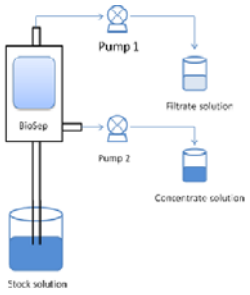
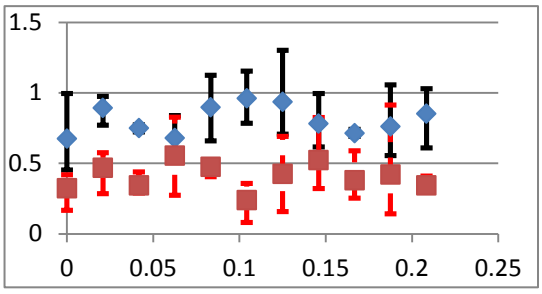
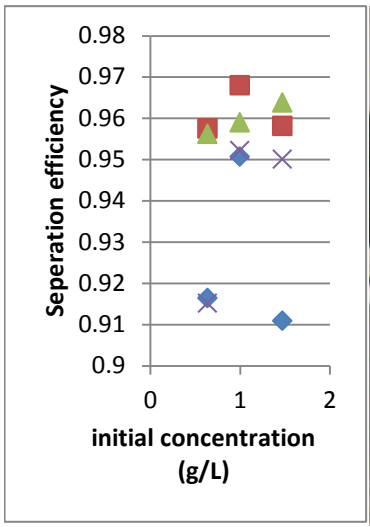
Biomass Refinery & Process Dynamics Group

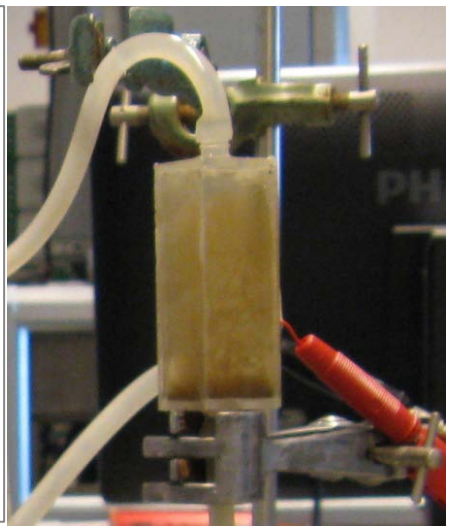
Thesis Systems and Control

Ultrasound bioreactor design and testing









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Ultrasound bioreactor design and testing

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Summary

Ultrasonic separation is a technique which can be used to separate suspension. A variety of particles can be retained and purified water can be harvested during the process. Although mostly applied in medical technology, ultrasonic separation can also be used in wastewater treatment. Solid-liquid separation in wastewater is usually accomplished by large settling basins or membrane filtration, which are prone to fouling. This study researches the possibility of using ultrasound as solid-liquid separator in wastewater treatment, thus creating an ultrasound bioreactor (USBR). The large settling basin and the membrane filtration are replaced by an ultrasonic separator. The ultrasound separator used in the experiments is a prototype separator and a commercial available. Using this prototype separator sludge suspensions can be separated with over 95% separation efficiency at a flow rate of 0.4 L/h. Biological activity test show that exposure of ultrasound does not diminish the biological activity of the activated sludge. Thus the ultrasound bioreactor provides an interesting alternative for wastewater treatment in small to medium scale wastewater treatment. The cost of such separation is estimated at 2.64 euro per m^3 of clean water. However optimizing the design of the separator will increase the flow rate and thereby lower the costs of the treatment

1. Introduction

In 2003 the United Nations world water development report stated:

"Some 2 million tons of waste per day are disposed of within receiving waters, including industrial wastes and chemicals, human waste and agricultural wastes."[1]

The pollution of water is a threat to humans, animals and even entire ecosystems. Therefore the wastewater treatment process is very important these days. Research to optimize current treatment process and development of new processes to treat water becomes more important every day, since the pollution caused by humans only increases.
Solid-liquid separation is a step in every wastewater treatment process. There are several different techniques for solid-liquid separation. Two groups of techniques are described; conventional methods that rely on gravity while the other group enhances separation with, for example, electric fields. Ultrasonic separation falls in the last category and is regarded a viable option for future solid-liquid separations. [2][3]

1.1 Problem definition

The main problem is to recover particles from solid-liquid suspensions in a non-conventional way and to extract water out of this suspension in a non-conventional way. This study focuses on the removal of particles from the suspension en thus recovering clean water and valuable particles.
In the study a commercially available separator called the Biosep (Applikon, the Netherlands), as well as a prototype separator are used. In both separators ultrasonic standing waves are employed to separate suspensions.

1.2 Objectives

The main objective is to study the separation efficiency of water-starch and water activated sludge suspensions using an experimental approach and to apply this separation technique to design an ultrasound bioreactor.

1.3 Research questions

The following research questions have to be answered to get a better understanding

- Is ultrasound enhanced sedimentation an effective compared to conventional methods and to what extent?
- How effectively can an ultrasonic separator retain activated sludge particles?
- How does ultrasonic exposure affect the biological activity of activated sludge?
- Which of the control strategies, suggested by Stefanova (2012), are effective in practice? [4]

1.4 Approach

To answer the research questions an experimental set up was build and several experiments were conducted. The separation efficiency of the Biosep was evaluated via turbidity measurements. In addition to this, activity measurements were performed to research if the activated sludge suffers from the ultrasound. The separation efficiency of the prototype separator was measured.

1.5 Outline report

In the second chapter the theoretical background on wastewater treatment methods and ultrasound is presented. In chapter 3 the experimental setups are presented. Chapter 4 contains the results of the experiments. In Chapter 5 the conclusions are presented. The last chapter, chapter 6, contains recommendations.

2. Theoretical background

This chapter contains the theoretical background behind several wastewater treatment processes. The principle behind ultrasonic separation and the design of the ultrasonic separator are discussed

2.1 Wastewater treatment

The wastewater treatment process removes and cleans the water up to certain standards before it is discharged to a receiving water body. The definition clean depends on the location where the treated water is discharged. Usually several treatment steps are necessary before the wastewater can be released. The purpose of these steps is to remove organic matter, phosphor, sulfur, nitrogen, heavy metals and pathogens. Many different systems are used to treat the wastewater; in the following section the two most applied principles are briefly introduced.

2.1.1 The conventional activated-sludge system

In any wastewater treatment the conventional activated-sludge system (CAS) requires pretreatment (see Fig 1A) [5]. During the pretreating the raw inflow of wastewater is screened and the grit is removed. The flow is also equalized in the pretreatment by having a large storage basin. After the pretreatment the wastewater is pumped to the primary treatment. In this treatment the sludge is allowed to settle and partly removed for further processing, floating substances, like grease or fat, are also removed during this step in the process. After the primary treatment the wastewater is aerated, this allows growth of bacteria and protozoa. The microorganisms oxidize organic matter, and often flocculate as their numbers increase. During the flocculation debris of dead cells, non-degradable particles and slow degradable particles get trapped in the floccules. These floccules are called activated sludge. This process is part of the secondary treatment. The secondary treatment ends with a sedimentation, in which the sludge settles on the bottom of a large tank. Part of the settled sludge is fed back to the beginning of the aeration tank; the other part is removed to prevent accumulation in the system. At the outlet at the top of the sedimentation tank the water contains little organic material and suspended matter, this water precedes to the last treatment step. The tertiary treatment step depends heavily on site of discharge, since it is a step to raise the quality of the water above the minimal norms for the discharge site.

2.1.2 Membrane bioreactors

The membrane bioreactor (MBR) combines the conventional method for wastewater treatment with a membrane filtration (Fig 1B). The process largely contains the same unit operators, where the large sedimentation tank at the end of the second treatment is replaced by a membrane filtration. This changes the properties of the process considerably.

