Messtechnische Datenerfassung und –analyse zur Prozessregelung einer dezentralen Abwasseraufbereitungsanlage

Monitoring and analysis for process control of a decentralized wastewater treatment plant

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anaerobe Anlage, Prozessregelung, Datenerfassung und -analyse, mathematische Modelle
anaerobic treatment, process control, monitoring and analysis, mathematical models

Abstract

The focus of the present study lies on the setup and start-up of a decentralized three-stage anaerobic plant for the treatment of domestic wastewater. The plant includes a two-stage process for the anaerobic degradation of organic matter followed by an anammox step for the removal of nitrogen components. Ensuring an operational and particularly efficient process flow, based on the microorganisms kinetics, represents the key role of the investigation. The complexity derives from the non-linear time-depending interactions between the different types of microorganisms involved, as well as their interaction to several environmental parameters. Key parameters are the influent composition, the operating temperature and the pH of the individual process stages. In order to achieve a high degree of process stability and flexibility, control tools were developed joining together expert knowledge about the process, analytical monitoring and mathematical models. Based on the Anaerobic Digestion Model No. 1 a simulation tool was developed for monitoring the two-stage anaerobic digestion. Moreover, artificial neural networks were used for the development of an ammonium estimator for the anammox step. In this context, an integral and throughout the process collection and analysis of measurement data becomes essential. Particularly, parameters such as pH, chemical oxygen demand and ammonium concentration are the main indicators of the process status and are given as input for the built models to ensure process stability.

Introduction

Compared to high-strength wastewater, the anaerobic digestion of the organic matter present in low-strength domestic wastewater is relatively a new technology where advantages like good performance, low space-requirements and biogas production are combined (Foresti et al., 2006). Since domestic wastewater usually holds a significant amount of nitrogen, a post treatment is required. The anammox process represents an innovative technology that anaerobically degrades ammonium into nitrogen gas without the need of an additional organic source (Strous et al., 1998). Therefore, it is suitable for the treatment of anaerobically digested effluents. Additionally, the decentralized approach becomes advantageous for rural areas or densely populated regions, as it allows an improved flexibility with respect to the application environment (Massoud et al., 2009).

Due to the complex interactions of the microorganisms involved in anaerobic processes, stability is hard to achieve. Through adequate process control an automated and optimized treatment plant that requires virtually no operator can be accomplished in order to increase efficiency and reduce costs. For this purpose, control strategies can be developed combining analytical monitoring and the implementation of mathematical models.

In this context, the focus of the present study lies on the setup and start-up of a fully-automated decentralized three-stage anaerobic plant for the treatment of domestic wastewater. The final effluent must be of service water quality that can be used, for example, for toilet flushing, irrigation, laundry, etc. With an increasing shortage of drinking water arising worldwide, proper treatment of the wastewater originated from anthropogenic activities is not sufficient. Re-using treated wastewater as service water will help to reduce freshwater consumption.

Decentralized three-stage anaerobic treatment plant

The anaerobic wastewater treatment plant consists of a two-stage anaerobic digestion process (reactors 1 and 2) for the degradation of organic matter and a third-stage (reactor 3) for the removal of ammonium by means of the anammox process.

The pilot scale treatment plant was designed for a capacity of 2 m³/d, which corresponds to a population equivalent (PE) of 20. It is built up in the communal sewage plant of Erlangen, Germany, within two office containers that are connected to one room cell. The three reactors in which the biological reduction reactions take place have a capacity of 1000 liters each. By the reason of cost effectiveness the reactors are cylindrical tanks made out of polyethylene.

Reactors 1 and 3 were designed as batch stirred tank reactors (BSTR) with a height of 1300 mm and a diameter of 1100 mm each, which corresponds to a filling height-diameter ratio of one. In contrast, reactor 2 is a fixed bed reactor (FBR) with 2100 mm in height and 900 mm in diameter. The filling height-diameter ratio of two in the case of the FBR was provided due to less tunneling effects between the fixed bed and the inner vessel shell. As support material completely three-dimensional permeable blocks of the type BIO-NET® from Norddeutsche Seekabelwerke GmbH are used.

