WP4: Nitrogen management in side stream

D4.2: Planning and Design of a full-scale membrane ammonia stripping

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Deliverable 4.2	***Planning and Design of a full-scale membrane ammonia stripping***
Related Work Package:	4
Deliverable lead:	Eawag
Author(s):	M. Böhler, J. Fleiner, W. Gruber (Eawag) A. Seyfried (ATEMIS GmbH) L. Luning, D. Traksel (SUSTEC BV)
Contact for queries	M. Böhler (marc.boehler@eawag.ch)
Grant Agreement Number:	n° 641661
Instrument:	Horizon 2020 Framework Programme
Start date of the project:	01.07.2015
Duration of the project:	36 months
Website:	www.powerstep.eu
Abstract	Documentation of the successful planning and design of the full-scale ammonia stripping plant

Dissemination level of this document

X	PU	Public
	PP	Restricted to other programme participants (including the Commission Services)
	RE	Restricted to a group specified by the consortium (including the European Commission Services)
	CO	Confidential, only for members of the consortium (including the European Commission Services)

Versioning and Contribution History

Version	Date	Modified by	Modification reasons
v.01	2016-11-05	Marc Böhler	1st Draft
	2016-11-15	Eberhard Morgenroth	1st review
v.02	2016-11-25	Marc Böhler	2nd Draft
	2016-12-07	Jörg Krampe	2nd review
	2016-12-11	Hansruedi Siegrist	3rd review
v.03	2016-12-14	Marc Böhler	Final version reviewed by Christian Loderer
Final	2016-12-22	Marc Böhler	Based on feedback from Christian Loderer

Table of Content

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

List of figures

List of tables

Executive Summary

The present report describes the work and outcomes of case study 6 in the first period of the project POWERSTEP. The case study – implemented in work package 4 "Nitrogen management in side stream " is intended to demonstrate the recovery of nitrogen by means of gas permeable membranes immersed in liquids from sludge treatment in full scale. Full-scale technical implementation at the WWTP Altenrhein will be treating about 75'000 m³/year, corresponding to about 52 t N/year (700 mgNH$_4$-N/L).

At the beginning of the POWERSTEP project, worldwide no nitrogen recovery plant by means of gas permeable membranes was in operation. Against this background, the case study 6 consortium and his local partners discussed and prepared the fundamentals for such an implementation in workshops. These included the definition of the central design values for the different process steps and also an detailed elaboration of the flow schemes (pre-treatment of the sludge liquids, membrane units). Also the allocated site and how to integrate this innovative and new technology into the facilities of WWTP Altenrhein were discussed.

This intense work by the CS6 consortium led to detailed tender documents. An invitation to tender was launched in spring of 2016, resulting in three proposals by two bidders, which are all usable to implement the membrane plant needed for CS6. The proposals were quite intensely and detailed evaluated by the consortium and the suppliers were asked about additional details of the plant engineering. In particular, the specific expenses and costs for the maintenance of the installations (e.g. life time of the membranes or specific chemical demands) are of great interest.

This was followed by additional discussions with the local authorities in order to secure funding for the building of the plant. The final decision is still outstanding. As a result, the future of CS6 hangs in the balance. Until the end of the first project phase, no decision or allocation of the plant was made.

1. Introduction and important preliminary notes Case Study 6

The case study 6 - integrated in WP 4 – is intended to demonstrate the full scale recovery of nitrogen contained in liquids from sludge treatment of the WWTP Altenrhein. The WWTP belongs to the *Abwasserverband Altenrhein* (association for sewage treatment in Altenrhein). In the course of this task, a public tender for this large facility was prepared and published under the local, national framework by the CS6 consortium (Eawag, ATEMIS GmbH and SUSTEC BV) and its local partners, the *Abwasserverband Altenrhein* and the local consulting company KUSTER & HAGER.

At the beginning of the case-study, worldwide no nitrogen recovery plant by means of gas permeable membranes was in operation. This necessitated several in-depth discussions (workshops) on the design of the pretreatment and of the membrane treatment of the sludge liquids. As a result, the publication of the tender documents was delayed by about 2 months. On the basis of a comprehensive, carefully prepared tender, which described and defined in detail the full scale plant, three offers were submitted by two tenderers. These proposals were carefully assessed by the consortium. In addition, each of the tenderers (separately, on consecutive days) presented during an all-day meeting with the consortium their proposals at WWTP Altenrhein. The CS6 consortium (minus SUSTEC BV) also prepared by mid of 2016 a recommendation for awarding the contract.

Due to the unexpected high submission costs for the implementation of the nitrogen recovery at WWTP Altenrhein, the *Abwasserverband Altenrhein* decided to postpone a decision on the assignment until the end of 2016. The wastewater association hopes to generate substantial co-financial support from two other pending project proposals, which are directly linked to the project (compensation of avoided CO_2-emmissions, combining of the liquid fertilizer with recovered phosphorous from digested sludge). Without positive decisions for these two projects, the operator of the WWTP Altenrhein foresees resistance to implement the costly membrane contactor project by the administrative board of *Abwasserverband Altenrhein* that have to approve the financing of the project.

According to the CS6 timeline, the construction of the plant should have taken place towards the end of this year. After stable operation, optimizations of the plants should have been undertaken together with a general evaluation of the process by the beginning of 2017.

Based on the considerable efforts that have been made to prepare the realization of the plant (planning, design and tender of the full scale plant), the deliverable title of D4.2 "Successful realization of the full-scale membrane ammonia stripping and its startup" was changed in “Planning and Design of a full-scale membrane ammonia stripping“. This change has been discussed and coordinated with the case study leader TU Vienna (Jörg Krampe) and the project coordinator Christian Loderer (KWB) and has been communicated to the EU Officer Erik Pentimalli.

The following report documents the procedure and implementation of planning, design as well as preparing tender invitation and reviewing tender of the full scale membrane stripping plant for the recovery of ammonium from sludge liquids at WWTP Altenrhein.

2. Background and motivation

In the last 50 years the growing production and application of artificial fertilizer surged, increasingly polluting both water bodies and the atmosphere with nitrogen-compounds. Today there are many efforts to break this trend, as for example the EU directive 91/676/EWG of the European Community from 1991, (the Council of the European Communities, 1991) which aims to protect water bodies and to reduce nitrate emissions. Both the production of nitrogen fertilizer via the Haber-Bosch process and the elimination of the nitrogen from municipal waste water streams by denitrification are cost and energy intensive. The latter also produces as a by-product some nitrous oxide (N_2O), a very strong greenhouse gas. In this context, technologies for nutrient separation and recovery out of the waste water will get more and more attention in the future.

Sludge side-streams are a result of an anaerobic sludge digestion and subsequent sludge treatment like dewatering and drying. The nitrogen load of these side-streams represents approximately 15 to 20% of the overall incoming nitrogen load of a municipal WWTP (Figure 1).

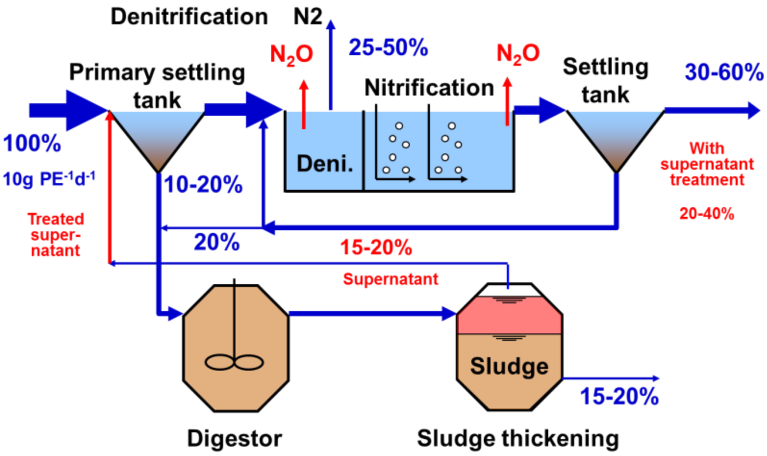

Figure 1: Nitrogen flux in a municipal WWTP without (blue) and with (red) pre-treatment of the liquid side-stream from the sludge treatment

In recent years, more and more WWTPs have been equipped with facilities for pre-treatment of the ammonia rich supernatant (side stream treatment), usually to reduce the N-load of the main WWTP lane to save denitrification volume or improve overall nitrogen removal (Figure 1). Denitrification releases the nitrogen as nitrogen gas to the atmosphere, which means a loss of nitrogen instead of producing fertilizer.

In terms of costs and energy consumption, anaerobic ammonium oxidation (anammox) is currently the optimal treatment of sludge liquids to reduce the internal N-load and to improve the nitrogen removal capacity of WWTPs. Although efficient, the process results in loss of nitrogen. Over the last years, experience in operating the biological anammox process showed some instability of the process. Therefore, ammonia recycling is an alternative robust technology to reduce the internal N-load.

Air and steam stripping are the most common processes for the recovery of ammonia from wastewater and sludge liquids respectively. Only around 10 pre-treatment plants in Europe are using the chemical/physical air stripping process and produce fertilizer in form of ammonium sulphate. Some of these stripping plants were designed by the POWERSTEP project partner and engineering company ATEMIS (Germany).

But, air stripping plants require a substantial height and a huge air to water flow ratio to strip the free ammonia from the water phase corresponding to a high energy demand of the blowers. In addition free ammonia air stripping requires large amounts of the energy intensive and costly sodium hydroxide to deprotonate the ammonium to free ammonia as well sulphuric acid to produce ammonium sulphate. Costs and energy consumption to produce the base (sodium hydroxide) are a significant part of the overall operational costs and energy consumption of an air stripping plant.

A new, innovative and alternative technology for ammonia recovery as a fertilizer requiring no air and only a small reactor volume is the use of gas permeable hollow fibre membrane modules (Ulbricht et al. 2009, Boehler et al. 2014).

3. Goals and task 4.2: “Membrane ammonia stripping of sludge process water [M1-30] (EAWAG, SUSTEC, ATEMIS) - Case study 6 (CS6)

3.1. Overall goals of CS6 – realization of a membrane stripping plant at WWTP Altenrhein

Case study 6 (CS6) is integrated in WP 4 “Nitrogen management in side stream”. The goal of CS6 is the realization of an ammonia membrane stripping plant at WWTP Altenrhein to produce a liquid fertilizer for agriculture use. In CS 6, the first full-scale membrane ammonia stripping plant will be assessed and optimized. The partners will provide guidance and engineering support both in the planning and the implementation phase of the project in order to ensure an optimal lay-out of the system. This includes for example the evaluation and definition of design parameters for the pre-treatment, the membrane unit, caustic soda dosage equipment (number and place of dosage points, number and location of probes and sampling points) and miscellaneous equipment like data-loggers for the dosing pumps, etc. In the first phase of the project the consortium will provide substantial support for the preparation of the documents to invite tenders.

3.1.1. The overall goals of CS6 in a condensed version

- Full-scale demonstration of recovery of ammonia from wastewater by membrane stripping at WWTP Altenrhein (AVA)
- Production of a marketable nitrogen fertilizer product
- Operational experience + long-term optimization of the process
- Comparison with alternative technologies in costs and efficiency
- Evaluation of energy balance and CO_2-emmissions of WWTP as well economic feasibility

3.1.2. Tasks in CS6 (months 1-18)

In the first phase of the project the central task by the partners was to provide significant support for the preparation of documents for the call for tenders. This included e.g.

the evaluation of the design parameters and lay out (flow schemes) of an efficient pre-treatment of the sludge water as well as the optimal configuration of the membrane units, etc. This included in detail:

- preliminary planning of the plant
- analysis of available and existing information on the amount of production, concentrations and properties of sludge water of WWTP Altenrhein
- definition of design parameters for pre-treatment + membrane units
- General lay-out and integration of the plant into the existing facilities of WWTP Altenrhein
- definition of preferred flow schemes and a piping and instrumentation diagram (P&ID) for the pre-treatment (as a base line for the invitation to tender)
- evaluation of an potential process flow diagram (PFD) of the membrane stripping unit
- analyses and laboratory tests to simulate behavior/composition of sludge water during (pre-) treatment
- Completion of tender documents and specifications on the basis of data and discussions
- Analysis and comparison of the tender
- Invitation of the tenderer to present and discuss their proposals
- Calculation of investment and operational costs

3.2. Additional goals in CS6 - N_2O measurement at WWTP Altenrhein

Biological nitrogen removal processes destroy the inorganic nitrogen. A fraction of the nitrogen is transformed into the very strong greenhouse gas nitrous oxide. In 2011 the Swiss CO_2 law was revised and provides the legal basis for Switzerland's climate policy from 2013 to 2020. The law came into force on January 1st 2013. The law sets the targets and means of climate policy and is intended implement sustainable energy and climate policies. The Foundation for Climate Protection and Carbon Offset (KliK. www.klik.ch) operates as a carbon offset grouping for mineral oil companies responsible for releasing fossil motor fuels for consumption.

