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ENERGY CONSERVATION IN WASTEWATER TREATMENT OPERATION

A case study at Himmerfjärden WWTP

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Abstract

Swedish wastewater treatment plants' energy usage equals a total of 0.6 TWh per year. Together with the Swedish drinking water treatment, the usage corresponds to approximately 1 % of the total electrical energy consumption in Sweden. Potentials for a reduction of this usage do exist. However, very modest efforts for energy usage conservation are attempted.

In a master thesis presented in 2006 by the authors of this article, the potential of energy conservation at Himmerfjärden WWTP was investigated. The thesis establishes a general methodology for performing an energy conservation project at any wastewater treatment plant. The methodology is then applied to the actual wastewater treatment plant, Himmerfjärden WWTP. Results when performing the energy conservation project and recommendations for future measures are presented.

The thesis clearly shows the existence of a potential for reducing energy usage in wastewater treatment operation, not necessarily implying a negative impact on the quality of the process.

Key words – Energy conservation; modelling; simulation; ASM1; energy balance

Introduction

The most important goal in wastewater treatment is to fulfil the demands stated by the government concerning the effluent water quality to ensure the environmental wellbeing. The second most important goal is to perform the required wastewater treatment as cost effective as possible; for the sake of the taxpayers as well as for the nature in form of reduced energy usage deriving from e.g. fossil fuel. Due to the fact that Sweden is becoming increasingly integrated with the rest of Europe and due to the now deregulated Swedish electricity market, the previously low Swedish electrical energy prices will most likely level out on a higher and more Europe-standard level. Naturally, this increases the financial benefits of reduced electrical costs even more in the future.

Swedish WWTPs use electricity corresponding to approximately 100 kWh per year and person equivalent, pe. This equals a total electricity consumption of 0.6 TWh per year. Together, the Swedish plants for wastewater and drinking water treatment corresponds to roughly 1 % of the total electricity consumption in Sweden (Wiberg 2006). Compared to German WWTPs, Swedish plants consume twice as much electricity per pe. Though the average German WWTP is larger than its Swedish equivalent, this indicates a great potential for a more effective electricity usage at Swedish WWTPs. Especially, considering official statements saying that German plants have a potential of reducing their electricity usage by 35 %. (Kjellén, Andersson 2002)

In a master thesis presented in 2006 by the authors of this article, the potential of energy conservation at Himmerfjärden WWTP was investigated. The main objective of the thesis is to present an energy management plan for Himmerfjärden WWTP. Facts, ideas and discussions presented should lead to a considerable energy conservation and thus, noticeable financial savings. A second objective is to present a general methodology of how to reduce the costs related to electrical usage at any WWTP. This methodology will then constitute the basis when performing the energy conservation project at Himmerfjärden WWTP.

The cost of the electrical use consists of different fees based on energy use and power demand respectively. Hence there are two main questions related to reducing the total electrical cost:

- Is it possible to reduce the cost associated with energy use?
- Is it possible to reduce the cost associated with the power demand?

Himmerfjärden WWTP

SYVAB is a municipal joint stock company with six municipal owners; Botkyrka, Huddinge, Salem, Stockholm, Nykvarn and Södertälje. SYVAB Himmerfjärden WWTP serves the main part of the population in Botkyrka, Salem, Nykvarn and Södertälje together with parts of Huddinge and Stockholm.

The Himmerfjärden treatment plant is located by the northern shores of Himmerfjärden, south of Stockholm, in Botkyrka municipality. A total of 250,000 persons are connected to the treatment plant. In addition to this, several industries are also connected to the WWTP, e.g. Tumba Bruk and Spendrups brewery, representing a load of 35,000 pe. Today the average influent flow to the treatment plant is 100,000 m^3 of wastewater per day, and the maximum flow that can be treated is 130,000 m^3 of wastewater per day.

The treatment plant was built during 1970–1973 and is a conventional Swedish WWTP with mechanical, chemical and biological treatment. Denitrification is performed by fluidised beds subsequent to the aeration basins. (SYVAB 2005)

Energy management plan

The first step when performing an energy conservation project is to develop an energy management plan. This does not have to be as complicated as it first may seem. A management plan can be set up fairly easily with five simple steps: collect data, analyse data, create a plan, implement the plan and evaluate the plan. The evaluation of a plan implementation should then lead back to the initiating step of data collection, making the whole energy management process highly iterative.