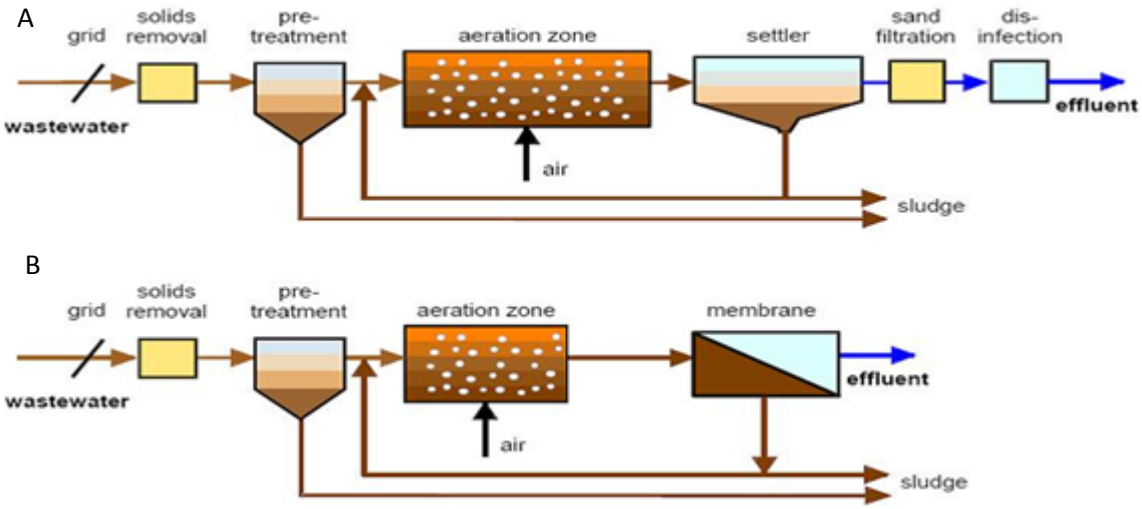

Fig 1. Schematic representation of A. a conventional wastewater treatment plant and B. a membrane wastewater treatment plant

The concentration sludge in MBRs is higher compared to conventional treatment plants. In the conventional treatment plant a high sludge concentration would affect the settling negatively. Further, the sedimentation requires some time and limits the flow through the entire system. A high flow would disturb the settling. In a MBR the settler is no longer present so the flow through the entire system can be higher. With a higher flow the retention time automatically becomes smaller. With both the concentration of the sludge and the flow through the system increased the productivity of the MBR is much better than the conventional plant. The MBR is able to produce cleaner effluents, which are required for some discharge sites. Conventional wastewater treatment plants are unable to reach this effluent quality [5]. However the MBR has several drawbacks. The membranes are prone to fouling, Fouling is the blocking of the porous caused by particles (cells, lipids, amino acids etc.), fouling increases the power needed to maintain a certain flow across the membrane. To prevent fouling the membrane needs to be cleaned. The MBR is cleaned twice every day quickly; this can be either by back flush or relaxation. Back flush reverses the direction of the flow while membrane relaxation stops the permeate flow and scours the membrane surface with air bubbles. [6] The membrane is thoroughly cleaned once or twice a week with chemicals. Such cleaning takes 30 to 60 minutes and requires chemicals; these chemicals need to be removed from the product streams later. A recovery cleaning session is performed every half year; this is the most intensive cleaning the membrane gets. The membranes create extra resistance for the pumps, which increases even more when fouling occurs, and thus increase the power requirements and therefore the costs.

2.1.3 Advantages of ultrasonic separation in wastewater treatment

An ultrasonic separation device would replace the separation device used in current wastewater treatment plants. The current separation devices are mainly large settling tanks even though the membrane bioreactor is starting to become more popular. As mentioned above the conventional wastewater treatment method requires large space for the big settlers. These settlers are required to clarify the liquids and remove the sludge. In membrane bioreactors the operation costs required to overcome the extra membrane pressure are immense. Ultrasound separation techniques might solve these problems. Ultrasound separation techniques do not require mechanical components in the reactors and tubes nor chemicals for cleaning; this decreases the operation costs compared to the membrane bioreactor. Ultrasound separation techniques do not require large amounts of space and therefore may be an efficient solution for effective wastewater treatment.

2.2 Ultrasonic separation of suspensions

In this section the basics of ultrasound separation are presented, as well as the principles of the design of the separator. Ultrasound techniques are currently mainly being used for manipulating cells [7][8][9] Ultrasound is also an efficient technique to separate plasma from whole human blood [10].

2.2.1 Ultrasound separation principle

Separation of solid-liquid suspensions with acoustic energy is a relative new technique. Much of the early work combined the ultrasound with other techniques such as filtration or electrical enhanced separation techniques [11][12]. In the 1990's the research started to focus on solid-liquid separation using only acoustic energy. Designers started to search for optimal designs for the separation device. The best separation is achieved when the sound waves are standing waves [12]. Standing waves have stationary nodes and antinodes. Suspended solids in the liquid undergo the forces of the standing waves and are collected in node lines. In node lines the force on the suspended solids is lower than in any other place in the separation device. The node lines depend on a couple of parameters such as wave frequency, length of the device but also on the liquid viscosity and liquid temperature. These parameters can be calculated [13].

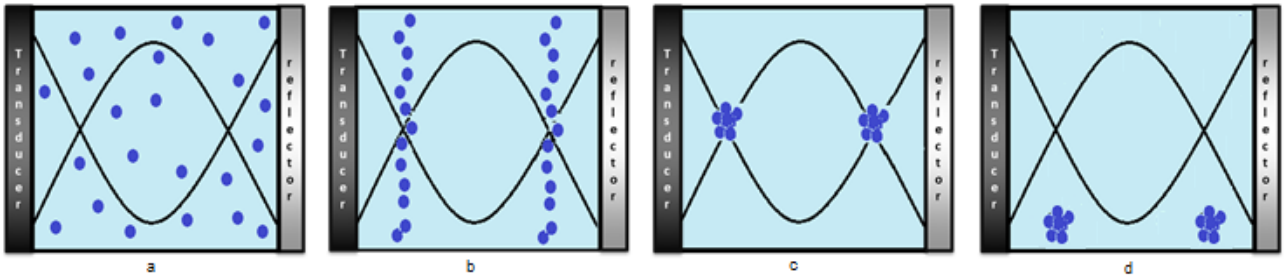

Fig 2. Enhanced sedimentation, particles within an ultrasonic field (a) are concentrated in node lines (b) then the particles agglomerate (c) and then tend to sediment under gravity (right).

Particles in an ultrasonic field are concentrated in node lines within the separator (Fig 2 b). These particles agglomerate as more particles are forced to the node lines (Fig 2 c). These agglomerates sediment faster than the individual particles (Fig 2 d). The acoustic enhanced sedimentation is called ultrasound enhanced sedimentation when the frequency of the standing waves in is the ultrasound area.

2.2.2 Ultrasound field

To create an ultrasonic standing wave field a five layer system is usually used [14]. One layer generates the sound waves; this layer is called the piezoceramic transducer. The second layer is an adhesive layer which binds the transducer to the carrier layer. The carrier layer separates the liquid from the transducer. It is called the carrier layer because it carries the transducer [15]. The fourth layer is the liquid layer and the fifth and last layer is the reflector.