The compensation processes have to take place in Switzerland. Cost of up to CHF 120.- per ton of CO_2 are guaranteed as revenue for projects reducing CO_2 equivalents and meeting the goals of the law. Against this background the N_2O-emmisssions of the main lane at WWTP Altenrhein are of high interest. Recovery of nitrogen and therefore a reduction of the internal N-load will reduce the N_2O-emissions of the plant significantly. These activities are directly linked to CS6 and to the economic feasibility of the membrane stripping plant. If a considerable reduction in the N_2O emissions can be achieved by recovery of nitrogen, there will be a financial benefit, which compensates partly the operational costs of the stripping plant.

Full-scale studies for N_2O emissions at WWTP Altenrhein are carried out since December 2015 up to date.

3.3. Structure and partners of CS6

The project team of CS6 consists of the POWERSTEP consortium and the local partner WWTP Altenrhein and their local engineering consultant Kuster & Hager. The following partners and persons have fundamental input into CS6:

3.3.1. Partners involved in POWERSTEP and in CS

Marc Böhler	**Eawag**, case study leader, process engineering, scientific supervision, (CH)
Julian Fleiner	**Eawag**, project manager, process engineering scientific supervision, (CH)
Wenzel Gruber	**Eawag**, N_2O-studies, process engineering, PhD-student, (CH)
Hansruedi Siegrist	subcontractor, consultant and scientific superviser, (CH)
Luchien Luning	**SUSTEC BV**, process engineering, plant manufacturer, (NL)
Danny Traksel	**SUSTEC BV**, process engineering, plant manufacturer(NL)
Alexander Seyfried	**ATEMIS GmbH**, engineering consultant, (D)
NN	**ATEMIS GmbH**, engineering consultant, draftsperson (D)
Steffen Zuleeg	**Kuster & Hager**, local engineering consultant, (CH)
Christoph Egli	**Abwasserverband Altenrhein**, director/operator of WWTP (CH)

3.4. Proposed timeline and status of CS6

The scheduled time-line and work-progress were fulfilled to during the first year of the project. Later, the progress of the project delayed from schedule and the milestones of the case-study 6 had to be redefined.

During the first year, the documents required for invitation to tender were prepared and published by the consortium and the local partners:

- 27.03.2015 Internal Kick-Off of project with all involved partners
- definition of design parameters for pre-treatment + membrane units at seven full day workshops (between 3/2015 and 12/2015)
- definition of the site and integration of the stripping plant (between 3/2015 and 8/2015, three site visits)
- evaluation of functional layout and process flow sheet of pre-treatment and membrane unit of full scale installation (Between 6/2015 and 4/2016)
- laboratory tests to simulate behavior and analysis of sludge water composition (10/2015-1/2016)
- 1/2016 – 4/2016 preparation and transaction of invitation to tender
- the documents for the invitation to tender were published online at the 4th of April 2016
- successful evaluation of proposals and formulation of an recommendation for assignment at three all day workshops (between 5/2016 and 8/2016)

It was intended to reach the following milestones during the first 18 months. Due to delayed decision by the WWTP Altenrhein, the milestones could not be reached.

- Second half of 2016 realization of stripping plant
- Begin of 2017 commissioning and optimization of plant
- From mid of 2017 stable operation of plant

The decision, if and by whom the full-scale plant will be built is intended to be made at the end of 2016 by the *Abwasserverband Altenrhein*. The outcome of this decision will influence the future actions in the CS6.

4. Fundamentals

4.1. Basic principle of free ammonia stripping and reduction of the specific base demand by CO_2-stripping

The ammonia of sludge liquid is released to the water phase by the degradation of proteins and other nitrogen containing compounds during anaerobic digestion. Stripping is the most common process for the selective recovery of ammonia from wastewater. For an efficient stripping most of the ammonium has to be present as free ammonia, NH_3. The ratio NH_3/NH_4 depends on the pH value and the temperature. It can be increased by adding a base, for example sodium hydroxide (NaOH), by pre-stripping of carbon dioxide (CO_2) and by raising the temperature (Siegrist et al., 2013).

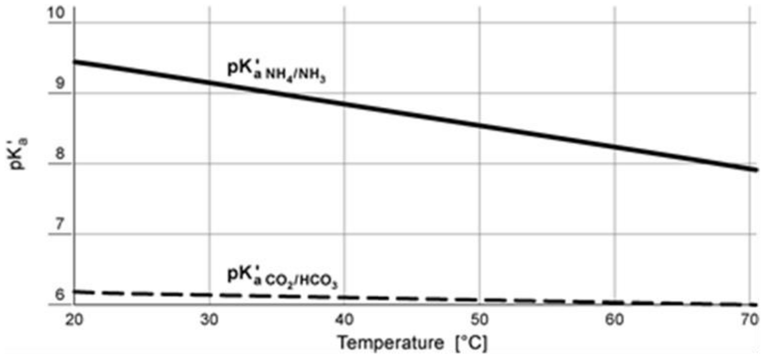

Figure 2: Temperature dependency of the acidity constants pKa' for NH_4+ and CO_2. Ionic strength I = 0.1-0.4 mol·L^{-1}

Figure 2 demonstrates that the equilibrium of NH_3/NH_4 has a much stronger temperature dependency than the CO_2/HCO_3^- equilibrium. Just by raising the temperature the inlet pH can be lowered for the same fraction of NH_3 and less base has to be dosed, because less bicarbonate is deprotonated to carbonate. Figure 3 shows the equilibrium of NH_3/NH_4 at different temperatures and at pH values of 8 and 9 respectively.

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

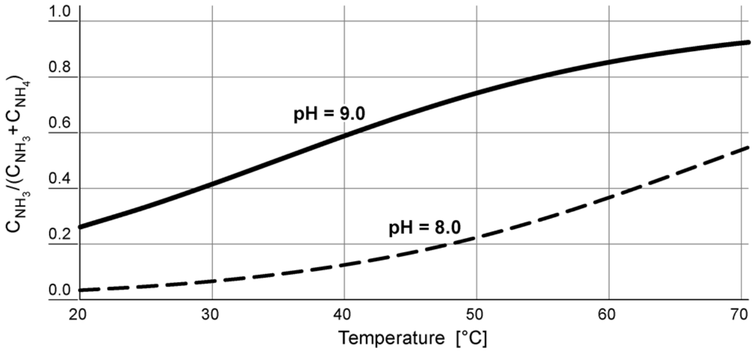

Figure 3: Fraction of NH_3 depending on temperature at pH 8 and 9

The dimensionless Henry's law constant H describes the distribution of a volatile compound between gas phase and water phase at thermodynamic equilibrium. Since carbon dioxide is about one thousand times more volatile than NH_3 (see Figure 4) it can be stripped in a separate column without losing a substantial amount of NH_3 in the off-gas. Due to CO_2 stripping the pH value of the sludge water phase is raised, which reduces the amount of base required to shift the NH_3/NH_4-ratio towards NH_3. (Siegrist et al. 2013). Full scale application of CO_2-stripping from sludge liquid as a pre-treatment for the recovery of nitrogen shows at WWTP Kloten/Opfikon (CH) for the air stripping process a reduction in base demand of 35 to 40% at 60°C. The process of CO_2-stripping to reduce the specific base demand can also be used as a pre-treatment step in the membrane stripping process.

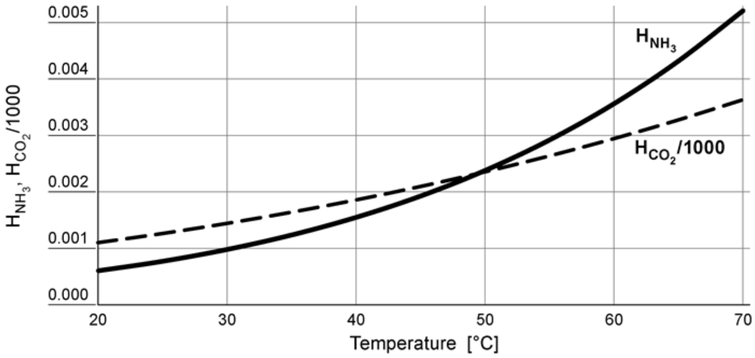

Figure 4: Dimension less Henry's law constant ($L_{water}\cdot L_{air}^{-1}$) for NH_3 and CO_2. NH_3 is a strongly soluble gas whereas CO_2 is rather volatile

4.2. Membrane stripping by gas permeable hollow fibre membrane module

The separation of gases from liquids by gas permeable membranes is known for some time. First experiences with this technology for the removal of free ammonia from sludge liquids in half scale were gained at WWTP Neugut (CH) between 2012 and 2013 by Eawag and partners (Boehler et al. 2014; Luning et al. 2015).

In the membrane stripping process free ammonia gas diffuses at high pH values and temperatures up to 45°C from the sludge water across the pores of the micro porous hydrophobic membrane as long as a sufficient driving force is maintained. The small pore size and the hydrophobic nature of the membrane prevent the liquid phase from entering into the pores or flowing through the porous wall due to the surface tension effect. Because of the very low Henry constant and high solubility of NH_3 (see Figure 4) compared to other dissolved gases in water (e.g., CO_2 or O_2); the free ammonia gas will be difficult to remove by applying a vacuum or sweep gas-vacuum combination as in typical degassing operations with a membrane contactor technology. However, an acid-solution will work very effectively in dissolving and removing the ammonia gas from the waste water. A low-pH sulphuric acid solution will instantly react with ammonia gas according to Equation 1 to form ammonium sulphate.

This will generate and maintain the concentration differential across the membrane that acts as the driving force for removing ammonia from waste water. Figure 5 shows a schematic drawing of a membrane contactor module with a hydrophobic hollow fibre membrane bundle. The right picture shows schematically the chemo sorption process across a single hollow fibre (Ulbricht et al. 2009). The sludge liquid flows through the shell-side of the membrane module (outside of the membrane), while the acid solution (sulphuric acid) is circulating on the lumen-side.

Equation 1: $2\ NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$

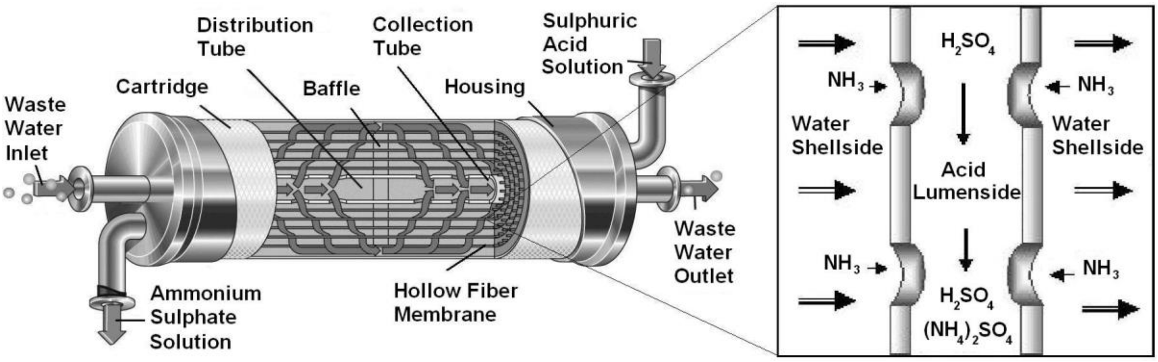

Figure 5: Commercial available membrane contactor module with a hydrophobic hollow fiber membrane bundle (Ulbricht et al., 2009)

Removal of ammonia using hydrophobic hollow fibre membranes has been tested in small pilot systems between 2012 and 2013 at WWTP Neugut (CH) and WWTP Venlo (NL). But there is still very limited data available to design full scale systems. Operating parameters such as waste water flow rate, pH, temperature, ammonia concentration as well as fouling and precipitations processes will significantly impact the ammonia removal characteristics and removal efficiency. Furthermore the pre-treatment of the sludge water before entering the membrane units is of great concern. Therefore, gathering more experience and experimental data in full scale is an important step towards developing and demonstrating this technology.