Energy basics

The rate structures applied to the specific customer have no direct effect on the electrical use. On the other hand, an understanding of the rate structure is essential in the pursuit for reduced electrical costs. There are many opportunities to save money just by understanding the rate structure on the current billing. Hence it is of great importance to have an understanding of the current agreement with the electric utility company. (Water Environment Federation 1997)

The billing for electric service can take many forms depending on the economic objectives and administrative concerns that are being addressed by the utility. WWTPs typically are subject to rather complex rate structures.

While it is of great importance to have an understanding of which parts in the wastewater treatment process that consume energy, it is difficult to present a general picture of how the energy utilization is divided at different WWTPs. Energy usage varies significantly depending on location, plant size, pollution level of the wastewater influent, type of treatment and mode of operation. Generally, plants with a more advanced treatment require larger amounts of energy. The major energy consumers at most WWTPs are pumps, blowers, mechanical aerators and solids-handling systems. (Water Environment Federation 1997)

Energy management at Himmerfjärden WWTP

At Himmerfjärden, as at most WWTPs, the electrical fees consist of a fixed customer charge, an energy charge and a power demand charge. The current power demand level at Himmerfjärden is set to 4.0 MW. The total cost for the power demand is 992,000 SEK/year. Concerning the energy cost the fee is approximately constant at 0.53 SEK/kWh. The total energy usage for Himmerfjärden WWTP for 2005 was approximately 23.43 GWh, resulting in a total electrical energy cost of 12.5 MSEK.

In accordance with the general methodology, a list of the most energy or power demanding equipment is required. Due to inadequate energy usage logging at Himmerfjärden WWTP, the list is based on the most power demanding equipment only.

The most interesting power consuming equipment from Table 1 was then thoroughly investigated.

Table 1. *Table of the most power consuming equipment at Himmerfjärden WWTP.*

Equipment	Power
Main pumps	6,015 kW
Aerating compressors	1,000 kW
Pumps, fluidised bed	200 kW
Water pump, sedimentation	180 kW
Centrifuges, sludge treatment	134 kW
Sludge recycling, aeration basin	132 kW
Tunnel fans	100 kW

Main pumps

The main pumps located at the inlet of the WWTP are accounted for a large part of the energy usage at Himmerfjärden. The inlet's location 54 meters below ground level causes a quite extreme situation where large volumes of water are elevated to ground level. To overcome the pressure difference, a total of 6,015 kW in pumping power is installed.

Since the influent water under all conditions must be elevated to ground level, no energy savings can be done in the process itself due to the laws of physics. Instead, the possible energy savings can be achieved by increasing the efficiency of the process. An investigation made by Vattenfall in June 1995 established that the pumping efficiency was good and that replacing the pumps would not result in an improved efficiency (Lundquist 1995). But since this investigation was performed more than ten years ago, it is strongly recommended that a new investigation concerning the main pump's efficiency should take place.

It is also of great importance that a maintenance program is implemented to make sure the pumping equipment is in the best possible condition. As a result of the large flows and the high elevation, even the slightest improvement in pumping efficiency would result in a rather large decrease in energy usage, and consequently reduced energy costs.

Aeration strategy

Second to the main pumps, the aeration is the most power demanding process at Himmerfjärden WWTP. The aeration at the WWTP is taken care of by four individually controllable 250 kW compressors, providing the aeration basins with air. The four compressors are all linked to the same aeration system, which is connected to all of the eight parallel aeration basins. Individual control of the basins is taken care of by an adjustable valve located at the inlet of each basin's aerating system. By changing the valve's opening angle, it is possible to control the amount of air supplied by the compressors. Each basin can hence be individually controlled.

The average total aeration power at Himmerfjärden WWTP during 2005 was 650 kW. This gives an annual total energy usage of approximately 5.7 GWh and hence an energy cost of roughly 3 MSEK per year. Considering the large costs involved in the aeration process, it is important that attempts to optimise the process as far as possible are made.

At present, the control of the aeration is based on oxygen concentration levels measured by a sensor located 15 meters from the end in each one of the eight 96 metres long aeration basins. By controlling in this manner, no consideration is taken of the relative differences in oxygen level inside the basin. The need for differences in oxygen input in the different parts of the basin is instead taken care of by a change in density of the aerators. Each basin is divided into six zones, with a difference in density of the aerators, which was calculated when designing the WWTP. Hence there are no possibilities of controlling the oxygen input individually in the different zones.