As the microorganisms of the three process stages have different optimum pH-values and particularly, the first-stage of the anaerobic degradation consists of acidification processes, a pH-control is required. For this purpose, a dosage system of caustic soda was implemented and is connected to the reactors.

The inlet of the reactors is positioned at the vessel cap. The sensor connections and the dosage nipples are mounted at the top of the reactors in order to reduce dead zones in the inner part of the vessels. Moreover, in order to avoid over- or under-pressure while filling or emptying the reactors, safety fittings from Albert Handtmann Armaturenfabrik GmbH & Co. KG are mounted on the flat reactor covers.

Furthermore, each reactor has one outlet centrally mounted on the reactor floor serving for the withdrawal of excess biomass, the complete reactor evacuation and recirculation. In the case of the FBR, the bacteria remain attached to the fixed bed and the down-stream recirculation through the fixed bed is essential for a good distribution. On the other hand, for the BSTR an extra outlet is located at the vessel shell at 200 mm height from the reactor bottom so that a retention volume of approximately 200 liters is provided. This was done as the bacteria in this type of reactors are suspended and need to settle down before pumping the effluent to the next process step to allow biomass retention. An axial flow field is implemented by stirring in the BSTR in order to guarantee homogenization of the medium and proper suspension of the bacteria during the degradation period. The BSTR is also designed with a recirculation circuit to enable an energetic comparison between mixing by stirrer and pumping. Especially for industrial scale it is very important to find an energy efficient solution for mixing.

Additionally, there is one buffer tank of 1000 liters capacity included to receive the untreated wastewater, facilitate the start-up phase of the three reactors, preheat the wastewater and buffer between the biological process and the post treatment. The tank is connected to the collector pipe after the pretreatment basins of the communal sewage plant which remove big particles from the wastewater.

Starting from the sampling point, one cubic meter per charge of fresh wastewater is pumped to the buffer tank in which it is heated to the process operating temperature (35°C). Afterwards, the wastewater is transferred to the first reactor (R1) where hydrolysis and acidogenesis take place. After six hours of retention time, the wastewater is transferred to the second reactor (R2) where acetogenesis and methanogenesis are carried out. This second-stage is the rate-limiting step with 12 hours of degradation time. Finally, the wastewater is pumped to the third reactor (R3) where the anammox process occurs. The complete layout of the plant is shown in Fig. 1.

