method for the continuous phase. At least one other phase is described with the Lagrange method, which can be particles, droplets or bubbles. This model is mostly used for low volume fractions of the Lagrange phase and tends to get unstable or inaccurate at higher volume fractions and has due to this not been used in this work. The VOF method and the Eulerian multiphase method are described in the following. The other methods all use the finite volume methods where the volume is discretized into cells for which the momentum and transport equations are solved.

Volume of Fluid

The VOF method is also a Eulerian method where the flow is described with the finite volume method in the entire setup. This method is describing resolving the interface between the phases. All the flow properties are shared between the phases in each cell, meaning that the phases have a shared velocity, density, etc. When modelling bubbly flows with the VOF method, the mesh and time-scale must be chosen sufficient to resolve the surface of the bubbles with high gradients in both volume fractions and velocities. Different methods exist to keep the interphase between the phases, e.g. the high-resolution interface capturing (HRIC) scheme and the Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM) which have both been validated for free surface flows (Waclawczyk, Koronowicz 2008).

The VOF method has been applied in single bubble studies for FS MBR, and it has been shown valid to model single bubbles (Wei et al. 2013; Prieske et al. 2012; Essemiani et al. 2001). The computationally cost causes that the model is not feasible for full-scale modelling with a high number of bubbles. Furthermore, does the method not include modelling of coalescence hindrance which can lead to errors in bubble swarm modelling.

Eulerian multiphase method

The Eulerian multiphase method is a computationally lighter alternative for multiphase modelling. The method is used for modelling flows where two or more phases coexist in the entire domain. The use cases include the modelling of bubbly flows, with a continuous and a dispersed phase. With this method, all phases coexist in every single cell, where each phase has a volume fraction. Each phase has its own set of momentum equations in each cell, while the pressure is shared between all the phases. The momentum equation of the method is described with (2). A throughout the description of the method is outside the scope of the work. An important part of the equation is the last term on the right-hand side as it is the term for the interphase momentum transfer. This part if of particulate importance as it is not built on the same physical properties as the other parameters but somewhat empirical correlations of how the different phases affect each-other.

$$\frac{\partial}{\partial t}\int_V \alpha_i \rho_i \mathbf{v}_i \, dV + \oint_A \alpha_i \, \rho_i \, \mathbf{v}_i \otimes \mathbf{v}_i \cdot d\mathbf{a}$$
$$= -\int_V \alpha_i \nabla p \, dV + \int_V \alpha_i \, \rho_i \, \mathbf{g} \, dV + \oint_A \alpha_i \tau_i \cdot d\mathbf{a} + \int_V \mathbf{M}_i \, dV \qquad (2)$$

$\boldsymbol{\alpha_i}$	Volume fraction of phase $\boldsymbol{i}$
ρ_i	Density of phase i
$\boldsymbol{v_i}$	Velocity phase i
p	Pressure
$\boldsymbol{g}$	Gravity vector
τ_i	Shear stress
$\boldsymbol{M_i}$	Interphase momentum transfer

The interphase momentum transfer can be modelled with a wide variety of models including lift force and drag force as some of the most important. When modelling the interphase momentum transfer eqn. (3) must also be obeyed.

$$\sum_i \boldsymbol{M}_i = 0 \qquad (3)$$

There exist several methods for modelling of both the lift and the drag of bubbles. The drag force $\boldsymbol{F}_{ij}^{D}$ is described with (4) for phase j acting on phase i.

$$\boldsymbol{F}_{ij}^{D} = A_{ij}^{D}(\boldsymbol{v}_j - \boldsymbol{v}_i) \tag{4}$$

$\boldsymbol{F_{ij}^{D}}$	Drag force
A_{ij}^{D}	Linearized drag coefficient
$\boldsymbol{v_i}$	Velocity phase i
$\boldsymbol{v_j}$	Velocity phase j

For bubbles in water, different drag methods have been developed (Tomiyama et al. 1998; Schiller 1933). For Herschel Bulkley, fluids drag models have only been developed for rigid spherical particles (Atapattu et al. 1995). This makes the accuracy of the drag from the bubbles in non-Newtonian fluids uncertain and furthermore are they developed for non-confined geometries which deviate from the geometries in FS MBR. The lift force which is also influencing the flow of bubbles can be modelled with (5) (Auton et al. 1988).

$$\boldsymbol{F}_L = C_{L,effective}\, \alpha_d \rho_c [\boldsymbol{v_r} \times (\nabla \times \boldsymbol{v_c})] \tag{5}$$

$\boldsymbol{F_L}$	Lift force
$C_{L,effective}$	Effective lift coefficient
α_d	Volume fraction of the dispersed phase
ρ_c	Density of continuous phase
$\boldsymbol{v}_r$	Relative velocity between the phases
$\boldsymbol{v}_c$	Velocity of the continuous phase

From eqn. (5) it is clear that the lift depends on the curl of the flow, which can be seen from the last part of the equation which is the curl of the continuous phase. The description of the lift coefficient depends on the bubbles. It has been shown that it can be both positive for larger bubbles and negative for smaller bubbles (Tomiyama et al.

2002). This influences the overall flow pattern of bubbles and is important for modelling bubbly flows.

Both the drag and the lift depends on the size of the bubbles, making the results dependent on the choice of bubble size. In former works modelling FS MBRs with the Eulerian method has used a constant bubble size (Ndinisa et al. 2006b; Khalili-Garakani et al. 2011; Amini et al. 2013; Yang et al. 2016).

The Eulerian multiphase method has been applied for multiphase modelling in several FS setups (Ndinisa et al. 2006b; Khalili-Garakani et al. 2011; Amini et al. 2013; Yang et al. 2016). These works have shown that this method is a useful tool for full-scale optimization on FS MBR. There are though inconsistencies in the modelling of the phase interaction as it has been implemented differently in all the works. The drag is modelled with different approached for all the works. None of the works has implemented the lift force in their model; they are though all using the k_ϵ turbulence model, where (Ndinisa et al. 2006b) also include particle induced turbulence.

3.4. RHEOLOGY AND RHEOMETRY

The rheology of sludge is an essential factor when modelling the fluid dynamics and directly influences the shear stress (Ratkovich et al. 2012). The rheology describes the flow of a fluid when exposed to shear. For Newtonian fluids like water, there is a linear dependency between the shear stress and the shear rate expressed by the viscosity (μ), described with (6).

$$\tau = \dot{\gamma}\mu \tag{6}$$

This correlation is not valid for non-Newtonian fluids which show a non-linear relationship between the τ and $\dot{\gamma}$. It has been found that the rheology of sludge is well described by the Herschel Bulkley formula, described by (8) (Eshtiaghi et al. 2013). The slightly simpler correlation without the yield stress described with (7) is also used to describe the rheology of MBR sludge (Rosenberger et al. 2002).

$$\tau = k\,\dot{\gamma}^n \tag{7}$$

$$\tau = \tau_y + k\,\dot{\gamma}^n \tag{8}$$

τ_y	Yield stress
k	Consistency factor
n	Flow behaviour index

There have not yet been reached a consensus on how to describe the rheology of sludge which has been discussed in the works of Ratkovich et al. (2013) and Eshtiaghi et al. (2013). Another property of AS is that it is thixotropic, at least at low shear rates (Baudez 2008). Furthermore, is sludge viscoelastic (Chhabra et al. 2008). A complete description of the sludge is very complicated and set high demands for rheometers. The shear thinning behaviour is assumed to be the dominant factor in the description of the rheology of sludge with changes of the apparent viscosity of factor 10 to 100 while the rheological behaviour is only slightly time-dependent (Rosenberger et al. 2002). Therefore, it is only the shear thinning part of the sludge that has been considered in this work.