4.3. Current knowledge about the removal of ammonium from sludge liquids using membranes

To get a first insight into the technology of free ammonia membrane stripping, single trials were conducted in Winter 2012/13 at WWTP Neugut (CH) with a pilot membrane contactor (120 m²). In these trials the removal and recovery of nitrogen as ammonia sulphate was very successful. The elimination efficiency varied between about 80 to 99 % depending on pH and temperature of the sludge liquid. To get more experience with this new and innovative membrane technology and to evaluate specific operational data like optimal temperature, pH, specific load, optimal flow scheme and long term behaviour of the membrane additional tests with a second pilot scale plant were conducted.

In autumn 2013 a half-scale membrane plant of the company SUSTEC BV was tested for 6 months at WWTP Neugut. The membrane plant consisted of two membrane module in series (each module has about 53 m^2 surface area). In addition to ammonia separation by membranes the recovery of phosphorous as magnesium ammonium phosphate before a subsequent ammonia stripping was investigated. In this case CO_2 stripping to increase pH and to reduce the specific base consumption in front of the membrane was combined with struvite precipitation in a column. Initial pH values of the sludge liquids were in the range of 7.3 and were raised up to about 7.9. The pilot plant of the Sustec BV (106 m^2) offered the option to dose base in between the two membrane modules. Due to the removal of free ammonia in the first membrane module compartment the pH value is decreased in the sludge liquid and can be raised again by a second dosage. This effect of decreasing pH is a result of the release of protons in the bulk solution after removal of NH_3.

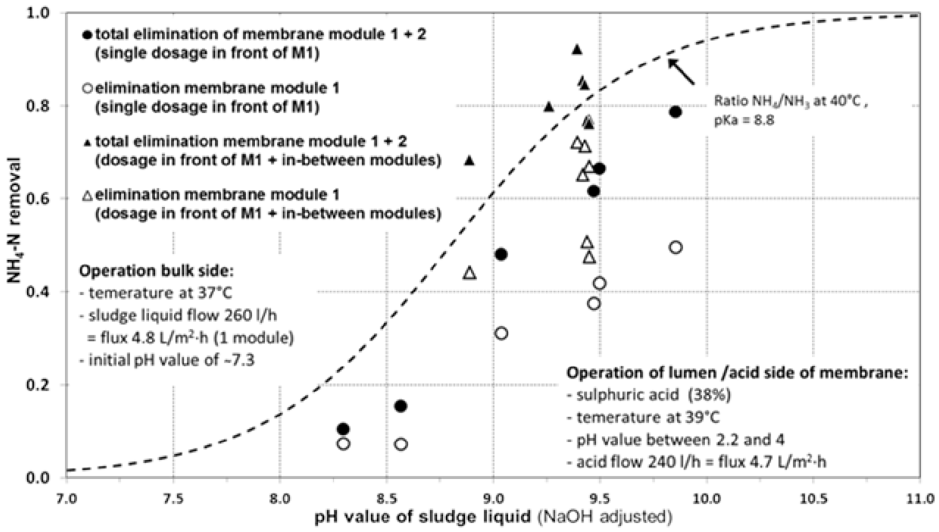

Figure 6: Results with two membranes in series at different pH values. pH was adjusted by adding NaOH

The results with respect to the removal of nitrogen from the sludge liquid are shown in Figure 6. In all cases the two modules were operated in series both for the sludge liquid flow as for the acid solution. Acid solution and sludge liquid were operated in counter current.

Experiments with two membranes with single dosage of base in front of membrane module 1 only (Figure 6) show that the elimination efficiency of the second membrane is reduced. After the sludge liquid passed through the first membrane module, the pH of the sludge liquid is decreased from 9.3 to about 8.9. As a consequence, the elimination efficiency in the second membrane module is reduced due to a limitation of driving force for the NH_3.mass transfer. The dotted black curve shows the ratio of NH_4/NH_3 at 40°C and varying pH values.

In contrast tests with two membrane modules in series and a dosage of base in front of membrane 1 and in-between the modules demonstrated the same elimination efficiency at the same inlet pH of both the modules. The strategy of a two point dosage guaranteed an optimum removal by both membranes and helps to prevent intensified precipitation at the surface of the membrane at higher pH-values. In addition, precipitates can result in hydraulic pressure drops in the plant combined with a high frequency of acid cleaning of the membranes.

The life span of the membrane influences the overall economic feasibility of the technology. In case of an intense decline of permeability due to intense aging of the membrane by operation or harmful compounds in the sludge liquid, a frequent replacement of the modules would increase the overall operational costs of the process. Against this background intermediate term tests with two different sludge liquids were conducted.

One sludge liquid originates from WWTP Neugut with enhanced biological phosphorous removal (bio-P-removal, (see Figure 7). Therefore, during these trials, a struvite precipitation for the recovery of phosphorous was added to CO_2-stripping as a pre-treatment. This pre-precipitation also avoids intense scaling on the membrane surfaces. Figure 7 illustrates the time line of the experiment regarding removal efficiency.

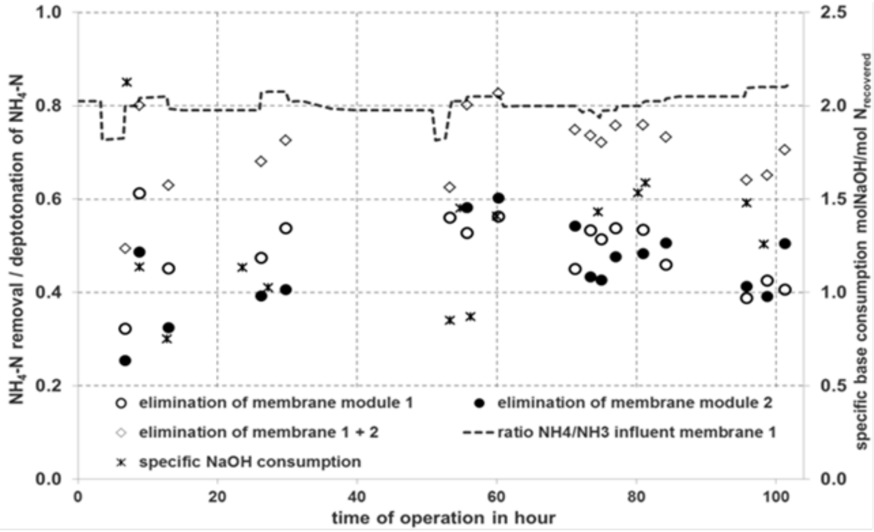

Figure 7: Removal efficiency over 5 days with sludge liquid of a bio-P removal plant, the pH was adjusted in front and in between the membrane modules in the range of 9.3 to 9.5, temperature was kept at about 42°C

During the test the removal efficiency of the first membrane was in the range of 50%, whereas the elimination of the second membrane was slightly lower in the range of 45%. This was caused by a limitation of free ammonia and not optimal dosage of base in front of the second membrane compartment respectively. The overall removal of the pilot plant was in the range of 75%. A second long term trial without struvite precipitation with sludge liquid from a conventional WWTP (WWTP Altenrhein) showed higher elimination efficiencies in the range of 80 to 85%.

The specific base consumption were for both sludge liquids in the range of 1.2 to 1.5 mol NaOH/mol $N_{recovered}$. This is higher than expected and is likely due to an inefficient CO_2-column upstream of the pilot plant. For the sludge liquid of WWTP Neugut with Bio-P-removal the specific base consumption was slightly lower than for the sludge liquid of the conventional WWTP. This could be caused by the addition of magnesium oxide for struvite precipitation.

In the previous paragraphs attention has been paid to the effect of pH on the NH_3 mass transfer on the side of the sludge liquid. The mass transfer is also influenced to a certain extent by the pH at the side of the acid solution. This effect is shown in Figure 8. The effect was investigated by stopping the dosing of sulphuric acid to control the pH in the acid solution and to monitor the pH resulting from the on-going absorption of NH_3.

Figure 8 shows the difference in pH between the inflow and the outflow of the membrane modules and the resulting effect on the removal efficiency. Typically the pH of the acid solution would be around 2. Figure 10 shows that if the pH value of the acid solution reaches values above pH =3 that the mass transfer is significantly affected. Another interesting feature from figure 10 is that with on-going circulation the acid solution outflow can reach pH values of around neutral (pH=7). This feature can be used for two purposes: (i) to maximise the utilisation of dosed acid and (ii) to neutralise the product solution. The latter is relevant for final application of the product solution as a fertiliser.

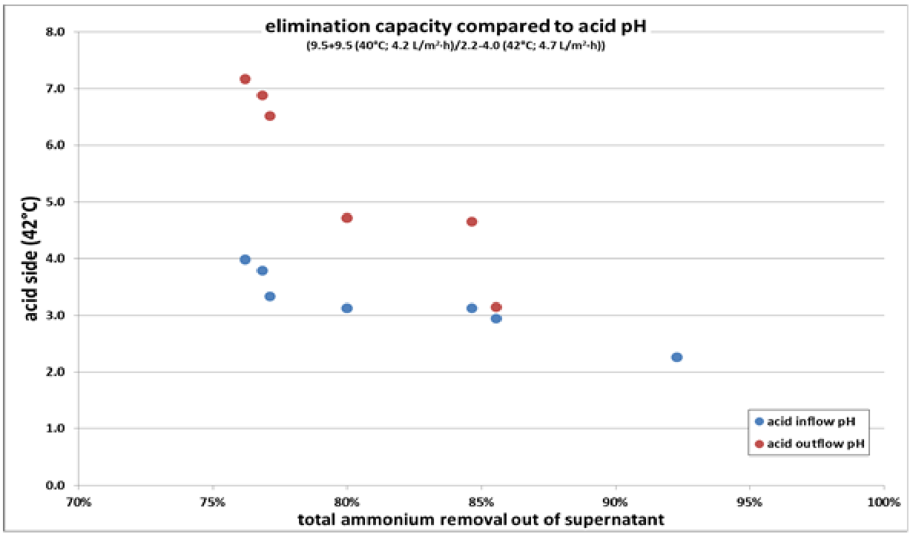

Figure 8: Effect of pH of acid solution on mass transfer

After completing the tests at WWTP Neugut the pilot plant was used to perform additional experiments at the WWTP Venlo in the Netherlands. The main subject of this research-project was the feasibility of phosphate recovery by struvite formation but some attention was also paid to nitrogen recovery.

The water to be treated originates from the final dewatering of the digested sludge. The WWTP Venlo is exceptional in this respect as the sludge being digested is pre-treated in a continuous thermal hydrolysis plant which was developed and delivered by SUSTEC BV. Further information on the performance of this plant is available in recent literature (Luning et al. 2015). Pre-treatment by thermal hydrolysis results in more concentrated sludge liquids. In the case of Venlo, the NH_4-N concentration in the sludge liquid from final dewatering is around 1035 mg/l . Part of the results are presented in Figure 9 a and b. The results at Venlo WWTP are very much in line with those at WWTP Neugut, considering the fact that the flow rate at Venlo was higher than at Neugut with values of 300 l/h and 220 l/h respectively.

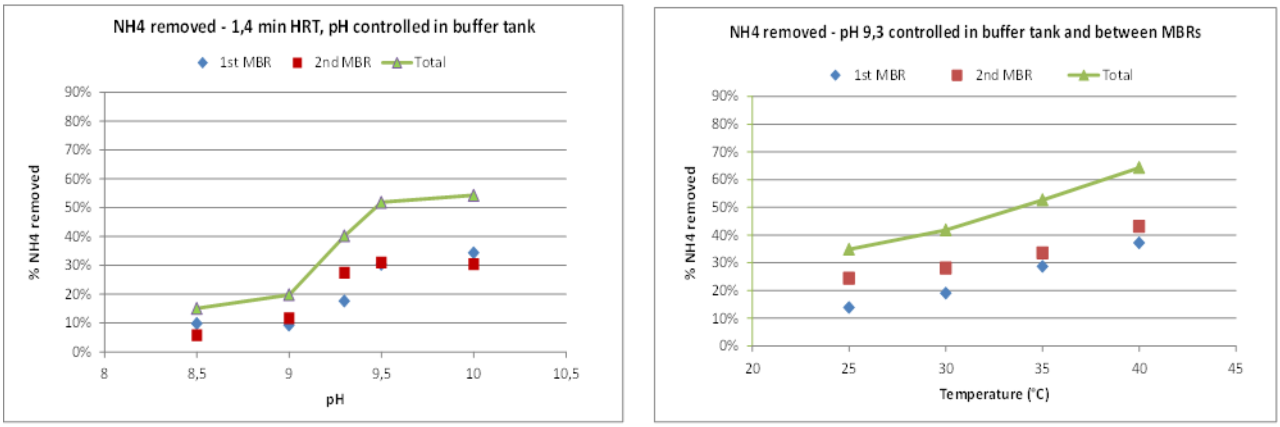

Figure 9 a/b: Effect of pH and temperature on NH_3 mass transfer and recovery

The tests performed clearly indicate the potential of the technology to contribute to the development of recovery of NH_3 as an alternative to destruction of this compound.