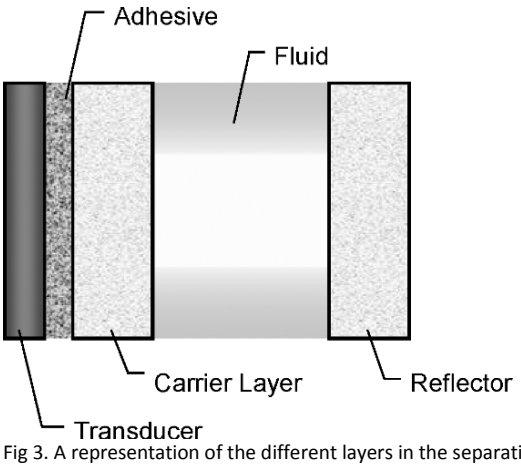

Fig 3. A representation of the different layers in the separation chamber. [15]

The most important parts of the device are the transducer, liquid and the reflector. (The first, fourth and fifth layer) The transducer layer is the layer which converts electricity into sound. The principle of piezoelectricity is used. Piezoelectricity is a property of some crystalline materials to store mechanical stress as electrical fields. This also works the other way around, applying an electrical field on these materials results in internal mechanical stress. This internal mechanical stress results in the production of sound waves, which can be controlled by the current applied to the material [15]. The reflector is essential for the creation of standing waves, since this is where the return wave is created. The space between the carrier layer and the reflector layer is the liquid layer. This is where the liquid flows through and is treated. The width of the liquid layer cannot be too large; otherwise the sound waves would become ineffective due to hydrodynamic effects. This practically limits the application on large scale processes.

2.2.3 Design of the separation device

The design of the ultrasound separation device consists of a separation chamber (Fig 3), at least one inflow and at least one outflow. Several different designs for the separation device have been made. In this part several designs are discussed. The first design is the Biosep design made by applikon. The Biosep uses a technology called sonosep™ [16]. The sonosep technology is based on the separation chamber shown in Fig 4 combined with an electronic device to control the chamber. The design of the Biosep is has one inflow and two outflows.


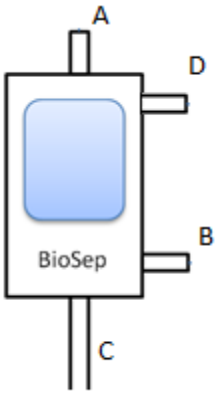

Fig 4. Left; photo of the Biosep separation chamber. Right: schematic representation of the Biosep. (A: filtrate flow, B: concentrate flow, C: suspension inflow, D: electricity supply and air cooling inlet (No liquid flow!))

In Fig 4 the right is a scheme of the Biosep. A is the effluent flow, B is the incoming flow, C the concentrated flow and D is connected to the controller and used for cooling the piezoceramic element. This Biosep device is designed to keep cells in a bioreactor while harvesting at the same time. The suspension enters the separation device at B and then enters the resonating field. The clean water leafs through A and the sedimentation leaves through C. To achieve high separation efficiencies the hydraulic turbulence should be minimized. Hydraulic turbulence adds to the force on individual particles and therefore slows the separation. To minimize the turbulence a laminar flow through the separation chamber is created.
A photo of the prototype separator used in this study can be seen in Fig 5. The principle of the design is the same as in Fig 4. However the Biosep has design features to make the flow through the separation chamber as laminar as possible. The prototype separator lacks these features; therefore it has a much higher hydraulic turbulence. The prototype also lacks an air-cooling inlet. The electricity is supplied via the red plug in Fig 5.

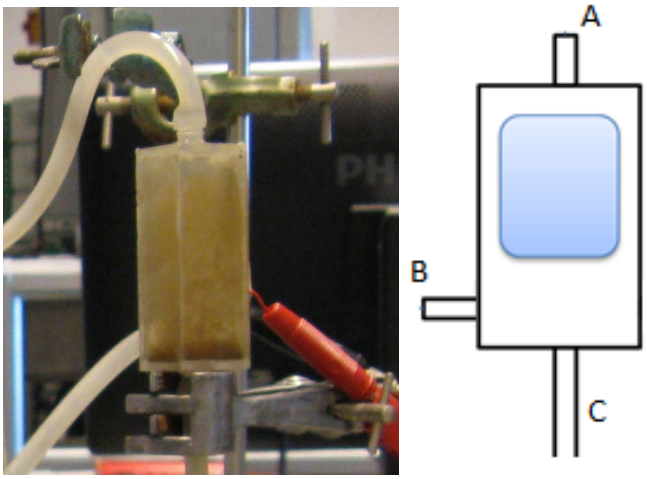

Fig 5. Left; photo of the prototype separator. Right: schematic representation of the prototype separator. (A: filtrate flow, B: concentrate flow, C: suspension inflow))

A different design is called the ultrasonic h-shaped separator. The h-shaped separator does not rely on gravity like the Biosep above. The h-shaped separator directly utilizes the acoustic radiation forces for separating the liquid into the cleaned outlet from the particle enriched outlet [9].

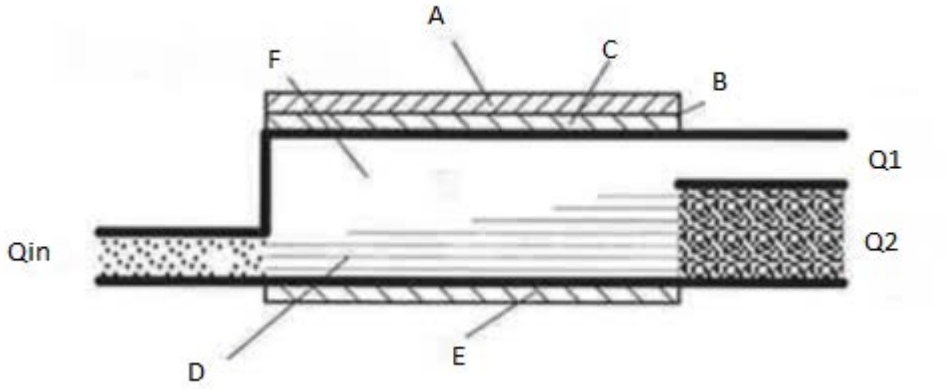

Fig 6. Acoustic h-shaped separator [13].

The h-shaped separator also exists of the 5 layers described above. The horizontal lines, D represent the node lines created by the acoustic sound. This system has one inlet flow for the suspended particles, Qin. The particle enriched outflow is Q2 in Fig 6. The clean water outflow is represented by Q1. This design is an optimized design of the Y-shaped separator [17]. Under micro gravity conditions the h-shaped separator still achieved good separation [18].

3. Material and methods

In this part all the experiments performed during this study are described. The experiments can be divided in two groups. The first group of experiments is related to previous work by Stefanova [4] and uses starch suspensions. The second group of experiments is done with activated sludge and aimed to create a prototype ultrasound bioreactor.

3.1 Starch experiments

The first part of the experiments was performed with starch suspended in demineralized water. These experiments are all preformed with a commercially available Biosep.

3.1.1 Determination of flow rates

Both the concentrate and filtrate flow rate needed to be determined in order to obtain the best possible separation.

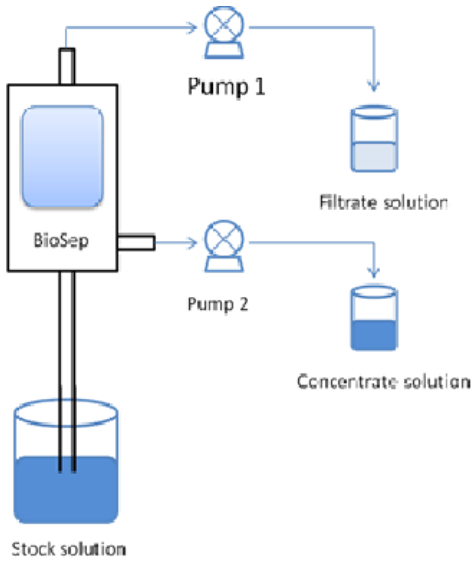

Fig 7. Photo and schematic representation of the experimental setup for the determination of flow rates.