3.4.1. RHEOMETRY

Rheometry is the experimental techniques used for measuring the rheology of fluids. A wide variety of rheometers for measuring the rheology exists. The most commonly used type of rheometers for sludge rheology is rotational rheometers (Eshtiaghi et al. 2013). In this work, the focus has been on the concentric cylinder setup which has also been shown favourable to other setups when measuring sludge rheology (Mori et al. 2006). The concentric rotational rheometer has a cylindric cup with a concentrically located bob in the middle where either the bob or the cup rotates to generate the shear. The measured parameters are the moment and the rotational velocities, from which the shear stress and shear rate are determined. The shear stress can directly be determined from the torque. The main issue arises when determining the shear rate on the surface of the bob. At the same time, it has been stated that the gap between the cylinders should be ten times larger than the particles (Dick, Ewing 1967). These two facts are counteracting each-other, resulting in the fact that the larger particles in the fluids, the larger geometries are also needed.

3.4.2. SHEAR RATE DETERMINATION IN RHEOMETERS

Different methods exist for determining the shear rate in rotational rheometers. The shear stress and shear rate are not uniformly distributed in the gap between the bob and the cup (Nguyen, Boger 1987). The shear rate depends on the fluid type and the geometry of the rheometer (Estellé et al. 2008). The simplest method for determining the shear rate is with the assumption of a constant shear rate, which is though not precise. For a Newtonian fluid, the shear rate in a rheometer with a rotating bob the shear rate can be described with (9) (Steffe 1996).

$$\dot{\gamma} = 2\Omega\left(\frac{\alpha^2}{\alpha^2 - 1}\right) \tag{9}$$

$$\alpha = \frac{R_c}{R_b}$$

As the shear rate depends on the rheology of the fluid, different methods have been proposed. The method developed in (Krieger, Elrod 1953) described in (10) is extensively used (Estellé et al. 2008). The method is though not precise for fluids with yield stress (Steffe 1996; Borgia, Spera 1990). Furthermore, is it not precise for noisy data (Borgia, Spera 1990)

$$\dot{\gamma} = \frac{\Omega}{ln\, a}\left(1 + ln\, a \frac{d\, ln\, \Omega}{d\, ln\, \tau} + \frac{(ln\, \alpha)^2\, d^2\Omega}{3\, \Omega\, d(ln\, \tau)^2}\right) \quad (10)$$

The accuracy depends on α and the rheology of the fluid. α is the ratio between the radius of the cup and the bob. Even for very small gaps, there can be significant errors for Herschel Bulkley fluids with high yield stress and low flow behaviour index (Chatzimina et al. 2009). Therefore, no precise method exists for Herschel Bulkley fluids. This is important to be aware of when using the methods, as it will influence the results.

CHAPTER 4. RESEARCH QUESTIONS

Fouling of the membranes is identified as the main issue in MBR, which reduces the effectivity of the treatment plants. It is still not clear how the treatment plants should be constructed an operated to achieve the optimal operation of the treatment plants. The fluid dynamics are important for optimal operation of MBR, which is shown in a large variety of studies. There is though much less literature concerning how the optimal flow conditions in full-scale treatment plants are achieved. This leads to the research question for this thesis.

- How can the optimal flow conditions in MBR be achieved by optimizing the operation and geometry of the filtration units?

To answer this question, CFD is used and has led to a series of sub-questions that needs to be addressed to answer the main question. This includes the study of rheology of the sludge as it influences the fluid dynamics as well as the evaluation of different methods for modelling the fluid dynamics in these systems.

1. How can low-cost rheometer be constructed which can measure the rheology of activated sludge?
2. How can the issues with the inaccurate determination of the shear rate for fluids with a yield stress be avoided in a cylindrical rotational rheometer?
3. What is the optimal method for when using CFD in MBR systems with rotating membranes?
4. How can the fluid dynamics in MBR systems with rotating membranes be optimized?
5. What methods for multiphase modelling with CFD does best describe flows in a flat sheet membrane setup?
6. What is the importance (Sørensen et al. 2018b)of the geometry of full-scale flat sheet MBR systems and how can it be optimised to secure an even aeration with optimal utilisation of the induced air?

CHAPTER 5. RHEOLOGY AND RHEOMETRY FOR SLUDGE

The rheology of sludge is a crucial factor for fluid dynamics in MBR. Therefore, both the rheology of the sludge in MBR and the rheology of the surrogate with CMC solutions was of interest. This led to the construction of the rheometer and a new method for determining rheological parameters for a Herschel Bulkley fluid as no precise method exists for evaluating the shear rate in the gap of a rotating rheometer.

5.1. CONSTRUCTION OF A LOW-COST RHEOMETER

A rheometer was built to measure the rheology of sludge and the CMC solutions which were used as a surrogate for sludge in the experimental setup in Paper C (Sørensen et al. 2015a). A principal sketch of the rheometer is shown in Figure 5-1. The rheometer was designed, so it was applicable on sludge. The chosen setup was a concentric rotating rheometer which has been shown favourable when measuring sludge rheology (Mori et al. 2006). The constructed rheometer is described in Paper A (Sørensen et al. 2015b). It was constructed to operate at shear rates of 20 – 1000+ s^{-1}. The rheometer was successfully built with the principle of a rotating rheometer. The rheometer was calibrated with eqn. (11) to be able to get the same viscosity as a Brookfield viscometer. This might be due to the area under the bob was not considered when evaluating the shear stress on the surface of the bob. Furthermore, was it for this low-cost setup unavoidable to have some hysteresis in the bearing. The constant added to the viscosity in the calibration of the rheometer was half the viscosity of water; this also means that it is only due to calibration it can give the reasonable results on low viscous fluid, and it is believed the rheometer is not that useful for low viscous fluids. On the other hand, is this value low compared to the rheology of sludge and is not believed to influence the results. The constant of 1.1 which is multiplied by the result can indicate that there is some friction in the bearing for the bob. Based on the experimental data it is not possible to precisely determine what causes this