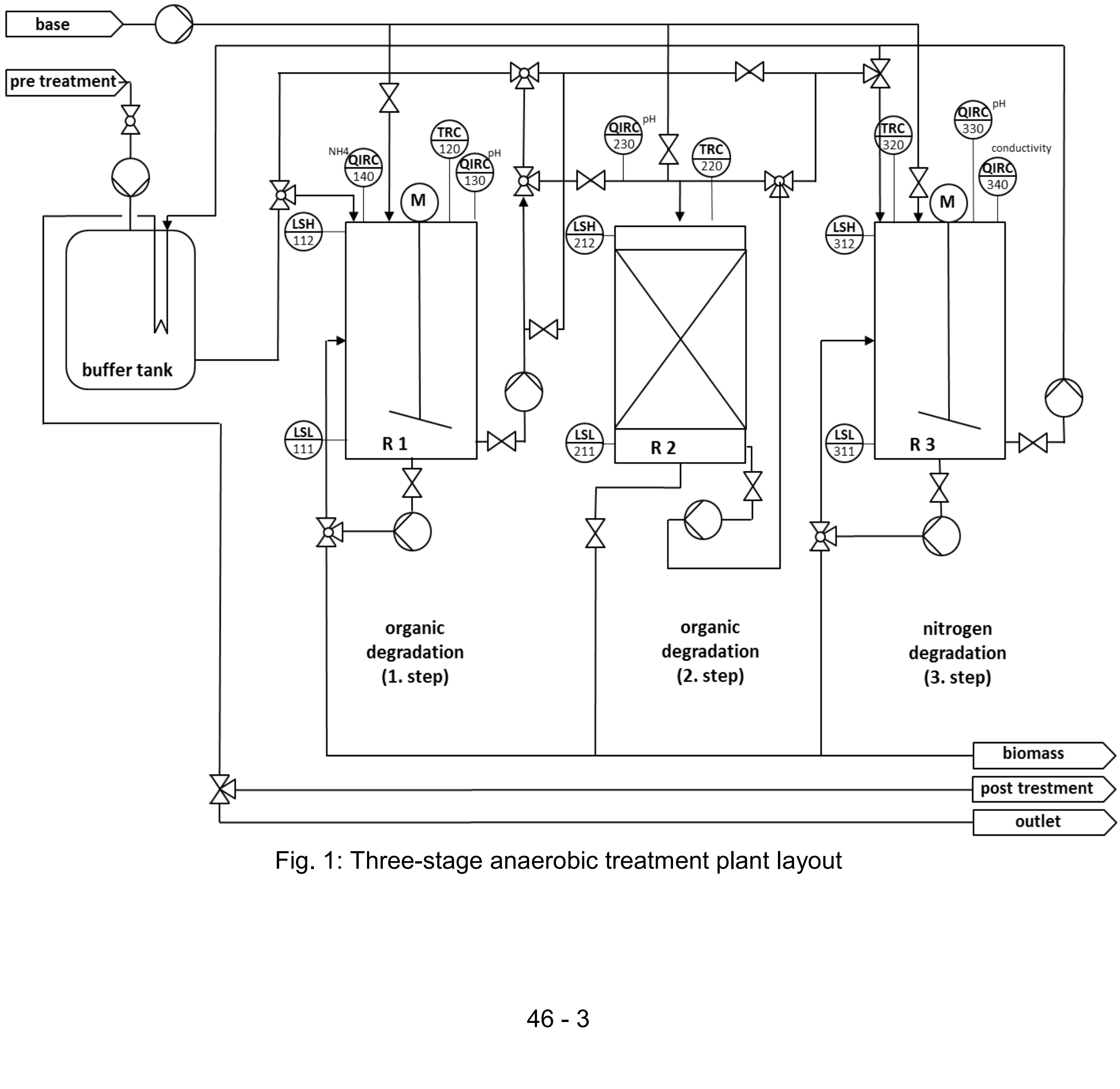

Fig. 1: Three-stage anaerobic treatment plant layout

Analytical process monitoring

In order to achieve a comprehensive collection of measurement data, different sensors are connected to the reactors according to their characteristics.

First, the fluid temperature inside the three reactors is monitored with a Pt100 SITRANS TH400 temperature sensor from Siemens AG, Munich, Germany. The temperature is regulated through a cascade control by means of an electrical heating cartrigdge in the vessels and heating wire system along the pipes. As mentioned before, the operating temperature is set to 35°C which means the plant is working under mesophilic conditions.

The pH is monitored in the three reactors with a pHD-S sc Digital Differential pH-sensor from Hach Lange GmbH, Düsseldorf, Germany. The pH of R1 and R2 is controlled through the dosage system with a PID-controller specially developed for the plant's concept (Benning et al., 2012). The set-point of R1, where acidogenesis takes place, is set to 5.5. The set-point of R2, where methanogenesis takes place, is set to 7.0. R3 does not require pH-control as the anammox process usually remains in the optimal range (approx. 7 – 8.0) unless an external influence is applied.

Additionally, R1 is equipped with an AN-ISE sc Combination Sensor for Ammonium and Nitrate from Hach Lange GmbH, Düsseldorf, Germany. Monitoring the ammonium concentration in R1 provides valuable information regarding this stage stability, especially during start-up.

Finally, chemical oxygen demand (COD) and total carbon measurements are performed with the analyzer QuickTOC® from LAR AG, Berlin, Germany. The COD is used in wastewater treatment as an indicator of the organic matter present in the wastewater. Therefore, monitoring the COD is essential to determine the effectiveness of the process. Particularly, most of the COD degradation occurs during methanogenesis in R2.

Monitoring the two-stage anaerobic digestion through mathematical simulation

A standalone program to simulate the two-stage anaerobic digestion of domestic wastewater was developed as first attempt to make complex mathematical modeling available in the daily operation of the decentralized treatment plant for control purposes. The program is able to reproduce the organic matter degradation throughout the two-stage process by simulating the COD.