The recovery of NH_3 in the form of ammonium sulphate by the application of gas permeable membranes instead of air-stripping has a certain effect on the characteristics of the product. As the membranes are gas permeable, not only the NH_3 will be able to pass, but also the vapour fraction of water that is present in the waste water. This effect was also described by Ulbricht. (Ulbricht, 2009) The magnitude of water transport depends on a number of parameters with the most important ones being:

- the temperature, as this determines the partial pressure of the water vapour and therefore the driving force for the transfer
- the total surface of membranes, since the solution is not depleted by extraction of water vapour, the transfer is proportional to the surface area included

For air stripping the effect of water evaporation can be mitigated by recirculating the air-stream over the stripper and the absorber. As the air becomes saturated with water, the evaporation of water will decrease and finally stop.

With respect to the temperature a balance has to be found between the increase of mass transfer due to increase of the Henry coefficient (see Figure 4) and the increased additional flow of water. Minimizing the operational temperature is also beneficial in reducing energy consumption point of view. From our laboratory experiments at various temperatures we find that a temperature of 40 – 45 °C presents a good working point.

Increasing the surface area for a fixed flow rate will result in an increase of the removal efficiency. This increase in surface area will however also increase the flow of water vapour through the membrane. The water vapour transport is directly proportional to the membrane surface, whereas the transfer of NH_3 will decrease with lower average concentrations due to a lower driving force. Increasing the membrane surface will therefore result in more dilution of the product solution. Similarly the concentration level of the product solution will be reduced if the initial concentration of NH_3 in the waste water is lower.

5. Preparation of the invitation to tender - Proceeding

5.1. Visits and workshops of partner

In order to prepare the invitation to tender for the realization of the membrane stripping plant seven all day meetings were conducted either at WWTP Altenrhein or at Eawag. In these workshops all partners (see section 3.3.1) were included such as WWTP Altenrhein (Christoph Egli, director and operator WWTP Altenrhein), the local consulting engineer KUSTER & HAGER (Steffen Zuleeg, in charge for the invitation of tender), SUSTEC BV (Luchien Luning and/or Danny Traksel, plant manufacturer), ATEMIS GmbH (Alexander Seyfried, engineer consultant, Eawag (Marc Böhler, Julian Fleiner) and Hansruedi Siegrist (subcontractor) for the scientific supervision. In these workshops the fundamentals for the invitation to tender were discussed and defined. These meetings were distributed over a period of nearly one year before the date of publication of the documents to tender. Due to confidentiality issues, subsequent meetings for the evaluation of the results and proposals respectively of the submission were executed without the partner SUSTEC BV.

5.2. Definition of design parameters for pre-treatment + membrane units

After collecting and evaluating of operational data of WWTP Altenrhein the following design values and parameter were defined for the pre-treatment and membrane stripping unit (see Table 1).

These data were published in the invitation to tender.

Table 1: Key design values for the dimensioning of pre-treatment and membrane stripping plant

Operational data of 2014	Average	Minimum	Maximum	Design value
Amount of sludge water	20 m^3/h	18 m^3/h	30 m^3/h	20 m^3/h
COD	1‘622 mg/L	489 mg/L	4‘540 mg/L	1‘700 mg/L
N_{total}	744 mg/L	450 mg/L	990 mg/L	
NH_4-N	630 mg/L	360 mg/L	1‘296 mg/L	900 ± 200 mg/L
Dry solids	836 mg/L	40 mg/L	3‘456 mg/L	800 mg/L
Temperature	17°C	14°C	20°C	min. 14°C
pH	8.2	8	9	min. 8

The average ammonium concentration of the sludge liquid of WWTP Altenrhein is in the range of 750 mg/L NH_4-N. At single days the concentration can vary between 500 to 1‘500 mg/L due to external digested sludge, which is delivered and dewatered at WWTP Altenrhein.

Due to high values of dry matter and total DOC an intense pre-treatment of the sludge liquid is necessary before entering the membrane units. A detailed evaluation of the pre-treatment was done (see section 5.3) and has been described in the documents to tender. However it was open for the tenderer to offer alternative solution or alternative flow schemes for the pre-treatment respectively.

The capacity of the planned pre-treatment is 20 m³/h. This equals about 100% of the produced sludge liquid. However, the membrane plant will be realized stepwise. In a first step the capacity will only be 30% of the total amount of sludge liquid produced at WWTP Altenrhein corresponding to about 7 m³/h. 70% of pre-treated sludge liquid will be recycled to the sludge liquid storage tank and influent of the WWTP respectively.

WWTP Altenrhein has only a very small sludge liquid storage capacity of 30 m³ that cannot be used as a buffer tank. Also the sludge liquid storage tank will collect raw sludge liquid (not treated), pre-treated and membrane treated sludge liquid and other residuals of sludge water treatment.

5.3. Definition of flow schemes (pre-treatment + membrane unit)

In the frame of the workshops different flow schemes for the optimal treatment were discussed. As a result, preferred flow schemes for the pre-treatment and also for the membrane unit were defined. In order to have a minimum quality of pre-treated sludge water before entering the membrane unit and also to have comparable proposals, the lay out of the pre-treatment was defined in the document of tender.

To ensure enough freedom for the tenderer to offer alternative solutions and ideas for the flow scheme of the membrane unit, it was not defined in the invitation to tender. In this context, aspects of confidentiality play also a major role, because there are in principle many different alternative solutions for the lay out, which generate different advantages and disadvantages for the process. Against this background it was open to the tenderer to submit an alternative offer, a so called "Unternehmervariante".

5.3.1. Evaluation and definition of preferred flow scheme for the pre-treatment (piping and instrumentation diagram base line for submission)

In the documents of tender a detailed description of the whole pre-treatment was given. Included was also a piping and instrumentation diagram (PID) which shows the preferred flow scheme (see Figure 10). The flow scheme of the pre-treatment was changed several times and is the outcome of intense discussions during the workshops. All the drawing work and adaptations of changes were done by ATEMIS GmbH.

Core elements of the pre-treatment are:

- Strain press (on site)
- Divider with collection container
- Disk-filter
- three heat exchangers (before and after CO_2-stripper with collection container to recycle heat)
- Dosing unit for anti-foam agent
- CO_2-stripper as packed column

- Contact and reaction chamber for precipitation with dosing unit for NaOH
- Sedimentation with an optional lamella clarifier cassette unit (a small amount of sludge will be brought back to the reaction chamber to serve as precipitation/flocculation nucleus)
- 2 Disk filters for polishing (second optional)

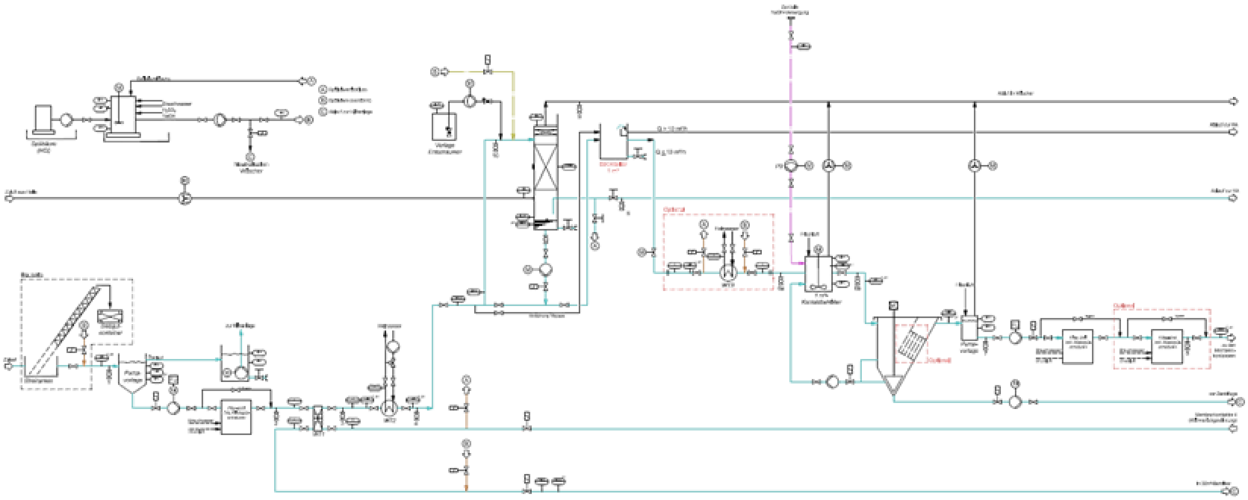

Figure 10: Piping and instrumentation diagram (PID) of the pre-treatment (by ATEMIS GmbH)

In the tender documents the function and lay out of the single components of the pre-treatment are described in detail. To ensure a minimal cleaning capacity of the core elements of the pre-treatment, requirements were defined e.g. maximal dry solid contents after filters and sedimentation, etc.

5.3.2. Evaluation of an process flow diagram (PFD) of the membrane stripping unit

Up to date there is only limited experience and knowledge on the optimal layout and flow scheme of an membrane stripping plant. Eawag and SUSTEC BV gained some very useful and valuable operational data and experience in a pilot study in 2013. But nevertheless in the workshops different potential flow schemes were discussed. To motivate the tenderer to offer new and innovative solutions no preferred flow scheme was defined in the documents of tender. But to ensure a necessary hydraulic capacity and minimal degree of nitrogen-removal resulting in a high quality of the product, the following key values and design capacities were given in the tender documents. A drawing of the membrane stripping plant was not published, but however the principle potential flow scheme is given in Figure 11. This drawing was prepared by SUSTEC BV.

The following specifications have been given in the tender documents:

- in a first phase only one lane will be realized with a hydraulic capacity of 7 m^3/h (corresponding to 30% of the total sludge liquid produced at WWTP Altenrhein)
- the one lane membrane system consists of three membrane modules in series
- optional the first membrane module could be also used as a polishing step (recycling of the product of module 2 and 3 to remove water)

- a parallel or serial operation of the modules must be possible
- the removal efficiency of the stripping plant is at least 75 % related to the ammonium concentration of the untreated sludge liquid
- the product must have a minimum nitrogen concentration of 3.5%
- the availability of the plant must be 85 %
- the possibility of installing an additional heat exchanger in front of the membrane unit should also be offered, to heat the product (to decrease water gas from the product solution in order to increase the nitrogen concentration and the quality of the product)
- the membrane modules should have a temperature resistance of at least 50 °C as well as an acid and base resistance