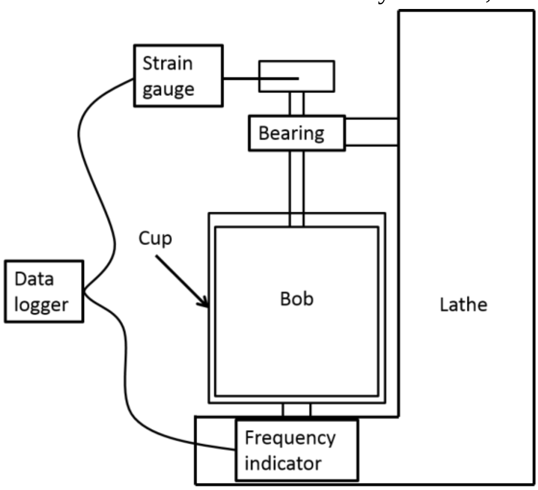

Figure 5-1: Setup for constructed rheometer described in Paper A (Sørensen et al. 2015b).

factor. It is clear from Paper A (Sørensen et al. 2015b) that the measurements did fit with these constants, both for different shear rates and different viscosities.

$$\mu_{cor} = 1.10\,\mu - 0.47 \cdot 10^{-3} \tag{11}$$

With the calibration, the rheometer yielded satisfying results and worked in a wide range of shear rates. With the relatively large geometry, a gap of 2.05 mm could be used while the radius ratio was kept low. The gap of 2.05 mm gives the possibility to measure on solutions with particle sizes of 0.2 mm as the gap should be 10 times size of the largest particles (Dick, Ewing 1967). The ratio between the bob and the cup of 1.038 a ratio where it can be discussed if $R_b \ll R_c$ as it was supposed to be (Steffe 1996). This can lead to lowered accuracy when determining the shear rate and thereby an inaccurate description of the rheology. This is also the reason a new method for determining the rheological parameters was developed in Paper B (Sørensen et al. 2018b), where the accuracy should be less dependent on the geometry and fluid.

5.2. DEVELOPMENT OF 1D FLOW MODEL FOR DETERMINATION OF RHEOLOGICAL PARAMETERS

When applying the rheometer on activated sludge, the rheology of the fluid influenced the velocity profile in the gap and thereby also the shear rate at the surface of the bob. As it was clear that the original method for determining shear rate used when building the rheometer was not accurate. As it is shown in Paper B (Sørensen et al. 2018b) with the comparison of the shear rates over the gap the Couette flow method underestimated the shear rates with as much as 28 % in the used range of shear rates with the rheology of the specific sludge samples. The developed method is described in Paper B (Sørensen et al. 2018b). This method solves the entire velocity profile for the fluid in the gap inside an optimisation algorithm. By doing so no need of inaccurate approximations for the shear rate it needed. The fit is based purely based on the measured quantities where the measured torque is used to calculate the velocity by (12). The derivation of the equation is described in Paper B (Sørensen et al. 2018b). The constants are optimised to fit the calculated velocities with the measured velocities of the cup. From (12) it is also clear that the method allows the calculation of the shear rate if the fluid which is only partly sheared in the gap as it then calculates the shear rate as 0 in the part where the yield stress of the fluid is not exceeded.

$$v = \sum_{i=1}^{N} \begin{cases} \left(\dfrac{\dfrac{M}{2\pi\, r(i)^2\, h} - \tau_y}{k} \right)^{\frac{1}{n}} dr\,, & \dfrac{M}{2\pi\, r(i)^2\, h} > \tau_y \\ 0, & \dfrac{M}{2\pi\, r(i)^2\, h} \le \tau_y \end{cases} \tag{12}$$

The given expression is based on a rheometer where the cup is rotating, and the bob is stationary, and a fluid assumed to be described by the Herschel Bulkley equation. It is though general in the way that the approach for calculating the velocity of the fluid from the measured torque and fit this to the measured velocity can be used for all rheological expressions. The expression for the rheology is the correlation between the shear stress and the shear rate can the shear rate always be determined from the torque and eqn. (12) can be rewritten to fit another expression for the rheology using the same approach.

A drawback of this method is that it does not give the well-known fit of the correlation between shear stress and shear rate as the fit is made on velocity vs velocity. The shear stress vs shear rate can then be plotted from the known parameters and to show the shear stress at the shear rate where the experiments are conducted. These shear rates are though determined from the measured shear stress and not from the rotational velocity.

The validity of the methods for describing the shear rate in rotational rheometers is usually is based on the error of the shear rate compared to the theoretical one determined from the shear stress. That validation is not meaningful in this setup, as the fit is not made for shear stress against the shear rate but velocity against velocity. The validity of the model is, therefore, best described by the ability of the method to calculate the correct velocity at the surface of the cup. It is shown in Paper B (Sørensen et al. 2018b), that the method can calculate the correct velocity of the cup with r^2 greater than 0.99 for all the data sets, whereby the method also must be valid.

In this work is the method used on the developed low-cost rotational rheometer. The rheometer did give noisy data, but despite that, the method was able to give a good fit of the velocity. As described noisy data is known to yield inaccuracies when evaluating the data with (10) (Borgia, Spera 1990).

5.3. RHEOLOGY OF ACTIVATED SLUDGE AND A SURROGATE FOR AS

The rheometer was used both for measuring the rheology of the activated sludge and the rheology of the CMC solutions, which were used as surrogate for AS. The rheology of activated sludge was measured at different concentrations as presented in Paper B (Sørensen et al. 2018b). The measurements showed that the rheology of the sludge was well described with the Herschel Bulkley method. The parameters were determined with the assumption of a Couette flow as described in Paper A (Sørensen et al. 2015b) and with the force balance method developed in Paper B (Sørensen et al. 2018b). This clearly showed the importance of choosing a correct method for determining the shear rate when determining the rheology of activated sludge, as the values of the found constants in eqn. (8) where the constants were as much as 33 % different for the developed method compared to the Couette flow assumption.

The rheology of the CMC solutions was well described by the power law where no yield stress was found and furthermore did it not show any thixotropic behaviour as illustrated in Figure 4 in Paper C (Sørensen et al. 2015a) which deviates from the activated sludge. It is though worth mentioning that the thixotropic behaviour usually is not included in the modelling of activated sludge.

When comparing the rheology of the sludge with the rheology of the CMC solutions, it was found that the CMC solutions did not have the same degree of shear thinning properties as the AS. This difference is illustrated with the plot of apparent viscosity of CMC solutions and activated sludge in Figure 4 in Paper C (Sørensen et al. 2015a). Xanthan gum solutions have been found to have a more pronounced shear thinning properties meaning that it is more comparable to AS (Buetehorn et al. 2010). It was though not possible to use it as surrogate due to the low transmittance of the liquid, making it impossible measure the velocities with the LDA. The transmittance was measured for both substances. The transmittance through 1 cm of the liquid with 0.3 g/l was only 0.27 for the xanthan gum while it was 0.98 for the corresponding CMC solution. Therefore, the CMC solutions are found to be the best available option as the surrogate for activated sludge when used for measuring velocities with LDA in a liquid depth of several centimetres.