The model used as basis for the implementation is the Anaerobic Digestion Model No.1 (ADM1) (Batstone et al., 2002). The ADM1 is a well-structured ordinary differential equations (ODE) model that describes the anaerobic digestion process through a set of biochemical and physicochemical processes. The biochemical processes considered are mainly catalyzed by intra- or extracellular enzymes produced by 7 different groups of microorganisms. These are sugar degraders, amino acid degraders, long chain fatty acid degraders, valerate and butyrate degraders, propionate degraders, acetate degraders and hydrogen degraders. On the other hand, the physicochemical processes are non-biological processes which include liquid-liquid reactions, such as NH_4^+/NH_3 and $CO_{2(aq)}/HCO_3^-$, and three gas-liquid transfer processes for CH_4, CO_2 and H_2.

Included in the program is also an interface method to calculate from the untreated wastewater the input variables required by the ADM1 using three monitoring parameters.

These parameters are COD, ammonium concentration and total inorganic carbon (TIC) measured from the influent domestic wastewater. The procedure followed is:

1) the influent COD is partitioned into the main reported components in domestic wastewater as 50% carbohydrates, 40% proteins and 10% lipids (Schlegel and Fuchs, 2007),
2) the ammonium is given as the initial ammonium concentration, and
3) the TIC is used to estimate the initial HCO_3^- concentration.

The ADM1 was initially implemented using the software MATLAB/Simulink and validated at laboratory scale in a previous study (Vega, 2014). Subsequently, the standalone program was developed using the Visual Studio 2010 Professional Software. Since the simulation covers one process cycle with each model run, the standalone implementation is suitable for plants already working with a stabilized biomass population. A comparison between the program output and the original model is shown in Fig. 2. Low mean absolute errors of 5.97×10^{-4} and 4.62×10^{-4} were found for the simulated COD in the first (R1) and second stage (R2) of the anaerobic digestion process respectively.

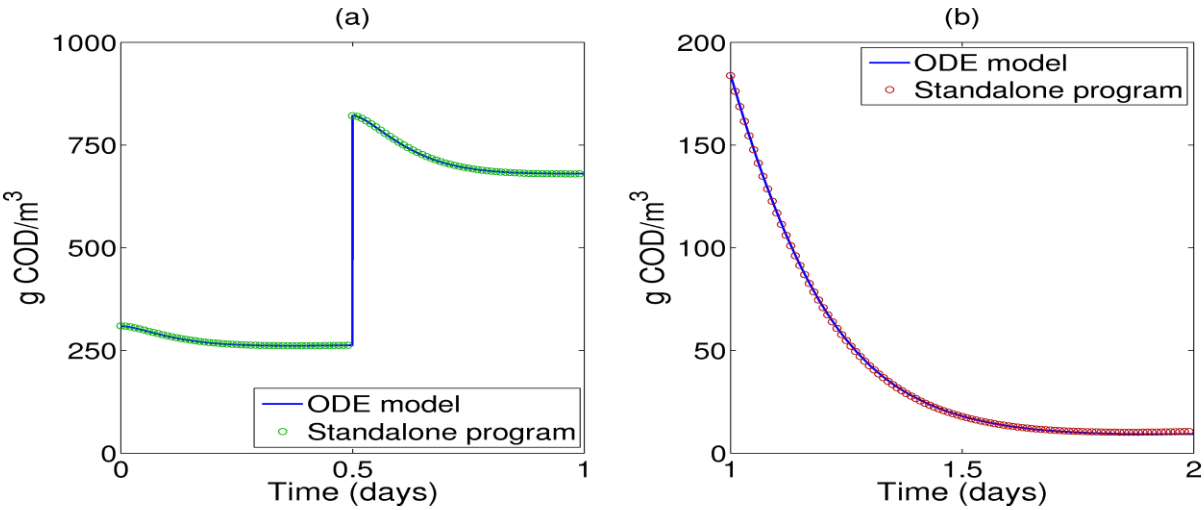

Fig. 2: Simulated COD degradation cycle during (a) the first-stage (R1) and (b) the second-stage (R2)

The developed application can be used without the need of specialized assistance or additional software in the automation system of the decentralized treatment plant. By periodically (e.g. once per week) recording the required input parameters, an integral view of the degradation process can be obtained beforehand. This allows determining the optimal hydraulic retention time at each stage of the process in order to optimize it according to the influent conditions.