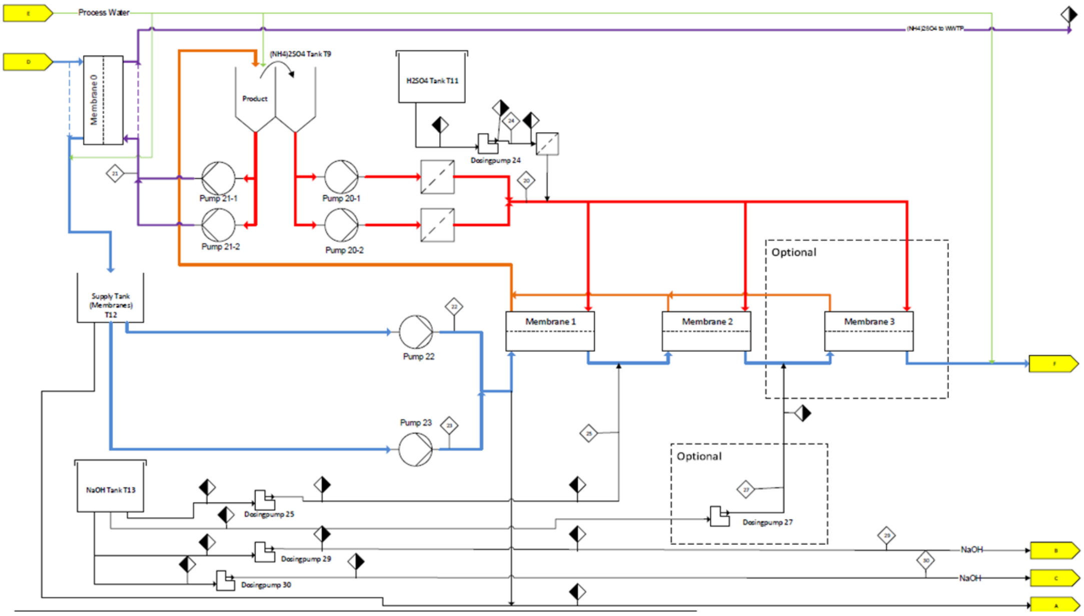

Figure 11: Principle flow scheme (PDF) of the membrane stripping plant (by SUSTEC BV)

5.4. Design of the CO_2-stripper

The CO_2-stripper for Altenrhein WWTP was designed based on the experience with a similar CO_2-stripper in Kloten/Opfikon, since there are no established rules for the design of CO_2-strippers. The stripper in Kloten/Opfikon was designed by Atemis GmbH too. During tests with this stripper, an air/liquid ratio of approximate 10 to 20 m^3/m^3 was observed to give good results at a low energy demand. From experience, the diameter of the column was designed with an air flow of 0,1 m/s. The height of the filling was designed based on a specific filling surface area of approx. 30 $m^2/(m^3*h)$. With these design parameters and additional empirical values, the dimensions of the CO_2-stripper were calculated as follows:

Throughput liquid	10 bis 20 m^3/h
Air to liquid ratio	10 bis 20 m^3/m^3
Air flow	100 bis 400 m^3/h
Air speed	approx. 0,1 m/s

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Column diameter	1,2 m
Surface needed	30 m²/(m³*h)
Spec. surface filling material	120 m²/m³
Volume filling	5 m³

With these values and some additional height for sump, probes, demister etc. the dimensions of the CO_2-stripper are shown in Figure 12. The pressure loss due to filling is approximately. 25 mbar @ 400 m³/h.

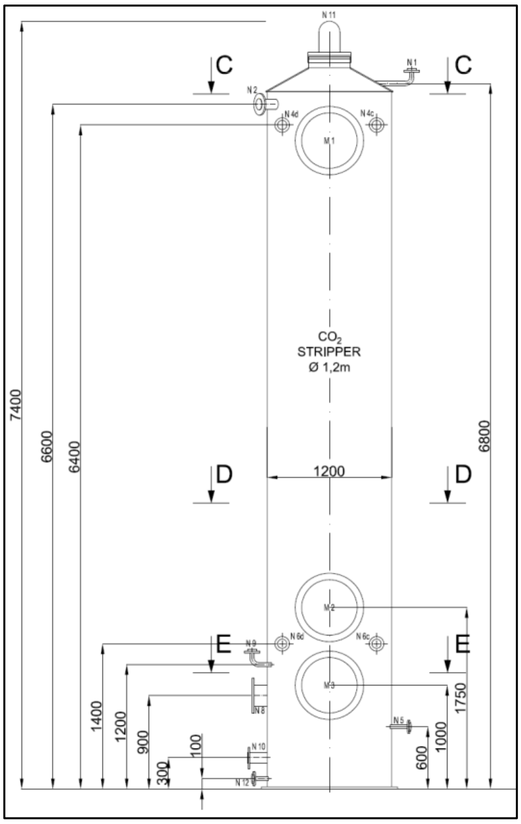

Figure 12: Dimensions CO_2 -Stripper

5.5. Probe instrumentation and definition of sampling points

In order to ensure a research-friendly lay-out of the system the number and location of probes and sampling points have been defined and integrated in the PID and PDF respectively. The following probes and sampling points are foreseen:

5.5.1. Sampling points

- effluent membrane 1 (shell side)
- effluent membrane 2 (sludge liquid, shell side)
- effluent membrane 3 (sludge liquid, shell side)
- effluent membrane 1 (product, lumen side)
- effluent membrane 3 (product, lumen side)

5.5.2. **Probes**

- effluent membrane 1 (sludge liquid, shell side): pressure
- effluent membrane 2 (sludge liquid, shell side): pressure; pH; temperature
- effluent membrane 3 pressure (sludge liquid, shell side): pressure; pH; temperature
- effluent membrane 1 (product, lumen side): pressure
- effluent membrane 3 (product, lumen side): pH; temperature

5.6. Selection of the site and integration of the stripping plant into the facilities of WWTP Altenrhein

At several site visits the location and the possible integration of the pre-treatment and the membrane units were discussed. As a suitable place it was decided to integrate it in the basement of an existing building to safe costs for the infrastructure. This building is in the middle of four big sludge storage tanks.

The new plant will extend over two floor levels. The intermediate ceiling has already an opening (see Figure 13). The membrane stripping plant will be positioned between the dewatering centrifuge and the 30 m³ storage tank, to avoid extensive piping.

Figure 13: Site of the pre-treatment and membrane unit in the building, left picture: existing opening that can be used

In the building four tanks are already exist, which can be used as storage facilities for the liquid fertilizer, base and acid e.g. NaOH, H_2SO_4, HCl, etc. For an impression of the future facility a 3-D animation was made by SUSTEC BV (see Figure 14).

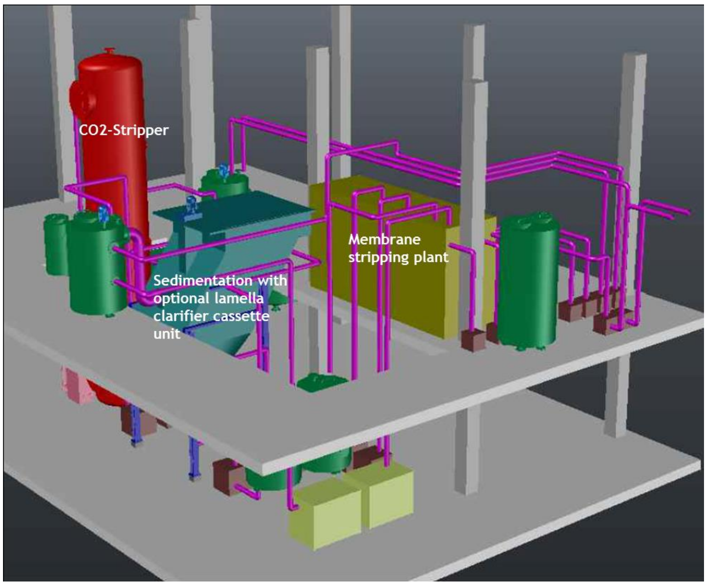

Figure 14: 3D visualization of the pre-treatment and stripping plant integrated into the designated building. The plant extends from the basement to the ground floor (visualization by SUSTEC BV)

5.7. Analyses and laboratory tests to simulate behaviour/composition of sludge water of WWTP Altenrhein

The requirement for the core elements for the pre-treatment were determined on the basis of additional experiments with the sludge water as it is presently produced at WWTP Altenrhein. Apart from characterisation of the sludge liquid, experiments were performed to simulate the effect of proposed treatment steps. This was necessary because some of these treatment steps (CO_2-stripping, NaOH-dosing, temperature increase) have an effect on the composition of the sludge water in particular due to the formation of precipitates. The research was performed to understand how this might affect the performance of the membrane modules and how adverse effects could be reduced. This research was performed by SUSTEC BV. Sludge liquid was brought from Switzerland to the Netherland. As a first test, samples from a number of consecutive days were analyzed to investigate the variations of the composition. Results are shown below in Table 2.

Table 2: Composition of sludge water of samples form a number of consecutive days

Parameter	0 (17-8)	Day 1 (25-8)	Day 2 (26-8)	Day 3 (27-8)	Day 4 (28-8)	Day 5 (29-8)	Day 7 (31-8)	Day 8 (01-09)	average
pH	8.18	8.22	8.16	8.19	8.15	8.16	8.22	8.16	8.18
COD total [mg/L]	1,120	815	801	809	974	1,278	1,244	1,115	1,020
COD filtered [mg/L]	746	514	487	513	512	615	688	600	584
P-total [mg/L]	7.4	9.15	9.56	9.72	15.3	21	19.7	16.5	14

Ortho-P [mg/L]	1.86	3.28	3.22	3.31	2.24	2.24	2.46	2.13	2.6
N-total [mg/L]	1,046	1,133	1,150	1,003	1,068	1,015	1,060	1,090	1,070
NH4-N [mg/L]	930	853	838	875	865	878	913	870	878
Total TS [mg/L]	1,862	1,642	1,631	1,687	1,877	2,184	2,306	2,186	1,922
TS after filter 0,45 µm [mg/L]	1,611	1,398	1,393	1,363	1,333	1,490	1,610	1,580	1,472
Suspended Solids [mg/L]	251	244	238	324	543	694	696	607	450

Of particular interest was the suspended solids concentration, as these might affect the performance and continuity of operation of both pre-treatment and membrane section. The tests show relatively high levels of these suspended solids, average @ 450 mg/l, but also significant variations: 238 – 696 mg/l. The tests also showed that overall TS-content is high, this is attributed to the level of soluble salts in the sludge water.

Another finding of these tests was that the sludge water contained a significant fraction of coarse plastic fragments (Figure 15). This was attributed to the co-digestion of food-waste at the WWTP Altenrhein. To prevent further problems with this material it was proposed to include a screen (Strainpress) upstream of the membrane stripping plant. This screen has already been implemented in the pipework of the sludge water, although still on temporary basis.

Figure 15: Light material in the form of relatively coarse plastic fragments. These solids resulted from the co-digestion of food-waste at WWTP Altenrhein (results by SUSTEC BV)

To simulate the composition of the sludge water as it is expected at the entrance of the membrane section, the following treatment steps were performed:

- Filtering (screening) of the raw waste water
- Heating of the sludge water to 45 °C
- Dosing of NaOH to pH = 9.5, to determine demand, to part of the sludge water

  - Aeration (stripping) of the remainder of the sludge water (see **Fehler! Verweisquelle konnte nicht gefunden werden.**)
  - Again dosing of NaOH to pH = 9.5, to investigate the effect of the CO_2-stripping
  - Screening of the sample after stripping and NaOH- dosing at different pore sizes to investigate effect on removal of suspended solids

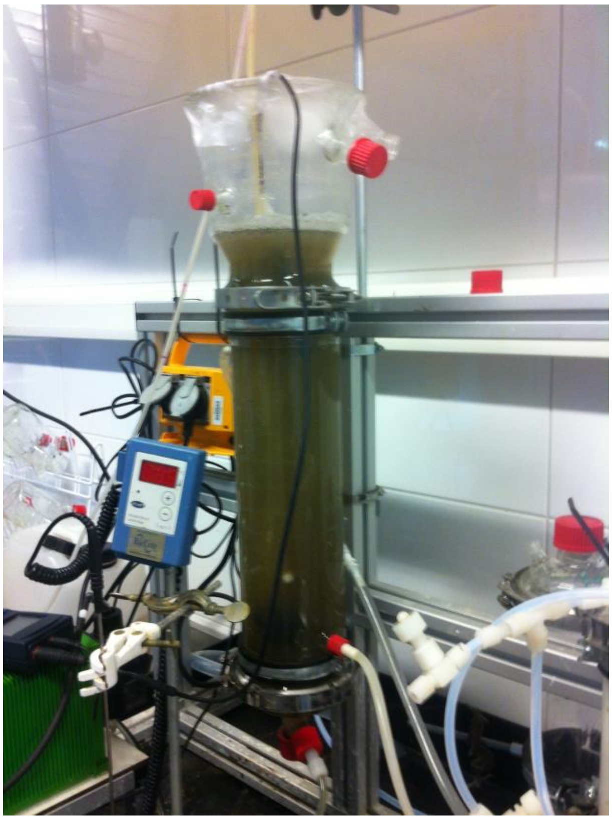

Figure 16: Lab-scale tests for removing CO_2 from sludge liquids by stripping with air (trials by SUSTEC BV)

For the first test, the screening of the waste water the expected practical circumstances were simulated by the application of a commercially available automatic back flushing filter, with different pore sizes for the screen (a so-called "Berkal"-filter).