In the first part of the experiments a stock solution of 1 gram starch per liter was used. The stock solution was continuously stirred by a magnetic stirrer to ensure a homogenous inflow into the Biosep. The inflow of stock solution into the Biosep is determined by the flow rate of both pump 1 and pump 2. Pump 1 was the filtrate pump and determined the flow rate at which the filtrate is harvested. Pump 2 determined the concentrate flow rate. In the Biosep the ultrasonic field was controlled by an ADI 1015 controller (Applikon, the Netherlands). The ADI 1015 controller was set to produce a resonance frequency of the field of 2.1 MHz. The ADI controller also switched the resonance field on and off during the experiment, using an internal timer. Following the results of Stefanova's study (2012) the resonance field was on for 30 seconds and then 3 seconds off [4]. The ADI controller turned off pump 1 when there is no ultrasonic field in the Biosep chamber. Therefore pump 1 harvested for 30 seconds and then stopped pumping for 3 seconds. Pump 2 was not connected to the ADI controller and pumped the entire cycle. The flow rates for both pumps can be controlled separately from a range of 1-10. To start a run the Biosep chamber was filled with the stock solution. When it was completely submerged the flow rates for both pumps are set and the timer was turned on. Each run the flow rates were changed to find an optimum. The optimal flow rate can be described as the flow rates at which the filtrate concentration

is low while the difference between the filtrate and concentrate turbidity is large and the filtrate flow rate is as high as possible. One run consisted of 10 cycles. After the run was completed the turbidity of both the filtrate and concentrate are measured with a turbidity meter (Martini instruments MM-Mi-415, United States). Each measurement was repeated three times and the average was used in the results.

3.1.2 Determination of separation efficiency

To determine the separation efficiency of any material the filtrate concentration can be compared to the initial concentration. These experiments were done on a setup as shown in Fig 7. the settings for the ADI controller and pumps were specified in section 3.1.1. The filtrate flow rate was always set at 1.8 L/h and the concentrate flow rate was set at either 5.5 or 8.2 L/h, as was found in the experiment for the determination of optimal flow rates. Both the filtrate and the concentrate turbidity were determined with a turbidity meter. The average of three measurements was used in the calculations.
Calibration curves for all the materials allowed calculating concentrations from the measured turbidity. The separation efficiency of the Biosep with respect for a certain material was determined by:

$$separation\ efficiency = 1 - \frac{filtrate\ concentration\ (^{g}/_{L})}{initial\ concentration\ (^{g}/_{L})} \quad (1)$$

3.1.3 Validation of the control strategy

Given the mathematical model proposed by Stefanova (2012) several control strategies were evaluated [4]. In an experiment some of these strategies were tested. The experimental set up is the same as in Fig 7. The outcome suggested that a good separation could be achieved by switching the ultrasound 3 seconds on and then 30 seconds off. The strategy were the ultrasonic field was turned off completely was also tested. Tests were performed with settings according to Table 1:

Table 1. overview of the different control strategies.

Control strategy	filtrate pump on (s/cycle)	Ultrasonic field (s/cycle)	Filtrate pump off (s/cycle)
1	30	30	3
2	3	3	30
3	30	0	3
4	3	0	30

In strategy 3 and 4 there is no ultrasonic field present, this can be considered as a reference.
For each setting three starch solutions were used. The concentrations of these solutions were 0.8, 1.0 and 1.2 g/L. The runs lasted for 10 cycles each. The turbidity of the filtrate and the concentrate solution were determined. Each measurement was repeated three times and the average was used.

3.2 Sludge experiments

The second part of the experiments focused on activated sludge solutions with a cheap prototype bioseparator.

3.2.1 Separation efficiency of sludge

The ultrasound bioreactor should be able to retain the sludge inside the bioreactor with the ultrasonic field. The experimental setup looked similar to the setup used in section 3.1.1. However, the Biosep was replaced by a prototype separator. The separator used for these experiments had a far more primitive

design then the one used for the experiments in section 3.1. Therefore new optimal flow rates were determined first. The new filtrate was determined to be 0.4 L/h and the new concentrate flow rate was 1.8 L/h.
With these new flow rates the separation efficiency of the Bioseparator for sludge was determined. This procedure was the same as the described in section 3.1.1, a different Bioseparator is used however. The stock solution used for this experiment consisted of 200 mL of activated sludge, obtained from the wastewater treatment in Bennekom, and 600 mL of deionized water.

3.2.2 Extensive sludge experiments

Since the separator will be used in wastewater treatment the separator has to function for long periods of time. Therefore a 30 minute experiment was performed.

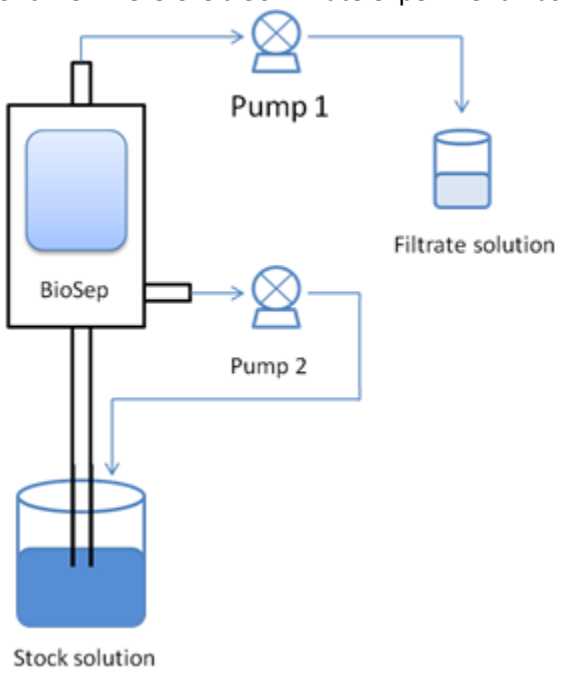

Fig 8. Schematic representation of the experimental setup used for extensive sludge experiments.

In Fig 8 the concentrated solution is pumped back into the stock solutions. In this experiment the stock solution is concentrated. The same apparatuses are used as in section 3.2.1. The filtrate flow rate during the experiment was set to 0.4 L/h and the concentrate flow rate was set to 2 L/h. Every 10 mL was collected and the turbidity was measured. At the end of the test all samples were mixed and measured again to determine an average over the entire experiment.

3.3 Activity experiments

Activity tests were performed on the activated sludge to see whether the ultrasound affects the overall biological activity of the activated sludge. The experiment was conducted in two steps. In the first step the activated sludge (800 ml) received the ultrasound treatment. To secure that all biomass is retained in the system, the filtrate solution is returned to the stock solution.