CHAPTER 6. FLUID DYNAMICS IN MBR

The fluid dynamics is as described important to achieve good operating conditions in MBRs. The use of CFD for studying fluid dynamics in MBRs seems like a good choice due to the many possibilities it gives. The advantages include the possibility to easy change configurations of the setup and the possibility to study flow patterns on both small and large scales which can be difficult to measure. This includes the wall shear stresses are crucial for the fouling mitigation of membranes but are difficult to measure experimentally.

6.1. MODELLING OF MBR WITH ROTATING MEMBRANES

The influence of the geometry in the side-stream MBR with rotating membranes was studied. This was done to evaluate if changes in the geometry could be used to optimise the fouling mitigation and thereby minimise the energy consumption. The study included both the validation of the methods used for modelling the fluid dynamics and the application of the method for minimising the energy consumption used for fouling mitigation.

The study of the influence of the location conducted with CFD is described in Paper D (Sørensen, Bentzen 2017). Though to make sure that the modelling was approach was valid a validation was carried out as described in Paper C (Sørensen et al. 2015a). The validation was made against velocities measured with an LDA. As mentioned there are some challenges with measuring velocities where the use of LDA requires a transparent fluid. Due to this, the experiments were carried out with CMC solutions as a surrogate for AS. This ensured that the model was valid not only for water but also a liquid with rheology comparable to AS.

The study included the evaluation of two different methods for the rotating membranes, which was the moving reference frame and the moving mesh method. It was found that the moving reference frame unsuitable for this setup as it yielded wrong results near the interface between the stationary and the rotating region. The edge of the membranes was located with a distance between 21.5 and 61.5 mm to the stationary container as illustrated in Figure 6-1, entailing that the interface could only be located close to the rotating part yielding errors in this area. This error affects the results on the surface of the membranes, which was the area of interest and is thereby not optimal for this study. With the use of the moving mesh method, the errors on the interface between the stationary and rotating part were much smaller. The model was able to describe the shape of the tangential velocity profiles both in the radial direction from the rotation centre and in the direction from membrane to membrane as illustrated in Figure 6 in Paper C (Sørensen et al. 2015a). Based on this validation, the moving mesh method was used for evaluation of the full-scale geometry in Paper D (Sørensen, Bentzen 2017).

The study included the effect of locating the membranes eccentrically compared to concentrically in the cylindric container as illustrated in Figure 6-1.

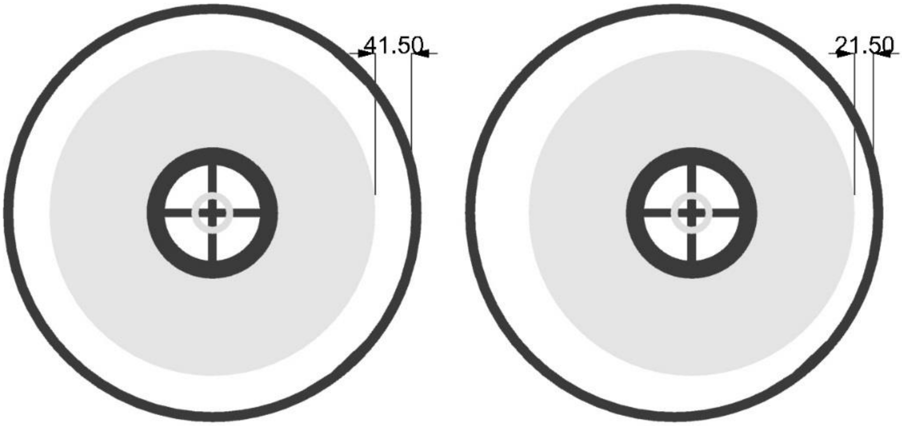

Figure 6-1: Concentric and eccentric location of rotating membranes in the container.

In Paper D (Sørensen, Bentzen 2017) the study the rheology of the sludge was described with literature values for activated sludge. There was later conducted measurements of the rheology of sludge from an active treatment plant operating with rotating membranes which is described in Paper B (Sørensen et al. 2018b). Therefore this rheology was also used for the modelling of the system with the rotating membranes. When conducting these measurements, the sludge was found to be very heterogeneous with only small particles. Measurements of particle size distribution were though not carried out. This heterogeneity is relevant as no particles were used in the modelling of the system, which from these observations seem to be a fair assumption. The rheology used in the modelling in Paper D (Sørensen, Bentzen 2017) was based on values from literature for a large range of different MBRs. As the rheology of the sludge, a system comparable to the one modelled was measured this rheology was also used for the full-scale modelling with the setup described in Paper D (Sørensen, Bentzen 2017).

The used sludge sample for modelling was the one with 27 gTSS/L, which had the sludge parameters found in Paper B (Sørensen et al. 2018b). The parameters used for modelling the sludge was; $\tau_y = 4.64\ Pa$, $k = 0.346\ Pa\ s^n$ and $n = 0.562$.

Table 6-1: Results for rotational membranes with use rheology found in Paper B (Sørensen et al. 2018b).

	Rotational velocity [RPM]	Mean Shear stress [Pa]	Power [W/m^2]
Concentric	120	9.38	12.2
Eccentric	80	9.36	8.06

In the paper was it found that the that the energy used for rotating the membrane could be reduced by 37% while maintaining the limiting flux for the eccentric setup as the rotational velocity could be lowered while the average wall shear stress was maintained.

The above study was made on a fluid described with the power law, and the same evaluation of the flux cannot be applied for sludge with Herschel Bulkley parameters as the relation between the shear stress and limiting flux was based on a power-law fluid. When evaluating the mean shear stresses, it was found that they were almost unaffected by the eccentric setup with the lower rotational speed, but the power consumption was reduced by 34 %. This power reduction shows that the eccentric setup is favourable to the concentric setup for both the different rheologies of the sludge. It shows the significant potential for optimizing the geometry for fluid dynamics as there is a considerable profit to gain only by small changes in the geometry. From Paper D (Sørensen, Bentzen 2017) is it clear that the given eccentricity is a good starting point as there was found a very even distribution of mean shear stresses as a function of radii. The same was seen for the maximum shear stress as a function of radius, which is also illustrated in Figure 6-2.

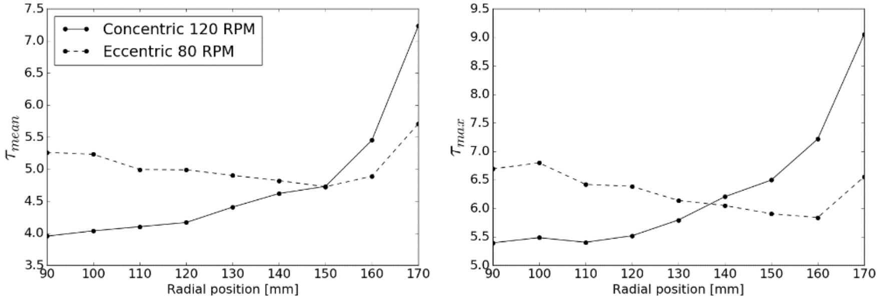

Figure 6-2: The distribution of the mean, max and standard deviation of the wall shear stress as a function of radius for the points fixed on the surface of the membranes following the membrane for five rotations.