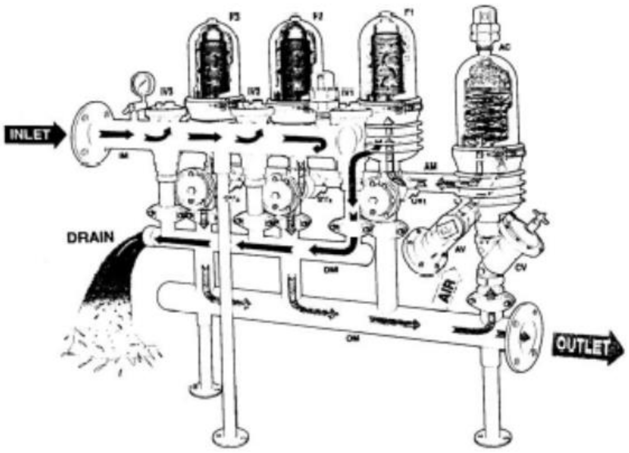

Figure 17: Principle lay-out of a “Berkal” -filter

In general, the tests with the filter were successful. The main limitation was the relative small amount of sludge water in comparison to the nominal capacity of the filter. A description of the filter is included in the attachment. The lay-out of the filter is shown in Figure 17. The filter was provided with two filter-units shown above on the left. The unit to the most right, is used for back flushing of the filter-units. In the example that we used the back flush was facilitated with the use of pressurised air (4- 6 bar). The back-flushing can also be designed on the basis of using only treated water, or by using an external source of water to back flush the filter.

For the filter-units different pore-sizes can be applied, these can be changed by opening up the holder for the filter units. Pore-sizes of 300 µm, 200 µm, 100 µm, 55 µm and 20 µm were tested. The filters were tested by pumping the available amount of sludge water of 200 l through the filter and collecting the filtered water. Afterwards the filter was changed to the next smaller size and the water was pumped through the filter once more. The water was sampled after each passage through the filter.

The content of suspended solids was determined by calculating the difference in TS-content of the samples before and after filtering over a 2 µm filter. This leads to the results in Table 3.

From the test with the “Berkal”-filter, samples were still available for the different stages of the filtering. The volumes per sample were 3.5 – 4 litres, so they could not be tested with the “Berkal”-filter itself. As an alternative a set of cartridge filters of different pore sizes were used. This also offered the opportunity to test even smaller pore sizes. For the filtering over 100 µm, 25 µm and 10 µm the results are shown in

Table 4. The concentration of suspended solids was determined in two ways (see also Table 4):

- Difference in TS-content before and after filtering;
- Measurement of the amount of SS left on the filter

The project “Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration” (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Table 3: TS-retention at different pore sizes of the “Berkal”-Filter

Filter pore size	TS- before filtering mg/l	TS after filtering mg/l	SS = difference mg/l
300 µm	2,137	1,650	487
200 µm	2,067	1,639	428
100 µm	1,917	1,643	274
55 µm	1,885	1,617	268
20 µm	1,656	1,641	15

Table 4: Concentration of suspended solids with cartridge filters

Filter size	TS after filtering mg/l	SS removed = difference in TS mg/l	SS removed = Mass caught in filter mg/l
100 µm	1,718		
25 µm	1,652	66	73
10 µm	1,630	22	18

The results of the two different methods are very similar. It is also clear that the mass removed by the filters even at the lowest pore size is quite small compared to the total TS-content. This can be explained by the large amount of soluble material (salts) present in the process water.

These results indicate that a filtration of the sludge liquid with a pore size of 20 µm with an Berkal filter the content of suspended solids (SS) can be reduced to 50 – 75 mg/l.

5.7.1. Conclusions and recommendations

- The filtering capacity of the Berkal filter is capable of reducing the SS-content of the process water considerably
- To reach the desired low values of suspended solids the smallest available pore-size of 20 µm has to be applied
- Due to the limited amount of water that was tested, the time between flushing cycles could not be determined, no detectable pressure-difference did build-up during the tests
- The supplier of the filter is concerned about the possibility of filter overloading and to short filter flushing intervals if a 20 µm pore-size is used, considering the high level of TS that is present in the process water
- The supplier suggests to put two “Berkal”-filters in series, to overcome this possible limitation. The size of the first filter can be determined on experience, 50 or 100 µm will probably be suitable; (pore-sizes can be easily adapted)
- The flexibility on the point of pore-sizes in combination with a smaller pore-size would give this type of filter a slight preference over a “Boll&Kirch”-filter

To stimulate the expected composition of the sludge water at various stages in the process, the following operations were done on a sample that was pre-filtered at 100 µm:

- Heating to 45 °C
- Aeration (stripping)
- Dosing of NaOH
- Final filtering at 25 µm

The results of these tests are summarized in the figure below with respect to the concentration of suspended solids.

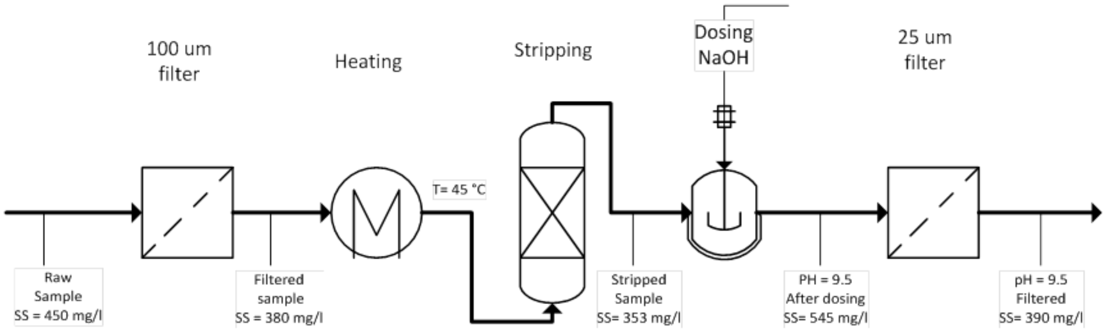

Figure 18: Development of suspended solids concentration at various points in the proposed plant. Due to the dosage of NaOH the solid concentration is increased by precipitates.

For these tests a different filter than the "Berkal" filter was applied, which may explain why the first filtering step at 100 µm is less effective than expected. The heating and stripping do not result in a significant effect on suspended solids, although it was observed during the tests that some material precipitated in the stripping bubble-column. The test result can be seen as the net result from the formation of suspended solids and their precipitation in the striping column.

NaOH dosing results in a significant increase of suspended solids from about 350 mg/l to 550 mg/l. Part of this material is afterwards removed by the 25 µm filter. The limited effectivity of this 20 µm filter shows that the particle size of the precipitation formed is quite small and difficult to remove by filtering alone. The settler included in the proposed design is aimed at assisting this filtering.

6. Invitation to tender

6.1. Implementation of the invitation to tender

The implementation of the invitation to tender has been performed by the local consulting engineering company KUSTER&HAGER. Specific text blocks (e.g. for the CO_2-stripper) have been delivered by ATEMIS GmbH. The documents of the invitation to tender were published online at the 4th of April 2016. The publication was delayed by 2 month among others due to open questions concerning the optimal pre-treatment.

6.2. Result of submission - number of proposals and consortia

The dead line of submission was the 26th of April. The submission resulted in 2 tenderer with 3 proposals.

One proposal was submitted by the POWERSTEP partner SUSTEC BV. SUSTEC BV offered in cooperation with the Swiss plant manufacturer WABAG WASSERTECHNIK AG and the Dutch membrane manufacturer BLUETEC BV.

Two proposals have been submitted by the Swiss plant manufacturer ALPHA WASSERTECHNIK AG in cooperation with the German membrane manufacturer KUNST GMBH. One proposal was in line with the invitation to tender description for the pre-treatment. A second proposal contained an alternative solution for the pre-treatment and for the membrane unit (Unternehmervariante).

6.3. Evaluation of submission

The evaluation of the results of submission was prepared at the beginning of May 2016. An intense review of the proposals has been done by KUSTER&HAGER, EAWAG and ATEMIS. **In this phase of the tender procedure SUSTEC BV was excluded from the deliberations.**

Comparisons have been made with respect to quality of the aggregates offered, of the processes (flow schemes) and the quality of the offers in general. A list of questions for the tenderer has been created.

At the end of May, the tenderer have been invited to WWTP Altenrhein to present and to discuss open questions concerning their proposals. At these meetings the costs for e.g. spare parts, the specific chemical demands as well as the energy demands have been asked and discussed to evaluate specific annual and operational costs.

6.4. Costs for mechanical engineering and constructional modifications

The Costs for the realization of the whole plant including mechanical engineering, measurement and process control system were in the range of 1.3 to 2.5 Mio CHF.

Costs for constructional modifications of the building and implementation of the stripping plant into the process control system of WWTP Altenrhein has been estimated by the local consultant KUSTER&HAGER of about 0.5 Mio CHF.

Due to the fact, that the process of submission is not finalized yet no detailed information on the specific technical solutions offered by the tenderer can be given in this report

6.5. Estimation of operational costs

During the evaluation of the proposals, the specific energy and chemical demands for the treatment and processes were requested from the tenderer. In addition, costs for the maintenance of the plants as spare parts, re-placement of membranes, etc. were estimated. On the basis of these specific data it will be possible to estimate the operating costs of the plants. This work will be carried out in spring 2017.

In addition a collection of these data were given to Veolia and KWB as an input for their OCEAN energy balances and further planned LCA studies.

7. N_2O measurements at WWTP Altenrhein

7.1. Summary

N_2O is a strong greenhouse gas, with a greenhouse gas potential of 300 g CO_2-eq/ g N_2O (IPCC 2013). It represents an important driver in the CO_2 balance of WWTP, because it is during biological nitrogen removal. Hence, N_2O is an important factor in the performance analysis of new treatment technologies replacing nitrogen removal and plays a relevant role in the POWERSTEP project. On the wastewater treatment plant in Altenrhein (SG), N_2O emission were measured in order to assess the relevance for the carbon footprint and to estimate mitigation potential by reducing the nitrogen load. N_2O emissions were shown to be relevant for the CO_2 balance. On average, emissions of about 1% of the total nitrogen load could be detected. High variations could were observed on a seasonal scale. Especially in the winter season high emissions occurred in the activated sludge system. The emissions from the fixed bed reactors were lower. Experiments showed that a reduction of the nitrogen load by separate treatment of digester supernatant offers a great potential to reduce N_2O emissions. The emissions attributed to the dosage of digester supernatant were found to be significant. In particular, a fraction of 10-15% of the ammonia from the digester supernatant (or 3% of the total nitro-gen load) was emitted as N_2O during the four winter months. As a consequence, a certified emission reduction project combined with the planned stripping plant for digester supernatant will be elaborated. The project could generate up to 300’000 CHF in the next three year. However, further experiments are required and planned to consolidate the data basis for a monitoring base line and to precise estimate the revenues for the CO_2-reduction.

7.2. Background

Parallel to the strong greenhouse gas effect, N_2O is also a major thread to the stratospheric ozone layer (Ravishankara, Daniel et al. 2009). N_2O can be emitted from wastewater treatment plants (WWTP) during biological nitrogen removal (Kampschreur, Temmink et al. 2009). It is predominantly produced by ammonia oxidizing bacteria and less often by heterotrophic denitrifying bacteria in the biological treatment steps of WWTP (Wunderlin, Mohn et al. 2012). In fact, N_2O emissions can represent the major greenhouse gas emission of WWTP if roughly more than 1% of the incoming nitrogen load is emitted as N_2O (Wunderlin, Siegrist et al. 2013). In this case, N_2O emissions typically exceed CO_2 emissions caused by the plant’s energy consumption, normally the highest driver on the carbon footprint in wastewater treatment. Hence, a clear account of N_2O emissions is important when plants are optimized in terms of energy demand, for example. Similarly, in the evaluation of new technologies in wastewater treatment N_2O emissions have to be taken into account. This is a very important step in the approach of the POWERSTEP project, and is therefore tackled in WP4 and compared between the different work packages.