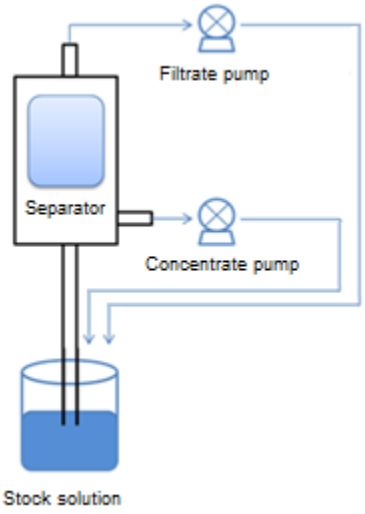

Fig 9. Schematic representation of the treatment setup used during the activity experiments

Since a low filtrate flow rate will lead to differences in the received ultrasound treatment, the flow rate was set to 2 L/h. The flow rate of the concentrate pump was set at 4 L/h to mimic the separation process. These flow rates were chosen to distribute the dose of ultrasound (DUS) evenly over the total volume and to collect homogeneous samples from the stock solution. Samples were collected over time; the dose of ultrasound between two samples was constant, where *DUS* is defined as:

$$DUS = \frac{V_{sep}}{V_{tot}} \cdot t_{exp} \quad (2)$$

Where V_{sep} (10 mL) and V_{tot} (800 mL) are the volumes of the prototype separator and the total volume used in the experiment (L), respectively, and t_{exp} the total time of the experiment (min). In the second step, activity measurements were performed. The activity of the biomass was determined in triplicate via the biological demand of the ultrasound treated sludge. The dissolved oxygen (DO) consumption rate was monitored in a closed reactor chamber (20 mL, T≈20^{o}C) using a DO sensor (PSt3, Presens Precision Sensing GmbH, Regensburg, Germany) with a sampling time of 5 seconds. Collected samples were first aerated for five minutes (such that DO was approximately 0.28 mmol/L), before the background oxygen consumption was measured. After the background measurement, the samples were aerated again for five minutes. Subsequently, 0.5 ml of a 20mM acetate stock solution was added and the dissolved oxygen was measured. From the initial slope of the obtained curves of these measurements, the dissolved oxygen consumption rate was calculated. As a control, the activity of activated sludge that did not receive any ultrasound treatment was also measured, both at the start and at the end of the activity experiment.

4. Results and Discussion

In this section the obtained result are presented and discussed.

4.1 Starch experiments

4.1.1 Determination of flow rates

In Table 2 the difference in turbidity between the filtrate flow rate and the concentrate flow rate are presented. This experiment was performed with a Biosep under control strategy 1 (Table 1).

Table 2. Difference between filtrate turbidity and concentrate turbidity. 1: flow rate used by Stefanova (2012) [4]

		filtrate flow rate (l/h)				
		1.8	3.1	4.5	5.8	7.1
concentrate flow rate (l/h)	1.9	48.47	75	-	-	-
	2.9	89.12	75.53	-	-	-
	4.3	92.34	80.6	32.22	-	-
	5.5	90.76[1]	98.31	87.43	72.75	-
	6.9	87.44	94.4	90.14	81.4	-
	8.2	**114.76**	95.51	91.55	83.3	-
	9.6	107.87	92.83	94.99	91.21	-
	10.8	95.12	97.24	101.9	97.1	77.7

To determine the optimal flow rate the difference between filtrate and concentrate turbidity has to be large, however the filtrate turbidity has to be small as well.

Table 3. Average of the measured filtrate turbidity. 1: flow rate used by Stefanova [4]

		filtrate flow rate (l/h)				
		1.8	3.1	4.5	5.8	7.1
concentrate flow rate (l/h)	1.9	1.45	15	-	-	-
	2.9	2.88	15.47	-	-	-
	4.3	2.66	8.4	31.78	-	-
	5.5	4.24[1]	6.69	11.57	16.25	-
	6.9	2.56	3.6	5.86	12.6	-
	8.2	**1.24**	2.49	5.45	11.7	-
	9.6	1.13	3.17	5.01	8.79	-
	10.8	1.88	3.76	4.15	7.9	20.3

Generally the separation becomes less efficient when higher filtrate flow rates are applied. This can be seen in both Table 2 and 3. The filtrate flow rate has a high influence on the separation process; this flow rate harvests the filtered water. The concentrate flow rate recycles water from the separation chamber back to the tank. When applying this technique in wastewater treatment a clean effluent is necessary, otherwise discharge requirements may not be met. With these two tables the optimal filtrate flow rate can be determined. The optimal flow rate can be described as the flow rates at which the filtrate concentration is low, the difference between the filtrate and concentrate turbidity is large

and the filtrate flow rate is as high as possible. In table 2 and 3 some flow rate combinations result in better separation than other flow rate combinations. For instance a filtrate flow rate of 3.1 L/h and a concentrate flow rate of 5.5 L/h result in a difference in turbidity of 98.31 NTU and a filtrate turbidity of 6.69 NTU. The difference between concentrate and filtrate turbidity suggest it is a good separation however the filtrate concentration is high compared to different flow rates. A filtrate flow rate of 4.5 L/h and concentrate flow rate of 10.8 L/h resulted in a good separation (difference between filtrate and concentrate turbidity: 101.9 NTU). The filtrate flow rate is high which would result in a quick separation process, however the filtrate turbidity is high (4.15 NTU). The optimal flow rate was found at a filtrate flow rate of 1.8 l/h and a concentrate flow rate of 8.2 l/h. this resulted in a difference between the flow of 114.76 NTU and a filtrate concentration of 1.24 NTU. This combination of flow rates gives the best separation.

4.1.2 Determination of the separation efficiency

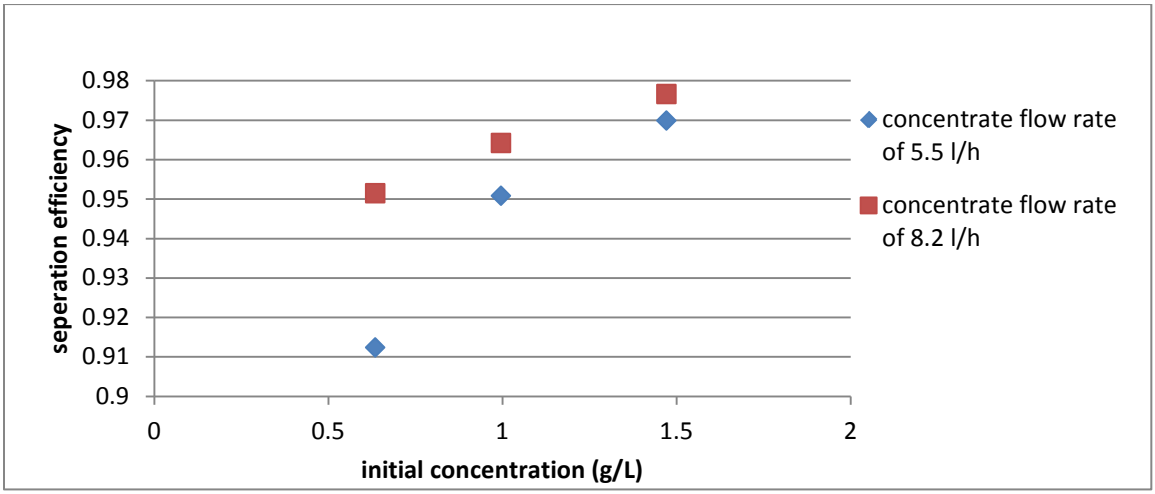

Fig 10. Separation efficiency of starch solutions.

Table 4. Concentration starch in the filtrate.

		filtrate concentration (g/l)	
		concentrate flow rate of 5.5 l/h	concentrate flow rate of 8.2 l/h
initial concentration (g/l)	0.635	0.055663	0.030824
	0.99625	0.049004	0.035686
	1.47125	0.04435	0.03445

In Fig 10 the separation efficiency, defined in 3.1.2 rises as the concentration of initial starch solution increases. Furthermore, the separation efficiency of the starch solutions is higher when the recycling pump is set to 8.2 L/h instead of 5.5 L/h. at a concentrate flow rate of 5.5 L/h the filtrate concentration decreases as the initial concentration increases, as can be seen in Table 4. The higher initial concentration may result in better flocculation of the starch particles and therefore lower the final filtrate concentration. In Table 4 the filtrate concentration hardly drops when the initial concentration is increased from 0.99625 g/L to 1.47125 g/L at a concentrate flow rate of 8.2 L/h. decreasing the initial concentration from 0.99625 g/L to 0.635 g/L, at a concentrate flow rate of 8.2 L/h, results in a lower concentration in the filtrate (Table 4), however the separation efficiency decreases (Fig 10).