Since the aeration system is a complex process, optimizing the dissolved oxygen control is far from an easy task. Nevertheless, it is possible to achieve an understanding whether a change in control strategy is beneficial or not. As always, when discussing optimization of any process, one has to be aware of not only the possible economical profits gained by a change in strategy, but also the consequences in the process quality itself. This is also the case when trying to optimize the aeration process, where it is important to balance process cost against process quality.

The question as to what extent the effluent quality may be affected by minimising the treatment process cost should be discussed in every unique case. At Himmerfjärden WWTP, the total nitrogen in the effluent is set in accordance with governmental regulations at a maximum of 10 mg/l. No demand for the ammonium level is set, but a maximum ammonium concentration of 2 mg/l is preferred.

Currently an oxygen concentration of 3.5–4 mg/l is set. The rate can be considered to be high, but can be justified by the relatively short process time. At Himmerfjärden WWTP, the water passes the aeration basin in a total of approximately four hours. This can be compared to the average aeration process time at most WWTPs of approximately ten to twelve hours. Nevertheless, there is still a capacity for a change in the oxygen level and hence a potential for a more efficient aeration process.

By measuring the oxygen levels in the different zones and averaging the values, an oxygen profile is received.

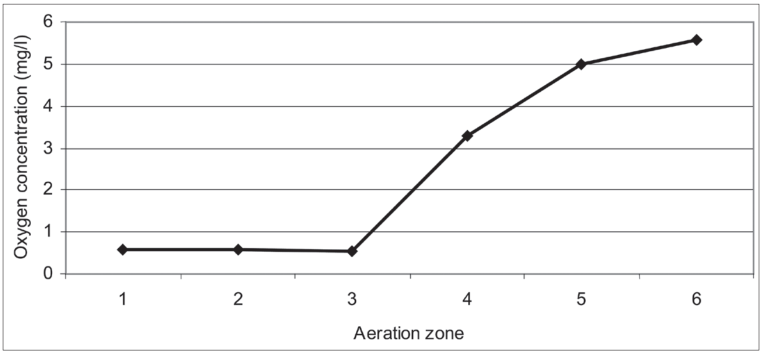

Figure 1. *Average oxygen concentration in the aeration basins based on manual measurements made at Himmerfjärden WWTP in January 2006. The aeration zones represent the six zones in the basins with different aerator density. The oxygen sensors are located in zone 5.*

Measurements made in January 2006 gave the profile shown in Figure 1.

The oxygen profile indicates that there are distinct differences in measured oxygen concentration between the first three zones and the last three zones of the aeration basins. This can be explained by the design of the aeration basins. The basins are shaped as a 'U', with a fall shaft in the turn between zone three and four, preventing the water in the second part to return to the first part. The constant level of oxygen in the first half and the rapid increase in the second half is a consequence of the fact that the basins are submitted to constant mixing. Turbulence in the basins, caused by the aerating process, levels out the oxygen concentrations in the two halves.

By studying the oxygen concentration profile in Figure 1 another conclusion can be made. When the oxygen measurements were made, a set point of 3.5 mg/l was set. Now looking at the oxygen profile chart at zone five where the oxygen sensors are installed, the manual measurements showed an average oxygen concentration of 5.0 mg/l. Given the complex nature of the process, this can of course be the result of many factors, but most likely because of poorly working oxygen sensors. This explanation is confirmed by the fact that the control system in this specific case actually did measure a value of approximately 4.0 mg/l. Insufficient maintenance of the sensors in form of calibration and cleaning might be the reason for this difference. Hence it is of great importance that a proper maintenance program is applied to make sure the equipment is in good condition to avoid excessive aeration. Regular maintenance would secure a condition where process engineers can obtain a better view and better control abilities of the current process state.

Furthermore, the low oxygen level in the first part of the aeration basin can cause problems in the nitrification process. Constant low levels of oxygen can stimulate growth of a certain type of filamentous bacteria (Jenkins et al. 2003). The shape of these bacteria causes development of a bulking sludge, which may cause problems in the treatment process. Additionally, this problem may be further enhanced by the relatively low COD load to the plant. A low COD load results in a low F/M (food to micro-organisms) ratio, which in combination with low oxygen concentration have been reported as a possible cause for sludge bulking.