Ammonium estimator for the anammox step from artificial neural networks

An ammonium estimator based on artificial neural networks (ANNs) was developed for control of the anammox step. The estimator requires as input the change in pH, calculated from online pH measurements, and the elapsed time. The network yields in return a normalized value for which the initial ammonium concentration is required to obtain the final output.

The successful implementation of ANN’s is restricted to the availability of sufficient and representative data to be used for training. Therefore, an alternative method that aimed to reduce the amount of experimental work required was proposed. The method consists in using a much smaller set of experimental data (than required by an ANN) to calibrate a comprehensive ODE model. Afterwards, the simulated ammonium concentration (broadened data set) is used as target data for training of the ANN. This increases the learning capacity of the network while reducing the amount of measurements needed.

The ODE model chosen to simulate the nitrogen removal processes taking place in the anammox reactor includes a two-step nitrification-denitrification model extended with the anammox process (Wyffels et al., 2004; Dapena-Mora et al., 2004). The model considers four types of microorganisms commonly present in autotrophic nitrogen removal reactors. These are ammonium oxidizers, nitrite oxidizers, anammox bacteria and heterotrophic bacteria. The software used for implementation was MATLAB/Simulink. The ODE model was calibrated in a previous study at laboratory scale (Vega, 2014).

On the other hand, the ANN included in the developed estimator corresponds to a multilayer feedforward neural network (Svozil et al., 1997) (1 hidden layer with 14 neurons and hyperbolic tangent activation) found in a previous study to yield the best performance after training (Vega, 2014). As exemplification, the results obtained without performing further training while applying fluctuating influent conditions are shown in Fig. 3.

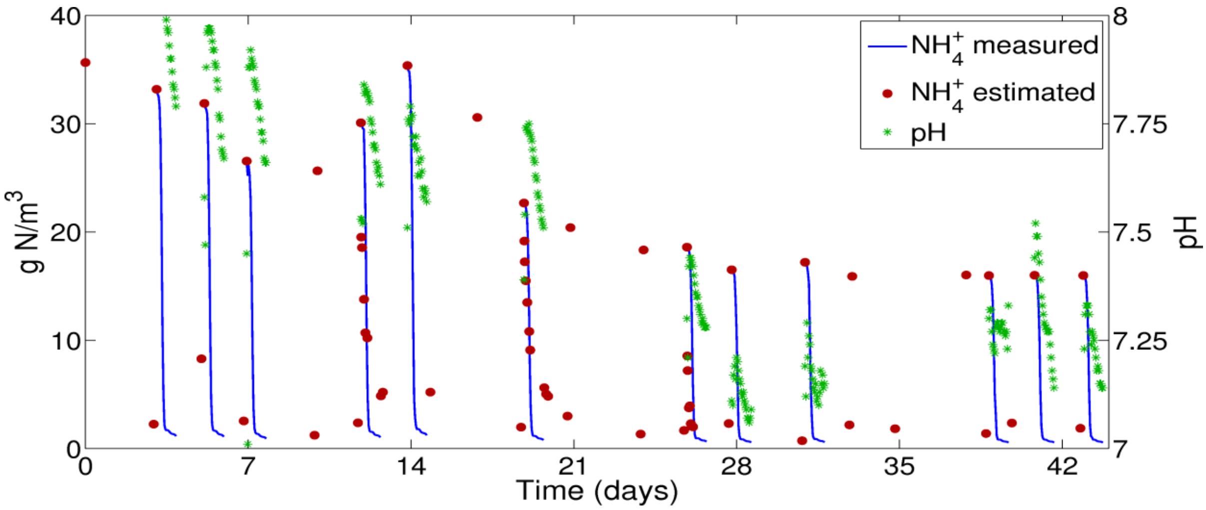

Fig. 3: Experimental and simulated ammonium removal with the online pH measurements.