4.1.3 Validation of the control strategy

The strategies in this section refer to the strategies mentioned in section 3.1.3 Table 1.

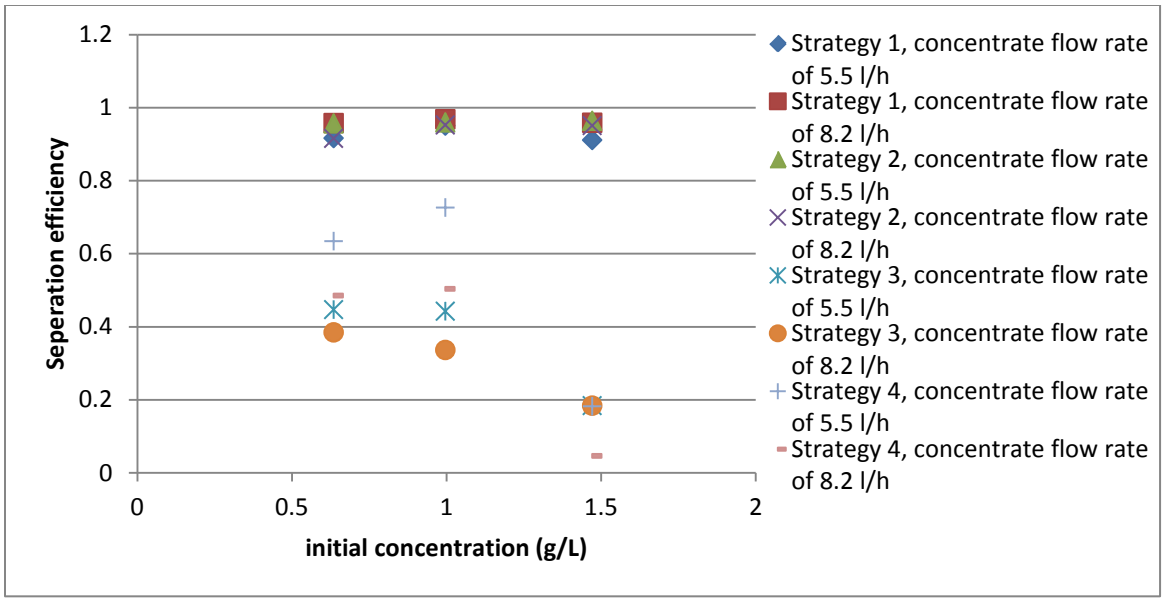

Fig 11. overview of the separation efficiency of starch solution with different control strategies.

From Fig 11 it can be seen that strategy 3 and 4, no matter which concentrate flow rate is used, are less efficient than strategy 1 and 2. Strategy 1 and 2 applied an ultrasonic field while strategy 3 and 4 did not. The separation of the starch solutions is significant better with ultrasonic field.

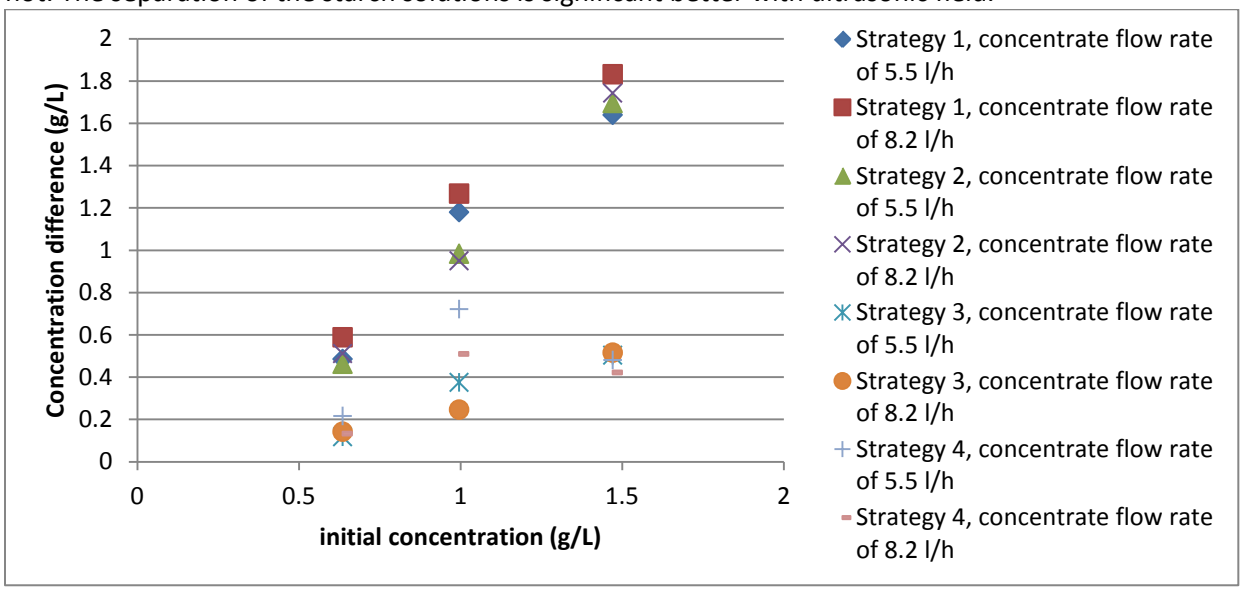

Fig 12. concentration difference between filtrate flow and concentrate flow.

From Fig 12 it can be concluded that strategy 1 and 2 give bigger differences between filtrate and concentrate flows. Therefore the control strategies without the ultrasound, thus only using gravity for separation, are ineffective separation techniques. Both Fig 11 and Fig 12 suggest strategy 1 with a concentrate flow rate of 8.2 L/h is the most efficient way to separate starch solutions since the difference between filtrate and concentrate concentration is the biggest and the separation efficiency is the highest.

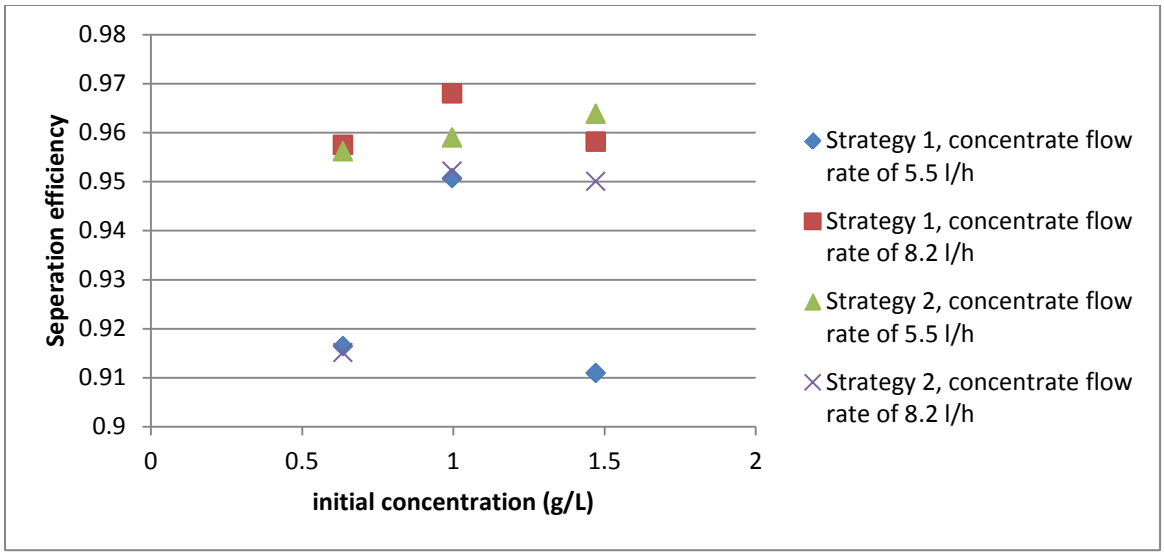

Fig 13. separation efficiency of control strategy 1 and 2.