N_2O emissions are difficult to measure exactly, due to their high spatial and temporal variation (Daelman, De Baets et al. 2013). For emission measurement, on-line off-gas measurement setups are used as a standard due to their high accuracy. Typically, these measurement devices are not available on normal WWTP and as a consequence the number of long term full scale measurement campaigns is still limited. The only two long term studies published to date found relevant N_2O emissions (above 1% of the nitrogen load) in the investigated plants (Daelman, van Voorthuizen et al. 2015), (Kosonen, Heinonen et al. 2016). Although various short term studies have been published, there is still a need for further long term studies as short term studies cannot representatively estimate N_2O emissions. Moreover, mitigation strategies have rarely been tested on full scale WWTP. The role of the nitrogen load and a separate digester supernatant treatment, for example, could be of importance for N_2O emission mitigation.

At WWTP Altenrhein, a comparatively high fraction (30%) of the totally treated nitrogen load attributes to the supernatant from sludge treatment and sludge dewatering of neighbouring plants. The separate treatment of these sludge liquids is bearing a substantial potential for nitrogen load and possibly for N_2O emission reduction. If N_2O emission can be lowered, an emission reduction project, in the framework of the CO_2 act in Switzerland, could help to co-finance the planned membrane stripping plant. Refunds of up to 120 CHF per ton CO_2-equivalents saved are making a carbon saving program interesting.

With a conventional three lane activated sludge process and a fixed bed biofilm process, the plant consist of two conceptually different treatment processes. Therefore, the plant offers a great potential for comparing the two technologies in terms of N_2O emissions. Only few long term studies have been published, so far.

7.3. Aim

This subproject within WP4 aims to investigate the influence of a reduced nitrogen load on N_2O emissions. The investigations should provide the scientific bases of an emissions reduction project combined with the planned ammonia membrane stripping plant at WTTP Altenrhein. Thereby further optimisation strategies should be tested, such as an improved supernatant dosing scheme. Additionally, N_2O emissions of two different treatment processes with and without sludge liquid addition should be compared spatially and temporally over a long period. This datasets will allow to characterise important factors influencing N_2O emissions.

7.4. Method

7.4.1. Data collection

For the calculation of the N_2O emission concentration measurements and air supply data provided by the plant operators were used and computed with the following formula:

Load N_2O*=concentration* N_2O**Air flow applied to lane*

To collect gas samples, floating gas hoods were placed, as shown in Figure 21, at seven different spots of the plant (cf. Figure 19). Each gas hood was sampled during 5 minutes. The concentration measurement was performed with an online non-dispersive infrared sensor. Prior to measurement the gas was dehumidified and cooled. A scheme of the measurement setup is depicted in Figure 20. The devices were calibrated once a month, according to manufacturer's advices.

The plant operators provided on-line data of water flow, air flow and operational modes for the lanes investigated in one minute intervals. Additionally, daily composite influent and effluent samples will be analysed foron chemical parameter like total nitrogen, chemical oxygen demand and several nitrogen species. This data will be used to get an overview of the nitrogen mass balance of the plant and to com-pare the behaviour of the two treatment processes.

7.4.2. **Experimental planning**

The whole monitoring campaign was planned for a year, with an optional extension. It started in November 2015. In two short experiments during two days each in December 2015 and January 2016, the effect of a reduced nitrogen load was tested by storing the digester supernatant in a storm water tank. By releasing the supernatant from the tank, an overload of ammonia was created. To investigated long term effects on a monthly scale, digester supernatant was bypassed to activated sludge lane 2 and 3, and the fixed bed reactors between March and April 2016. The dosage was varying strongly.

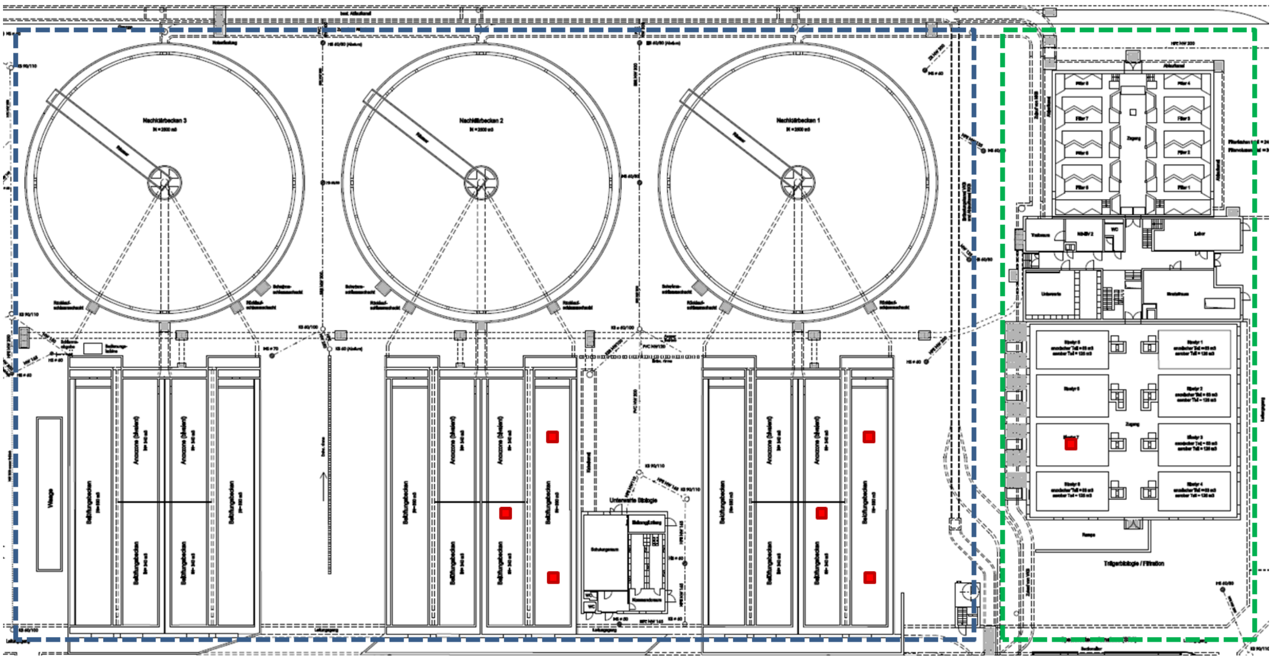

Figure 19: Layout plant of the biological treatment steps with activated sludge (blue line) and fixed bed(green line). The spots of the gas hoods are marked with red rectangles.

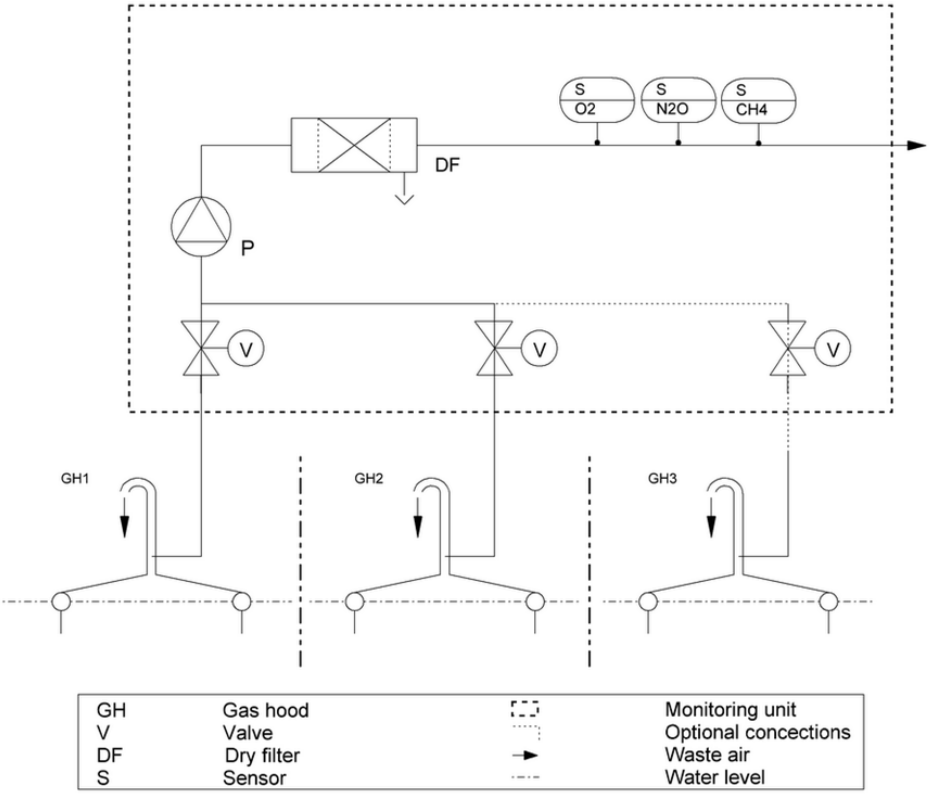

Figure 20: Scheme of the gas measurement setup

Figure 21: Floating gas hood on a reactor (right) and monitoring unit (left)

7.5. Results

7.5.1. N_2O emissions

The emissions from both processes were seasonally very dynamic, as displayed in Figure 22. In the activated sludge system, N_2O emissions peaked between December to February and were lower in spring and summer. This corresponds to previous observations from a measurement campaign at WWTP Real in Lucerne a nitrogen removal plant for 250’000 p.e.

The fixed bed reactor showed a different behaviour. In the colder period, emissions were rather low. But in March, during the experimental phase, a strong increase of the N_2O-emissions was detected. This was probably due to over dosage of digester supernatant in this phase, as in lane 1 (in purple) digester supernatant was not dosed and the dosage for the other activated sludge lanes and the fixed bed reactors was not proportional to the inflow. After this peak, emissions slowly decreased again to lower levels. Overall the emissions were above 1% for most of the time. Consequently, N_2O is an important driver in the green-house gas balance of the plant. Its relative share was not calculated.

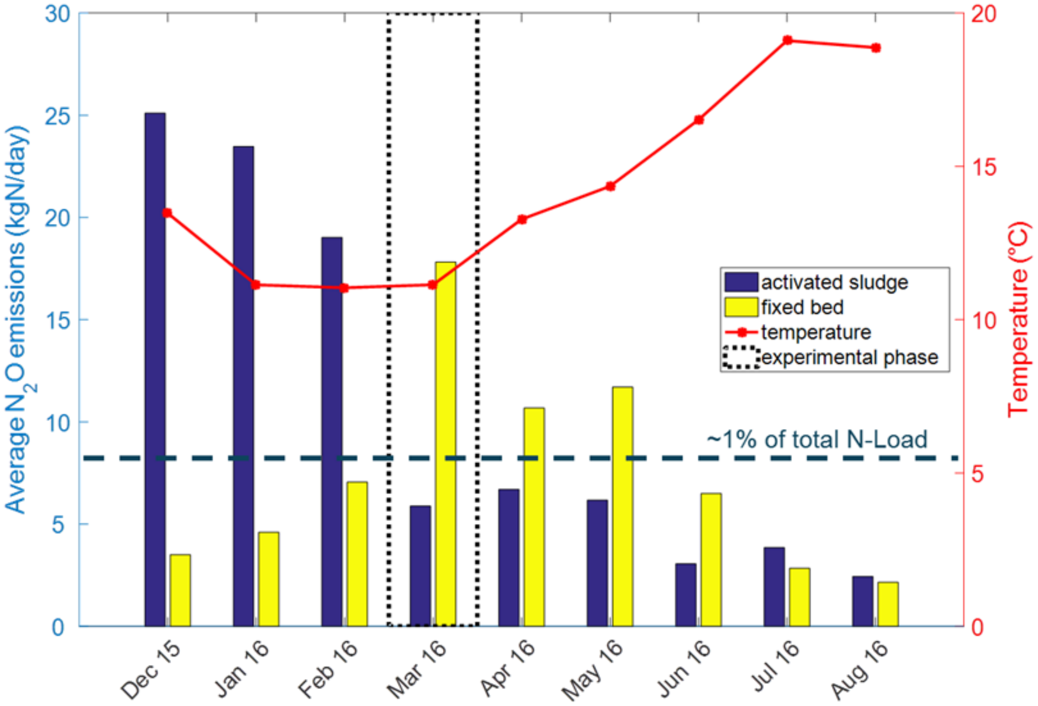

Figure 22: N2O emission during the measurement campaign

7.5.2. N_2O reduction strategies for carbon mitigation

For the estimation of the digester supernatant dosage on N_2O emissions, first two short experiments (two days each) were carried out. During the phase without dosage of digester supernatant, emission drastically decreased in both cases. The emission increased again after changing operation to standard dosage. The experiments clearly showed that digester supernatant has a strong impact on N2O emission. To show long term behaviour, the digester supernatant was bypassed around lane 1 for two months and only dosed to lane 2 and 3 and the fixed bed reactors. Shortly after the beginning of the experiment, N_2O emissions in lane 1 decreased off to very low levels compared to the control lane 2 (c.f. Figure 23). After three weeks, emissions had dropped in lane 2, whereas the fixed bed emissions increased sharply. This behaviour was due to no flow proportional distribution of the supernatant to lanes 2 and 3 and the fixed bed reactors, leading to temporary over dosage of either the activated sludge lane or the fixed bed. With rising temperature in mid-April, emissions dropped substantially and remained low throughout the summer months. This is in line with observations from previous observation at WWTP Real in Lucerne, where N_2O emissions only occurred at low temperatures. The two month experiment validates the findings from the preliminary test and indicates that a climate mitigation project is interesting. However, uncertainties on the long term efficacy of a separate digester supernatant treatment remain, because the test was only performed over two months. Possibly, the activated sludge will adapt to conditions with higher and lower ammonia loads and eventually emit N_2O in similar ranges as with the current operational pattern. Hence, an extended emission monitoring over a whole season is required for a future CO_2- mitigation project.