The more even distribution is also somewhat clear from Figure 6-3 where the eccentric setup have high shear stresses on the right side of the membranes, meaning that each point on the membranes is exposed to high shear stresses once per rotation, which is not the case for the concentric setup where it Is increasing with radius as illustrated in Figure 6-2.

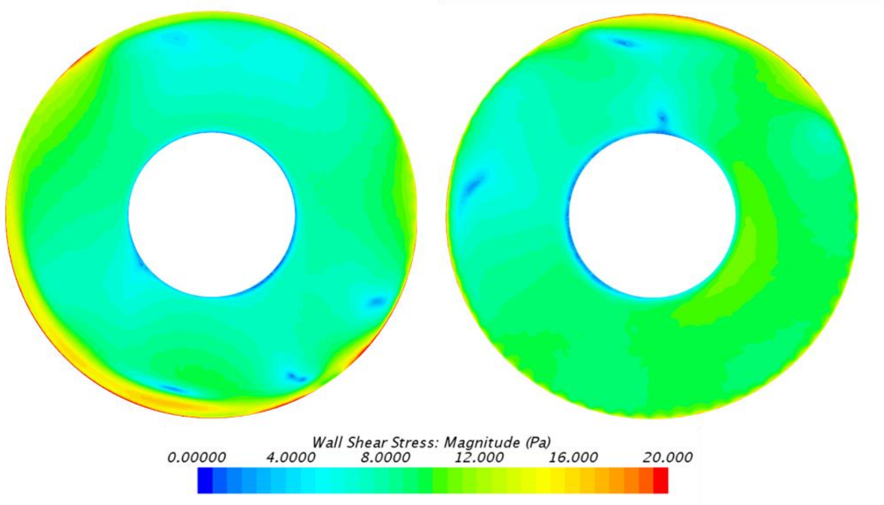

Figure 6-3: Snapshot of wall shear stresses for the concentric setup (left) and the eccentric setup (right).

Overall Paper C (Sørensen et al. 2015a) and Paper D (Sørensen, Bentzen 2017) showed that CFD is a useful tool for optimizing rotating MBR systems. In Paper C (Sørensen et al. 2015a) it was found that the model had a good precision for different setups. In Paper D (Sørensen, Bentzen 2017) it was shown how this tool could be used to study the effect different operation conditions and it was found that these conditions strongly influenced effectivity of the system and a reduction in energy used for fouling mitigation of 37 % at the same limiting flux was achieved.

6.2. FLUID DYNAMICS IN A FS MBR

The overall aim of the multiphase modelling is to model the wall shear stresses on the surface of the membranes for optimisation of the fluid dynamics used for antifouling. The multiphase modelling is more complicated than the single phase with rotating parts. As described in state of the art a wide variety of models are available for implementing the interphase interactions. The knowledge of the application of these models in flat sheet membrane setups is though limited. This limited knowledge made the validation of the different multiphase approaches a crucial part of this work. The former works have used the Eulerian multiphase method, which due to the low computational cost is a practical method for full-scale modelling where the VOF approach is too computational heavy in most cases. In the guidelines for the use of the Eulerian multiphase method, the following quote is used to describe the assumptions of the phases.

> "The phases are mixed on length scales smaller than we wish to resolve and can be treated as continuous fluids." (Siemens 2017)

This is a challenge when applying the approach in FS MBR setups, as the Sauter diameter of the bubbles is often larger than the gap between the membranes as described in Paper F (Sørensen, Bentzen 2018a) and Paper G (Sørensen, Bentzen 2018b). Thereby the assumptions for using this model not obeyed making the precision uncertain. The model is though still the model of choice in studies for similar conditions (Ndinisa et al. 2006b; Amini et al. 2013; Essemiani et al. 2001; Khalili-Garakani et al. 2011; Amini et al. 2013; Yang et al. 2016). Especially the modelling of the wall shear stresses is uncertain with bubbles fill the entire gap between the membranes, except for the liquid film.

The validation performed in this work can be divided into to two main parts. The ability of the model to describe overall flow patterns correctly which was the base of Paper F (Sørensen, Bentzen 2018a), where the overall flow pattern between the membranes was modelled. The other part was the ability of the method to model wall shear stresses on the surface of the membranes.

6.2.1. MODELLING OF WALL SHEAR STRESSES IN AN FS MBR

The ability of the Eulerian multiphase method to model the wall shear stress is important as this is a value that is important for optimising the system. The accuracy is uncertain due to the nature of the model, where all the high gradients in the flow around every single bubble are not resolved. Therefore the study was conducted where the different types of models were compared with experimentally measured values of the wall shear stress in an FS lab scale setup from Böhm, Kraume (2015). It is believed that the large local gradients in the flow field will also influence the wall shear stress. The only way to take his into account in the Eulerian multiphase method is by use of turbulence modelling. As found in Paper E (Sørensen et al. 2018a), the Reynold number is low due to the confined geometry and the high viscosity of the fluid meaning that the flow in most cases is laminar and there will be little or no effect of turbulence at all when modelling the wall shear stresses. The low impact of the turbulence was substantiated from the results in the Paper E (Sørensen et al. 2018a), where it was found that the wall shear stresses were higher for the laminar Eulerian multiphase model than for any of the models where the turbulence was included. Furthermore, did the VOF model where the bubbles are resolved by the mesh show that the turbulent viscosity was only significant in the wake of a bubble, while the turbulent viscosity was neglectable in the rest of the volume F (Sørensen, Bentzen 2018a), which is also shown in Figure 6-4. This was with the turbulence modelled with the realizable k_ϵ turbulence model. In Paper E (Sørensen et al. 2018a) it was also found that the Eulerian multiphase method underestimated the wall shear stresses compared to what has been found experimentally. This was a significant underestimation as all the modelled shear stresses all was under 50 % of the measured shear stresses with use of the Eulerian multiphase model. On the other hand, did the studies in Paper E (Sørensen et al. 2018a) show that the VOF approach gave reasonable results when modelling the wall shear stresses. It was also able to give satisfactory bubble sizes, which is modelled with this approach contrary to the Eulerian multiphase model where the bubble size normally is given as a user input to the model.

When conducting the experiments described in Paper F (Sørensen, Bentzen 2018a), it was found that the velocity profile had very high shear rates close to the walls. In the measurement points in the centre of the gap, the shear rate was on the other hand very low. With the use of the high-resolution VOF model, it was possible to resolve the largest bubbles and get a proper description of the velocity profile between the membranes as shown in Paper F (Sørensen, Bentzen 2018a). In this study was the Eulerian model able to give the same magnitude of the average wall shear stresses as the VOF method with 2.77 Pa and 2.73 Pa respectively contrary to is shown in Paper E (Sørensen et al. 2018a). It was though found that the wall shear stresses in the horizontal direction were much smaller for the Eulerian method compared to the VOF method.