The ammonium estimator will be implemented directly in the control system of the decentralized treatment plant to work as an online estimator. This makes possible the simulation in real time of the anammox process with the help of an online pH sensor. As in the case of the standalone program described in the previous section, the initial ammonium concentration required for the estimations can be periodically monitored from the untreated domestic wastewater composition. The estimator can then be used to determine the end point of the process to optimize its performance.

Conclusions and outlook

The setup for the decentralized three-stage anaerobic treatment plant has been realized combining in the design analytical monitoring with control tools developed to ensure a stable and optimized process.

The layout of the plant was carried out focusing on minimizing costs and space requirements. The sensors included for the analytical monitoring were chosen according to previous knowledge about the biochemical processes involved. The control tools (preliminary validated at laboratory scale) were developed following a method that reduces the amount of experimental work required. This was done for the purpose of allowing great reproducibility at larger scales.

Lastly, a complete outlook of the reactions taking place at each one of the three process stages can be obtained beforehand allowing the control and optimization of the treatment plant. The pilot-scale plant is now ready for start-up and further experiments will be performed to evaluate the efficiency of the developed concept.

Acknowledgment

The authors acknowledge gratefully the Hans-Sauer Foundation for financial support, the communal sewage plant in Erlangen, Germany, for the facilitates, as well as SIEMENS AG, Germany, Schraml GmbH, WEBFactory GmbH, ZWT Wasser- und Abwassertechnik GmbH, Maschinenbau Biermann GmbH, Albert Handtmann Armaturenfabrik GmbH & Co. KG and Norddeutsche Seekabelwerke GmbH for the support and equipment provided.

References

Batstone, D. J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V., Pavlostathis, S. G., Rozzi, A., Sanders, W. T. M., Siegrist, H., Vavilin, V. A., 2002: "Anaerobic digestion model no. 1", Scientific and Technical Report No. 13, IWA Publishing, London.

Benning, R., Delgado, A., Forstner, J., 2012. Controller unit (Reglereinheit). Patent DE 102011050266 A1.

Dapena-Mora, A., Van Hulle, S., Campos, J., Mendez, R., Vanrolleghem, P., Jetten, M., 2004: "Enrichment of anammox biomass from municipal activated sludge: experimental and modelling results", Journal of Chemical Technology and Biotechnology, Vol. 79, pp.1421-1428

Foresti, E., Zaiat, M., Vallero, M., 2006: "Anaerobic processes as the core technology for sustainable domestic wastewater treatment: Consolidated applications, new trends, perspectives, and challenges", Reviews in Environmental Science and Biotechnology, Vol. 5, pp. 3-19

Massoud, M. A., Tarhini, A., Nasr, J. A., 2009: "Decentralized approaches to wastewater treatment and management: Applicability in developing countries", Environmental Management, Vol. 90, pp. 652-659

Schlegel, H. G., Fuchs, G., 2007: "Allgemeine Mikrobiologie", 8th Edition, Georg Thieme Verlag, Stuttgart, p. 625

Strous, M., Heijnen, J., Kuenen, J., 1998: "The sequencing batch reactor as a powerful tool for the study of slowly growing anaerobic ammonium-oxidising microorganisms", Applied Microbiology and Biotechnology, Vol. 50, pp. 589-596

Svozil, D., Kvasnicka, V., Pospichal, J., 1997: "Introduction to multi-layer feed-forward neural networks", Chemometrics and Intelligent Laboratory Systems, Vol. 39, pp. 43-62

Vega, M., 2014: "Modeling, simulation and control of biotechnological processes in decentralized anaerobic treatment of domestic wastewater", Doctoral Dissertation in progress, Friedrich-Alexander University Erlangen-Nuremberg

Wyffels, S., Van Hulle, S., Boeckx, P., Volcke, E., Van Cleemput, O., Vanrolleghem, P., Verstraete, W., 2004: "Modeling and simulation of oxygen-limited partial nitritation in a membrane-assisted bioreactor (MBR)", Biotechnology and Bioengineering, Vol. 86, pp. 531-542