In Fig 13 the separation efficiencies of control strategy 1 and 2 are presented. Fig 13 is the same figure as Fig 11 with an adjusted y-axis to visualize the difference between strategy 1 and 2. Control strategy 1 is the same strategy as used in section 3.1.2. The results for strategy 1 are similar to the results found and discussed in section 4.1.2. However the measurement with an initial concentration of 1.47 and a concentrate flow rate of 5.5 l/h using strategy 1 is very low, most likely this measurement is an error Strategy 2 is just as effective to achieve high separation efficiencies. Both strategies use a 33 second cycle. Strategy 1 uses 30 seconds of the cycle to harvest while strategy 2 only uses 3 seconds to harvest (Table 1). The harvest volume can be calculated by multiplying the harvesting time with the flow rate of the harvesting pump. Using strategy 1 the harvesting time during a run consisting of 10 cycles is 300 seconds. With a flow rate of 1.8 L/h the harvested volume after 300 seconds is equal to 0.15 L. Using strategy 2 the harvesting time during a run consisting of 10 cycles is 30 seconds, with a flow rate of 1.8 L/h only 0.015L is harvested. Thus, it can be concluded that strategy 1 is more time efficient then strategy 2 and since there is no difference in separation efficiency, strategy 1 is more efficient.
Using strategy 1 for one hour the harvested volume will be 1.636 L. On average the separator uses 80% of the applied power (6W). The energy consumption of the separation apparatus is 10/11*80%*6W*3600s = 15709 J (=$4.36*10^{-3}$ kWh). With a price of 22 eurocents per kWh, the separation process costs 0.096 cents per 1.636 L. The treatment of 1L would cost 0.059 cents, consequently the price of 1 m^3 costs 58.7 cents.

4.2 sludge experiments

As mentioned before, the sludge experiments were performed with a different design of separator. New optimal flow rates were visually determined. The filtrate flow rate was set at 0.4 L/h and the concentrate flow rate was determined at 2 L/h. These values are lower because the hydraulic turbulence in this design is greater and the flow through the separation chamber is not laminar.

4.2.1 Separation efficiency of sludge

Table 5. Separation efficiency of sludge.

average filtrate turbidity	25.13611
average concentrate turbidity	463
separation efficiency	0.94571
Blanco filtrate turbidity	259.1111

An experimental separation efficiency of 94.6% was achieved at a filtrate flow rate of 0.4 L/h. Both the separation efficiency and the filtrate flow rate suffer from the design of the separator. For testing the ultrasound separation technique this does not matter. Experimental results suggest using ultrasound fields can increase the efficiency of the separation a 10 fold. The design used in this experiment is produced very easy and still results in proper separation.
The treatment costs can be calculated again: when the separator runs for an hour 10/11*0.4=0.3636 L is collected the power input for one hour is 15709 J (=$4.36*10^{-3}$ kWh), the same as calculated in section 4.1.3. With a kWh price of 22 eurocents, the treatment costs for running the set up one hour is 0.096 cents. In this time 0.3636 L is harvested, to harvest 1 liter the treatment costs will be 0.26 cents per Liter. Thus treating 1 m^3 of wastewater will cost 2.64 euro. This is way more than the treatment for the starch solutions; however the costs can be reduced by increasing the filtrate flow rate. Optimizing the design of the prototype separator will result in an increased filtrate flow rate.

4.2.2 Extensive sludge experiments

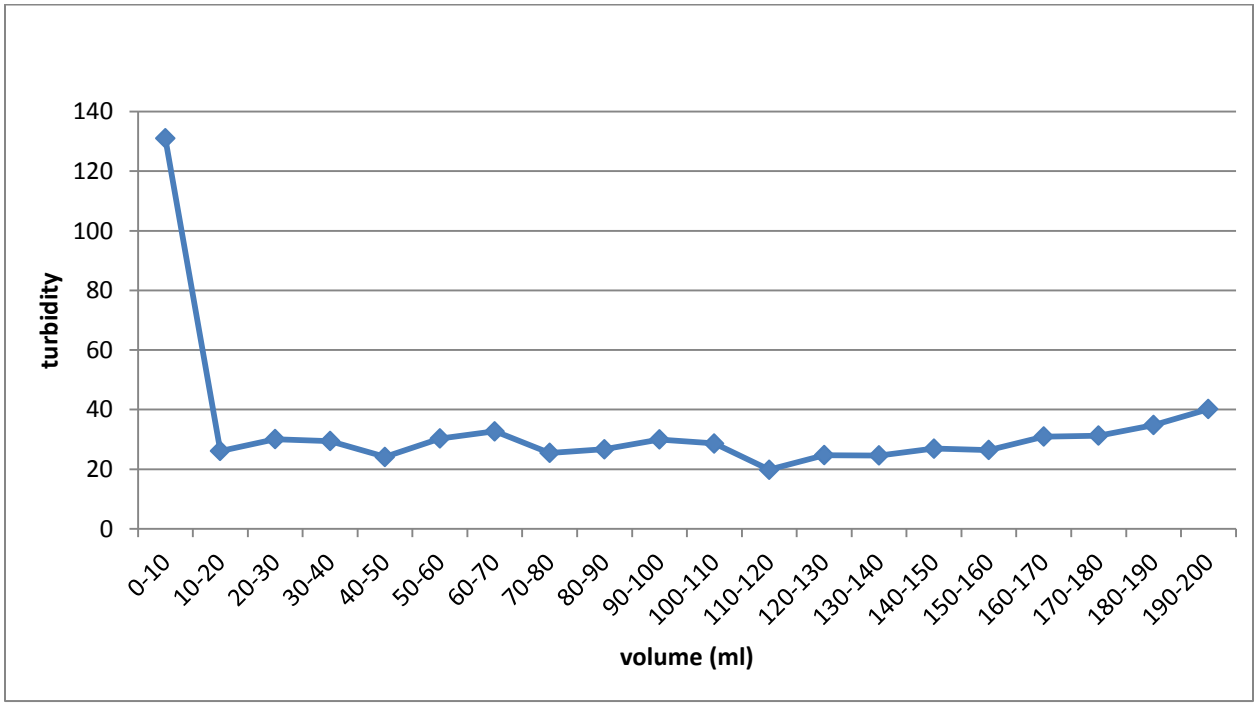

Fig 14. Average turbidity after measuring the turbidity every 10 ml.

In Fig 14 the measured turbidity is plotted against the harvested volume. At the end of the experiment all the samples are mixed and measured. The turbidity of this measurement was 32.33. In Fig 14 it can clearly be seen that the Separator needs some time to establish equilibrium. The time needed to establish this equilibrium is no longer than 36 seconds. The exact time at which this equilibrium settles cannot be determined in this experiment; online turbidity measurements are required for such an experiment. During the main time of the experiment the turbidity remains constant. Near the end the outgoing concentration starts increasing. Sludge accumulates in the Separator and unfavorable hydraulic flows inside the separation chamber result in the harvesting of sludge particles. This is a consequence of the design of the Separator used in this experiment. Optimizing the design will decrease the turbidity in the outgoing flow and might delay, or remove, the increasing turbidity at the end.