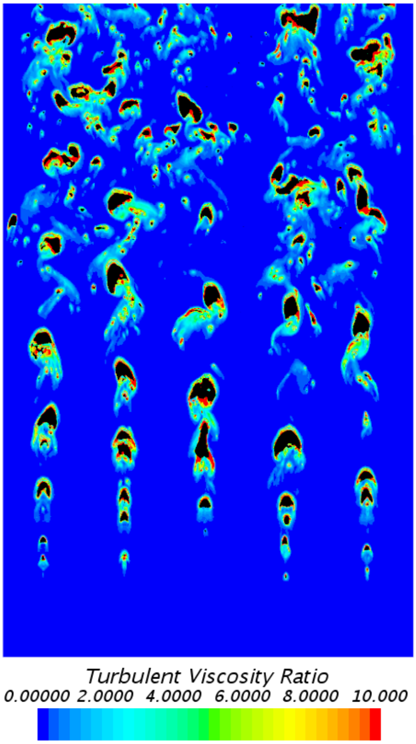

Figure 6-4: Bubbles (black) and turbulent viscosity ratio modelled with VOF method for the experimental setup with sludge properties for the liquid phase.

The VOF model gave valuable information about the direction of the wall shear stresses for the bubble swarms. The averaged wall shear stress in the given setup with a liquid phase with sludge properties was 2.73 Pa while the average of the absolute value of the horizontal component was 1.05 Pa with a maximum value of 9.6 Pa. This is interesting as none of the former works measuring the wall shear stresses has been able to quantify the different components of the wall shear stresses.

From the VOF model, it can be concluded that the wall shear stresses in the horizontal direction have a significant contribution to the total shear stress. It is believed that this is a positive effect for fouling mitigation since the lift coefficient of the deposited material on the surface of the membranes is likely to change dependent on the angle of attack and some particles will be more exposed to shear stress from a different direction.

With the use of the high resolution of the VOF model, it was possible to study the flow patterns on a low temporal and spatial scale in a bubble swarm setup comparable to full-scale FS MBR setups. It has already been described in the literature that the shear stress is largest in the wake of the bubble on single bubble setup (Wei et al. 2013). The same was found here for the bubble swarm setup. Furthermore, did this study show that the lowest pressure on the membrane is in the wake of the bubbles. This lower pressure results in a lower TMP whereby the flux the through the membrane is also lowered (Koustrup Jørgensen 2014). The combination of these two things leads to a large net force on the particles in the direction away from the surface of the membrane compared to the same shear with a single-phase flow.

6.2.2. MODELLING OF OVERALL FLOW PATTERNS IN AN FS MBR

For the overall flow pattern between two membranes, an experimental setup with one single gap setup, as described in Paper F (Sørensen, Bentzen 2018a) was used. The geometry of this setup is also illustrated in Figure 6-5, where the flow is induced from the pipe in the bottom with 5 outlets. In this setup was the vertical velocities measured with the use of an LDA for different flow rates diameters on the outlets.

Figure 6-5: Experimental setup, with modelled sludge surfaces.

The experiments in this setup gave valuable information about the flow field between the two membranes. It was clear that the bubbles were rising in an oscillating pattern resulting in a dispersion of the air. The effect of this is seen in Paper F (Sørensen, Bentzen 2018a), where the plot of the velocities show that the velocities are more evenly distributed at greater heights over the inlet. The experiments showed that bubbles rose relatively straight in the free area underneath the narrow gap, which is also illustrated by the high peaks in the velocity profiles for the lowest located measurements points. The same was seen for the high-resolution VOF model with sludge properties in the single membrane setup in Paper F (Sørensen, Bentzen 2018a), which is also illustrated in Figure 6-5. At some point did the flow tend to turn into a more chaotic, and the bubbles did not rise along this relatively straight line.

When conducting the experimentnts for Paper G (Sørensen, Bentzen 2018b), it was clear this straight rising behaviour was not present in the full-scale setup, as an extremely chaotic behaviour of the bubbles was present underneath the membranes. The high turbulence underneath the membranes also resulted in a rapid break-up of the bubbles resulting in smaller bubbles than what was seen in the setup with a single gap.

This also concludes that the results from the single membrane setup in Paper F (Sørensen, Bentzen 2018a) cannot be directly transferred to full-scale cases flow underneath the membranes deviates strongly. Since the area between the membranes is very confined, it is still believed that if the model can describe the flow between the membranes for the single membrane setup, the same should be the case for a full-scale setup.

The aim of this work was also to validate a setup for the Eulerian multiphase model with a low computational cost allowing it to be used for full-scale modelling. When validating the Eulerian multiphase model with the experimental data from the single membrane setup it was clear that the mixing of momentum and volume fraction was not sufficient with the standard choice of models. This lag of mixing led to a calibration of the turbulent dispersion force with a factor of 100. This calibration also showed that the results to a high degree were dependent on the choice of this calibration factor. While it gave good results for the shape of the velocity profile for the setup with water, it cannot be concluded that the same turbulent dispersion is present with sludge as the liquid phase.

When evaluating the mean vertical velocity, it was clear that this was higher for the experimental setup than for all the models. By calibration of the drag, it is possible to calibrate the terminal rise velocity of the bubble. By lowering the rise velocity of the bubbles, a higher volume fraction of air in the gap can be achieved in the gap and thereby a

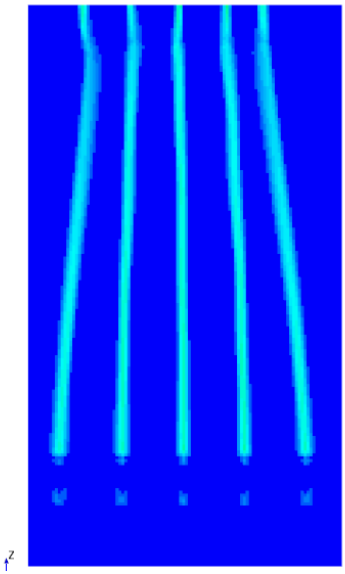

Figure 6-6: Volume fraction of air with implementation of lift force.

larger difference in density compared to the rest of the setup which influences the recirculating flow. It has though not been possible to calibrate the drag to give the correct mean vertical velocity, and the Tomiyama drag which gave the best results was used for the modelling.