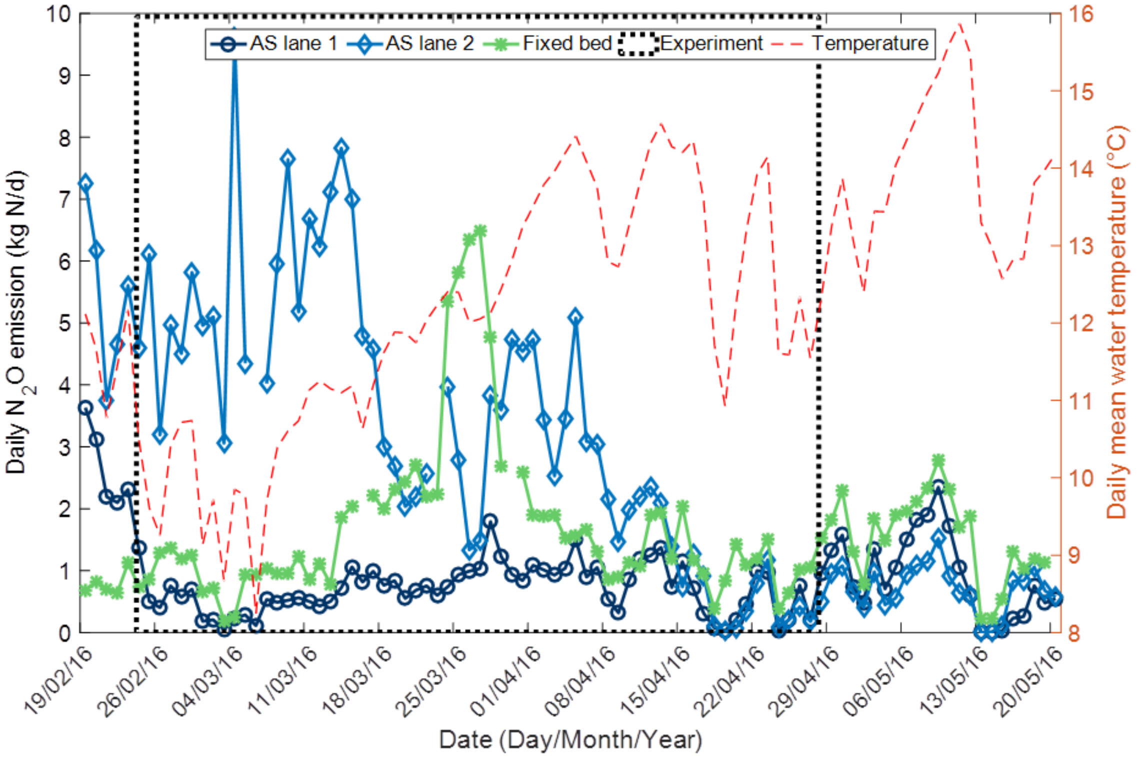

Figure 23: N_2O emissions during the digester supernatant bypass experiment

In the experimental phase differences of emissions between 2 and 7 kg N2O-N per day could be detected between the activated sludge sub-lanes 1.1 and 2.1. This corresponds to a reduction of 60-90% of the N2O emissions. Similarly, the fraction of nitrogen from digester supernatant transformed to N2O on lane 2.1 is between 5-15%. For a plant wide nitrogen supernatant load of 250 kg N per day, a separate treatment of the digester supernatant would reduce emission by 15-35 kgN2O-N per day. With a guaranteed price of CHF 120.- per ton CO2-eq saved, CHF 90’000-200’000.- could be gained per year. However, these measurements and calculations have to be confirmed with long-term monitoring phases, where the activated sludge lanes have adapted to higher or lower sludge liquid loads.. Furthermore the separate super-natant treatment will only treat 60% of the total digester supernatant load, leading to predicted in-comes of

60'000 to 130'000.- per year or 200'000 to 300'000.- over the whole three years of the climate mitigation program.

7.6. Outlook

An extended monitoring of the N_2O is planned to refine the revenue calculations. During a whole winter season, digester supernatant will be added to the inflow of lanes 2 and 3 as well as the fixed bed reactors as described in Figure 24, while lane 1 is operated without supernatant. This experiment will take place between November 2016 and March 2017. The experiment will also enclose AOB (ammonia oxidizing bacteria) and NOB (nitrite oxidizing bacteria) activity measurements of lane 1 and 2 to check if bacteria adapts to the lower or higher nitrogen load. In parallel, the emission reduction project will be developed and handed in to the federal office of the environment.

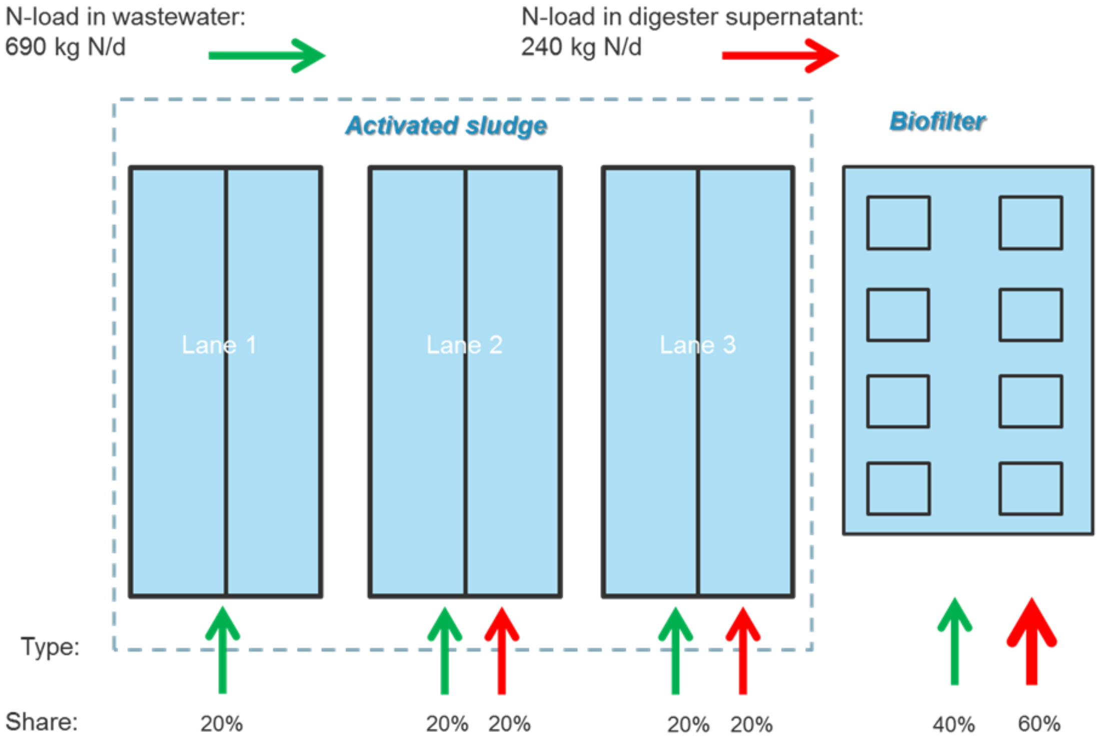

Figure 24: Overview of the relative nitrogen flows during the digester supernatant experiment

8. Conclusion and outlook CS6

Intense work by the CS6 consortium led to a detailed tender documents and three tenders offered by two suppliers resulted, which are all realistic to implement the membrane stripping plant required for CS6. Additional discussions with the local authorities followed in order to get funding for the realisation of the plant. The final decision is not yet made, because the operator is waiting for a possible co-financing by two other projects based on N_2O emission mitigation and fertilizer production with sludge. As a result, the future procedure of CS6 is not decided yet. Due to lower total N2O emissions from a WWTP with a membrane contactor to treat it's sludge liquid, there is still a good chance for a positive outcome.

9. References

Boehler, M., Heisele, A., Seyfried, A., Grömping, M. and Siegrist, H. (2014): (NH4)2SO4 recovery from liquid side streams, Environ Science Pollution Research, DOI 10.1007/s11356-014-3392-8, Springer-Verlag Berlin Heidelberg, accepted 28 July 2014.

Boehler, M., Heisele, A., Seyfried, A., Grömping, M., van Dijk, L. and Siegrist, H. (2014): Processes for obtaining a liquid fertilizer (NH4)2SO4 from wastewater, full paper, proceedings of IWA Specialist Conference on Global Challenges for Sustainable Wastewater Treatment and Resource Recovery, Kathmandu (Nepal), 26 – 30 October 2014.

Daelman, M. R., B. De Baets, M. C. van Loosdrecht and E. I. Volcke (2013): "Influence of sampling strategies on the estimated nitrous oxide emission from wastewater treatment plants." Water Res 47(9): 3120-3130.

Daelman, M. R., E. M. van Voorthuizen, U. G. van Dongen, E. I. Volcke and M. C. van Loosdrecht (2015): "Seasonal and diurnal variability of N2O emissions from a full-scale municipal wastewater treatment plant." Sci Total Environ 536: 1-11.

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Kampschreur, M. J., H. Temmink, R. Kleerebezem, M. S. Jetten and M. C. van Loosdrecht (2009): "Nitrous oxide emission during wastewater treatment." Water Res 43(17): 4093-4103.

Kosonen, H., M. Heinonen, A. Mikola, H. Haimi, M. Mulas, F. Corona and R. Vahala (2016). "Nitrous Oxide Production at a Fully Covered Wastewater Treatment Plant: Results of a Long-Term Online Monitoring Campaign." Environ Sci Technol 50(11): 5547-5554.

Luning, L., van Dijk, L., Boehler, M. and Siegrist, H. (2015) "Results from pilot tests for ammonia stripping by Membrane modules", 9. Aachener Tagung, Erfahrungsaustausch Deammonification, 1-2 September 2015 , Leipzig. (Germany).

Ravishankara, A. R., J. S. Daniel and R. W. Portmann (2009). "Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century." Science 326(5949): 123-125.

Siegrist, H.; Laureni, M.; Udert, K.M. (2013): Transfer into the gas phase: Ammonia stripping In “Source separation and decentralization for wastewater management”, Larsen, T.A.; Udert, K.M.; Lienert, J., Eds. IWA publishing: London, UK, 2013.

Ulbricht, M., Schneider, J., Stasiak, M., Munoz, J., Sengupta, A. and Kitteringham, B., (2009): Liquid-liquid extraction of ammonia using hollow fiber membrane contactors, Filtech conference, Wiesbaden , Germany, 13 – 15.10.2009.

Wunderlin, P., J. Mohn, A. Joss, L. Emmenegger and H. Siegrist (2012). "Mechanisms of N2O production in biological wastewater treatment under nitrifying and denitrifying conditions." Water Res 46(4): 1027-1037.

Wunderlin, P., H. Siegrist and A. Joss (2013). "Online N2O measurement: the next standard for controlling biological ammonia oxidation?" Environ Sci Technol 47(17): 9567-9568.