4.3 Activity experiments

The results of the performed activity tests are presented in Fig 15 and Fig 16

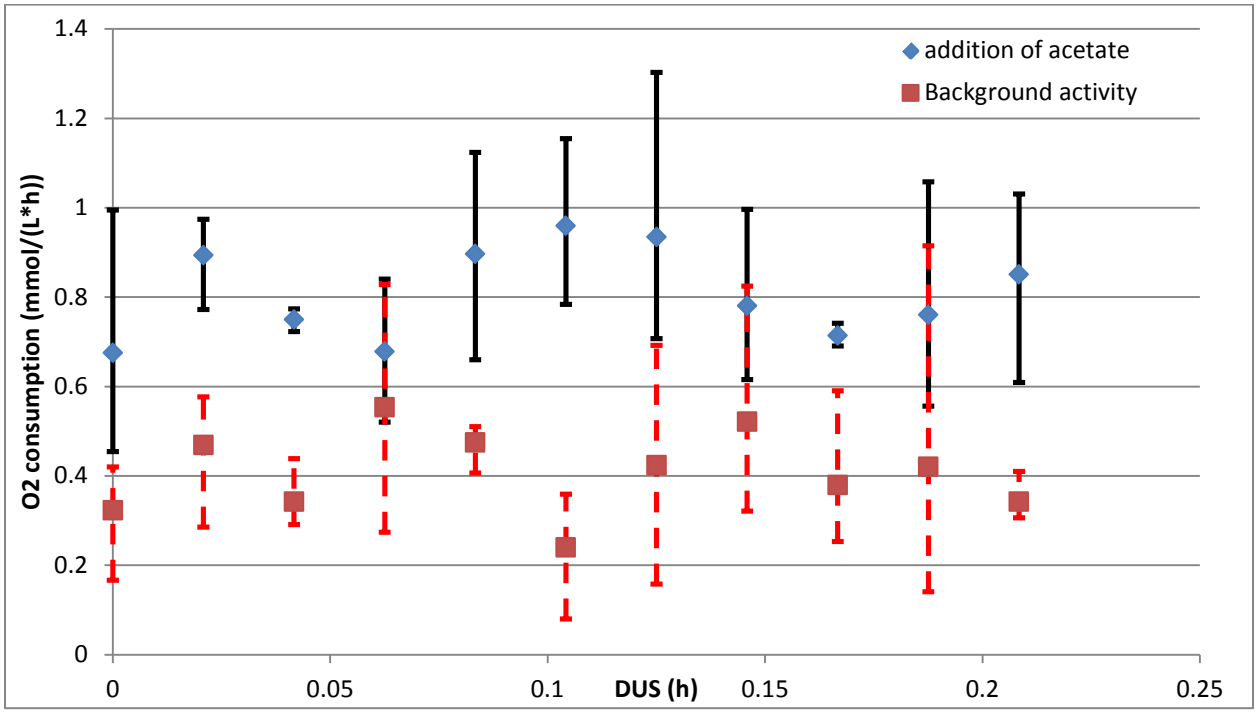

Fig 15. Measured oxygen consumption as a function of the received ultrasound dose.

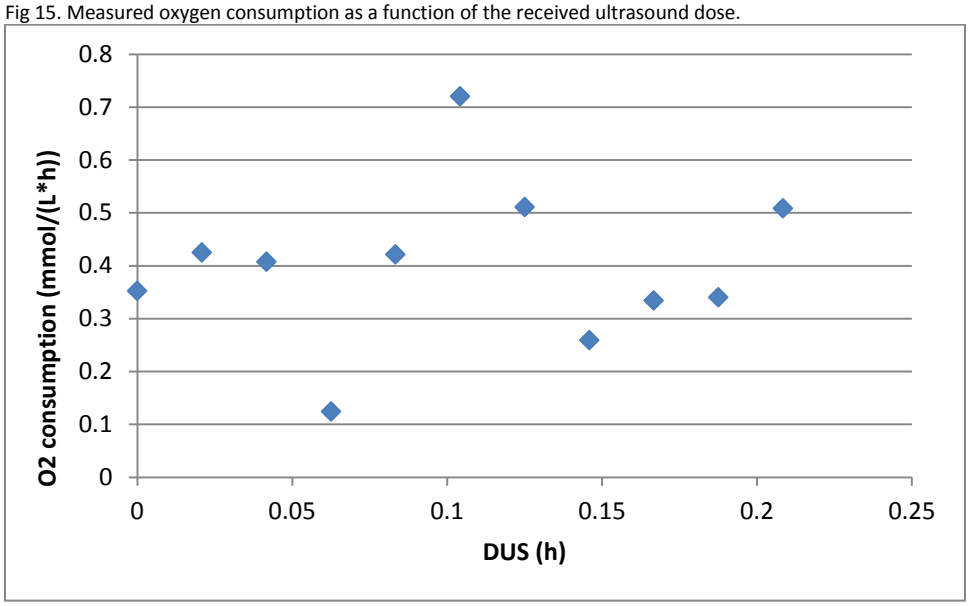

Fig 16. Biological oxygen demand by the sludge as a function of dose ultrasound

Figure 15 displays the oxygen consumption as a function of the received ultrasound dose. The background consumption is systematically lower than the oxygen consumption after addition of acetate. Three measurements show some overlap in the error bars between the background measurement and the acetate measurement. However from Fig 16 it can be concluded that an odd measurement is the measurement after about 0.06h of received ultrasound treatment. The biological oxygen demand suddenly drops. This is probably a measuring error and may have occurred by not cleaning the test tubes

properly. The measurement at about 0.1h in Fig 16 is high. The measurement with acetate is in line with other measurements, the measured background is low.
Since Fig 16 does not show an increasing nor decreasing trend in biological oxygen demand of the treated sludge as the dose of ultrasound increases. Therefore it can be concluded that exposure of sludge to ultrasound does not affect the activity of the sludge.

5. Conclusion

The aim of this thesis was to study the separation of water-starch and water-sludge suspension by using ultrasound. From experimental data it was shown that both the water-starch and the water-sludge suspensions can be separated with a separation efficiency of 95% or more. This separation technique can be applied with a fairly primitive design of the separator, proving the principle of the separation; however the filtrate flow rate suffers from the primitive design. Using a more advanced design higher filtrate flow rates were achieved and the separation efficiency was slightly better. The cost for treating 1 m^3 of water-starch suspension with ultrasound was calculated at 58.7 euro cents. The cost to treat 1 m^3 of sludge is 2.64 euro.

Control strategies without ultrasound resulted in poor separation efficiencies. 3 seconds of ultrasound per cycle resulted in separation efficiencies similar to the separation efficiencies of control strategies which use 30 seconds of ultrasound per cycle. However, the strategy with only 3 seconds of ultrasound is time consuming, as the filtrate pump is synchronized with the ultrasonic field and thus produce small amounts of clean water per hour.

From the preformed activity tests it is concluded that ultrasound treatment does not affect the activity of the treated sludge. The biological oxygen demands did not increase nor decrease as the sludge was exposed to ultrasonic waves of 2 MHz. This is in line with previous work, which shows no decreased activity of different micro-organisms after ultrasound exposure [19][20]. Thus, a prototype ultrasound bioreactor can be designed for wastewater treatment. The filtrate flow was found in the order of a liter per hour. Even with a very simple designed separator the technique can be applied on small scale wastewater treatment systems.

6. Recommendation

In this research it is shown that ultrasound enhanced sedimentation can be used with a simple separator in small scale systems. To apply such a system on large scale systems the filtrate flow rate needs to increase. Further research into the design of the separator could achieve a larger filtrate flow rate without loss of separation efficiency.

The small scale ultrasound separation process discussed in this report can be developed into a wastewater treatment system for households. The wastewater treatment system needs to be evaluated on costs, efficiency and compared to similar systems.

More research into the different separation devices may give more insight in the separation process. Since several designs for the ultrasound separator have been proposed, these designs can be tested and evaluated to find the most effective design and improve the most effective design.

This researched focused mainly on obtaining a clean effluent from the separator. The separator can also be used to thicken slurry, concentrate particles or extract water in general. Viscosity and density effect should be researched if the aim is to extract water.

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