As described by Tomiyama et al. (2002) large rising bubbles tend to migrate to the centre of the column due to a shear lift force. The typical way to implement this is with the use of the shear lift force described with eqn. (5). With this implementation, the lift depends on the curl of the flow. The lift was applied to the setup in Paper F (Sørensen, Bentzen 2018a), and as shown in Figure 6-6 this led to very narrow columns where the air was rising. The is likely due to the narrow gap geometry which limits the turbulence of the flow, which is the only force preventing the migration to narrow columns (Tomiyama et al. 2002). Therefore, the method described in Paper F (Sørensen, Bentzen 2018a) where only the wall lubrication force is used, is the method found to be most precise. The size of the wall lubrication force was calibrated whereby it is likely that it also accounts some of the shear lift force. It is important to note that the wall lubrication force is modified compared to the standard implementation due to the confined geometry making the standard use of wall distances meaningless. This implementation does only use the wall distances and wall lubrication force in the x-direction on the coordinate system shown in Figure 6-6.

6.2.3. APPLICATION OF CFD FOR THE STUDY OF FLUID DYNAMICS IN AN FS MBR

When modelling the full-scale setups of the flat sheet MBR the setup with the Eulerian method described in Paper F (Sørensen, Bentzen 2018a) was used. The study for the optimisation included the study of several parameters which are possible to modify. Alfa Laval has with former production methods seen a deflection of the membranes, and even though they have solved the problem, it is still of interest to see how the curved membranes influence the flow patterns as extra care must be taken to achieve the parallel membranes.

For the optimisation of the systems different possibilities exist. It is evident that the aerator itself is of importance as it is used to distribute the air. The distance from the aerator to the modules is also crucial as some distance between the aerator and the membranes is needed to secure an even distribution.

The internal location of the modules is also of importance and is studied as well as the influence of a deflector above the membranes, which is used to minimize the high velocity in the centre of the column and thereby to increase the volume fraction of air between the membranes.

Influence of curving sheets

A study was made on the influence of curving sheets in Paper F (Sørensen, Bentzen 2018a). It has been seen in production that the hollow sheets tend to start curving if they are exposed to heat, which can be that case when mounting the sheets in the module or when the membranes are mounted on the sheets. From this study, it was clear that the curvature of just 1 or 2 mm of the sheets had a significant impact on the flow between the membranes. The liquid flow between the sheets was as little as 22 % of the flow between two parallel sheets. With the lower distance between the membranes and thereby a smaller cross-section area, it was though believed that a small flow is needed to sustain the wall shear stresses. The mean value of the wall shear stress was reduced as much as 40 % in average on the surface of the membranes with a deflection of the membranes on 2 mm. So as highlighted in Paper F (Sørensen, Bentzen 2018a), parallel membranes are crucial to maintaining good flow conditions everywhere in the system. Parallel membranes can likely be achieved by proper choice of production methods or material, where, e.g. softer plastics will have lower tensions and thereby have lower tendency to curve.

6.2.4. OPTIMISATION OF AERATION IN AN FS MBR

The proper aeration of the membranes is crucial for proper operation of the MBR. As already discussed an even aeration is achieving increasing interest in the industry (Judd 2016).

There are several factors which are of importance to achieve proper aeration in an FS MBR. The aerator itself should be able to provide an equally distributed flow. At the same time, it is wanted to keep the pressure loss in the aerator low as it influences the power consumption for the aeration. On a larger scale, the entire geometry of the modules and their location in the tank relative to each other is essential. It was studied how the distance to the aerator with a specific design, as well as the distance between the modules influences the overall flow pattern.

Design of aerator

For the study of the aerator, the experiments described in Paper G (Sørensen, Bentzen 2018b) was carried out. The study included the evaluation of a single aerator in determining the pressure loss through the aerator combined with the distribution of the air and the bubble size. The experiments showed that the pressure loss through the aerator could be described with eqn. (13) with a coefficient of contraction of 0.64.

$$dp = \frac{1}{2}\,\rho_{air}\left(\frac{\frac{Q}{A_{outlets}}}{c_c}\right)^2 \qquad (13)$$

dp	Pressure loss
ρ_{air}	Density of air
Q	Airflow
$A_{outlets}$	Area of orifices
c_c	Coefficient of contraction

The experiments did also show that there was a tendency that the flow was smallest through the orifices closes to the inlet. The flow through such small holes is though difficult to measure, and therefore CFD was used to evaluate the distribution of flow through the different orifices.

CFD confirmed the uneven distribution through the holes with an increasing flow from the first orifice towards the last. The model used for the study of the flow distribution in the aerator was a VOF model where the interface between the phases is resolved around the orifices. The entire setup of the model is described in Paper G (Sørensen, Bentzen 2018b). The model showed that the minimum flow through a hole was 76 % percent of the mean flow for outlets with a diameter of 6 mm while it was 95 % with a diameter of 3.5 mm. This showed the positive thing with the small outlet diameter, on the other hand, is it evident that the energy consumption increases with smaller hole sizes as it depends on the area squared as shown in eqn. (13). On the other hand, is the system constructed to be able to flush the aerator if a blockage occurs, which might need a high pressure which can be achieved with a lower flow rate for smaller holes. The length of the discharge pipe illustrated in Figure 3-2 must be adjusted to the hole sizes avoid a loss of air through this pipe during aeration while still being able to flush the system at high flow rates. The height needed to avoid a loss of air can be directly determined from (13).

Full-scale optimisation of modules for an FS MBR

The full-scale optimisation included the distance between the modules, the distance to the aerator and the application of a deflector on the top of the modules to optimise the flow pattern. A full description of the study can be found in Paper G (Sørensen, Bentzen 2018b). The main findings of this work were that when the distance between the modules exceeded +30 cm, the influence of a further module distance was neglectable. From these results it seems like the minimum distance between the modules should be 30 cm, to secure a maximum recirculation flow. It is for this specific setup, and if, e.g., a double pack with two modules on top of each other a larger distance might be needed. It is though not clear what the optimal recirculation flow is in such systems as the model is not able to describe how the wall shear stresses are influenced by the changes in the flow.

It was clear that the distance from the aerator to the membranes should be at least 30 cm to achieve an even aeration of the membranes in the given setups. In the entire range of setups with a maximum distance of 60 cm, a positive effect was seen for distribution of the air with increased distance from aerator to the module, though the effect was most significant until the distance of 30 cm, from where the effect was smaller.

From the experiments and the modelling, there were strong indications that the air tended to migrate towards the centre of the column and thereby resulting in the highest velocity in the centre. This is undesirable as it can give an uneven distribution of the air and thereby not the optimal effect of energy used for the aeration and it gives a short retention time for the air in the system. Alfa Laval has reported higher permeate flux with the use of a deflector above the modules. It was not clear what gave this positive effect, and therefore CFD has been used to study how it influences the flow patterns. The layout of the deflector studied in this work is shown in Figure 6-7: Principle of deflector added above the FS MBR modules where it is mounted above the modules. As described in Paper F there is a tendency that the air migrates to the centre of the column, which can lead to dead zones in the sides of the membranes. It has been shown that the migration of bubbles towards the centre can be mitigated by changing the geometry under the module with the membranes (Ndinisa et al. 2006b). In this work, the changes were made above the modules instead of under. By installing changes above the modules instead of under, it is easy to mount it after the modules are installed.

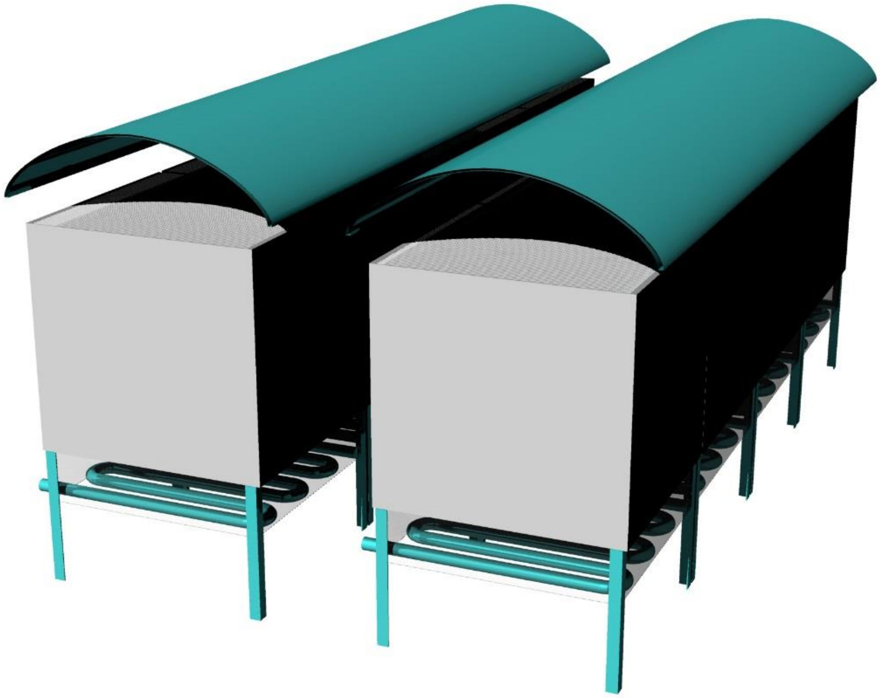

Figure 6-7: Principle of deflector added above the FS MBR modules

As described in Paper G (Sørensen, Bentzen 2018b) the deflector undoubtedly influenced the flow pattern between the membranes. Both the locations of the deflector resulted in a more evenly distributed aeration between the membranes but did also reduce the recirculation flow. For the setups with the air flow rate of 100 m^3/h was the vertical flow reduced from 151 kg/s to 120 kg/s and 175 kg/s for the high location and the low location of the deflector respectively. On the other hand, the volume fraction of air between the membranes increased by 29 % in average for the low location of the deflector.

It is not possible to give the optimal design of the deflector with the given modelling setup. As described there are some uncertainties with both the migration of bubbles towards the centre of the column as well as the turbulence and thereby dispersion of the air. It is likely that the higher volume fraction of air will lead to an increase in wall shear stresses. But due to the high uncertainty of the modelling of wall shear stresses with the Eulerian multiphase model is it not possible to conclude if this is correct with the given setup. When conducting the experiments for Paper C (Sørensen, Bentzen 2018a) the setup was also modified to run without the recirculation flow. In this setup was it seen that the bubbles had a much more chaotic behaviour than when the bubbles had free passage, and the same is likely to be seen when restricting the recirculation flow with the deflector.

It is clear from the results in Paper G (Sørensen, Bentzen 2018b) that a properly designed deflector can help to achieve a more even aeration of the membranes and increase the volume fraction of air between the membranes. Even though the recirculation flow is reduced, the effect of the deflector might still be positive since the lower recirculation flow increases the volume fraction of air between the membranes. It has been shown that there is no clear relationship between the liquid flow velocity and the wall shear stress for lab-scale experiments of FS MBRs (Böhm, Kraume 2015). The higher volume fraction of air between the membranes might lead to the possibility of using less air when operating the system and thereby reduce the energy consumption. It is though important to be aware that the lower recirculation flow might lead to a reduced mixing in the bioreactor, and the effect of this has to be studied further before the implementation of the deflector.

CHAPTER 7. CONCLUSIONS

In this work, CFD has been for optimisation of the fluid dynamics in MBR. The application of the two systems with rotating membranes and FS membranes was very different.

For the rotating membrane system, a high amount of energy is put into the fluid, and a very homogenous fluid is expected. This gave a relatively simple setup for the modelling, and the moving mesh method was successfully validated against velocity measurements on a comparable setup with a surrogate for sludge. When applying the method on an actual MBR system was it clear that there is a great potential for reducing the energy consumption by optimising the geometry and the operation of the system. With the use of an eccentric location rather than concentric location, the rotational velocity could be lowered while maintaining the average wall shear stress, leading to a decrease in power consumption of 34 % while keeping the average wall shear stresses.

In a flat sheet MBR, the flow is more complex than for the rotating membranes. The standard modelling method for this kind of setups is the Eulerian multiphase model, though it was clear from this study that extreme care should be taken when using this method as it is testing the limits of the validity of the model. The Eulerian multiphase method did show the ability to describe the overall flow pattern in the system with an increased turbulent dispersion and can be used to study general flow patterns in multiphase systems. With the Eulerian multiphase model, it was found that a proper distance from the aerator to the membranes is needed in an FS MBR to achieve even distribution of the air between the membranes. The installation of a deflector above the membranes in FS MBR is likely to give a more even aeration, and increase the increase volume fraction of air between the membranes with the same air flow rate, whereby the utilization of the air can be increased.

The Eulerian multiphase model does on the other hand, not seem suitable for modelling the wall shear stresses. The VOF method was successfully used for modelling the wall shear stresses and with the use of the VOF method was it found that the wall shear stresses in FS MBRs are dominated by the shear stress in the vertical direction, though the horizontal components do also attribute significantly to the total shear stress.

For determining the rheological parameters in a concentric rotating rheometer, a 1D flow model was used. The resolved velocity profile inside an optimisation algorithm renders the use of inaccurate approximations of the shear rate superfluous.

7.1. FUTURE PERSPECTIVE

This study showed that the multiphase modelling in FS setups is still uncertain. The particles in the sludge were not implemented in the modelling as well as the bubble size was modelled with a constant size woth the Eulerian multiphase model which is not the case in real-world systems. The effect of these two things should be studied as they will most likely influence the results. The rheology of the sludge was also simplified to a power law fluid of Herschel Bulkley though sludge is known to be both thixotropic and viscoelastic, and the effect of these approximations should be studied.

Furthermore, the implementation of the turbulence is very uncertain, and more work should be done to cover this area. The available methods for particle-induced turbulence did not yield sufficiently high shear stresses in the FS setup.

From the VOF model, it was clear that turbulence was present in the wake of the bubbles while the areas without bubbles were laminar, which differs from the Eulerian multiphase model where mean considerations of the flow field are used.

The use of deflectors in FS MBRs clearly influences the flow pattern in the system and increases the volume fraction of air between the membranes, but further studies should be made to determine how it affects a full-scale setup in operation.

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