Considering the ammonium profile for the aeration basins presented in Figure 2, based on measurements performed in March 2003, another explanation of the increase in oxygen concentration in the second half can be found. When reaching the last zone of the aeration

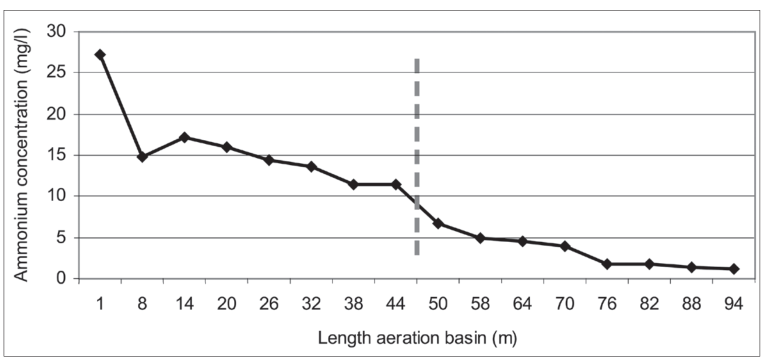

Figure 2. *Ammonium concentration profile in the aeration basin based on measurements performed by SYVAB in 2003. The striped line represents the position of the fall shaft in the middle of the basin.*

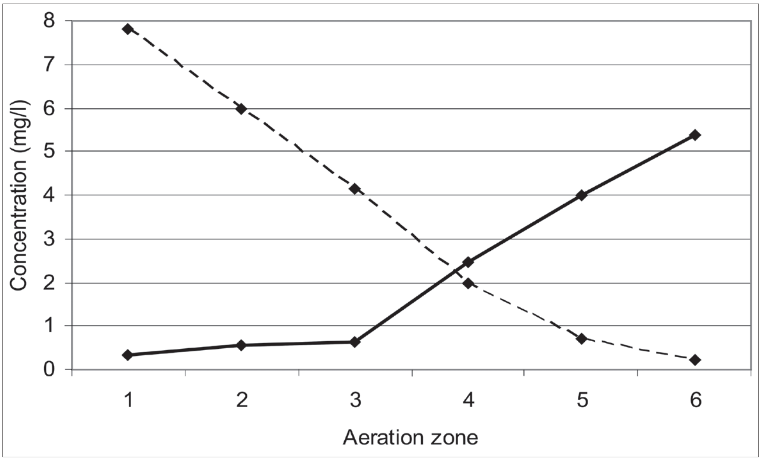

Figure 3. *Oxygen concentration (continuous line) and ammonium concentration (striped line) achieved by simulation in Matlab/Simulink when controlling with only one oxygen sensor in zone 5.*

basin, the ammonium concentration is low, and almost no nitrification occurs. Since low amounts of oxygen are consumed, the oxygen concentration increases rapidly.

The facts discussed above suggest that a different strategy should be used when controlling the aeration process. Due to the large differences in oxygen concentration between the two parts of the aeration basin, only small possibilities are given to the process engineer to actually control the nitrification and the oxygen distribution only by measuring at one location in the basin. A more flexible approach would be to install another oxygen sensor in the first part of the aeration basin. By controlling the different parts individually, an ability to control the oxygen levels for the two parts is given. This would not only result in better conditions for controlling the process, but also better abilities for a more efficient energy usage.

Evaluation by computer simulation

An effective and rather inexpensive tool when evaluating a suggested strategy change is a computer model. Developing a computer model can be considered as being quite a difficult and time-consuming task, but once the model is working it is a useful tool. In this thesis, a model developed by a Task Group (Henze et al. 2000) for the International Water Association, IWA, has been used in the environment Matlab/Simulink. The name of the existing model is the Activated Sludge Model No. 1, ASM1. The model has been modified and calibrated to fit the conditions at Himmerfjärden WWTP.

By comparing the measurements of the oxygen concentrations and the ammonium concentrations in the aeration basins at Himmerfjärden WWTP with the results achieved when running simulations in Matlab/Simulink, the model behaviour can be evaluated. As shown in Figure 3, the result of the simulations is similar to the real situation. A constant level of oxygen in the first half of the basin is followed by a linear increase. However, a limitation when using the model is the nitrification process behaviour. The model has some difficulties to simulate the actual nitrification process, and tends to exaggerate the process speed. But since the different simulations always are compared by the relative nitrification result, no consideration has to be taken to the absolute nitrification result.

Following the discussion presented earlier, installing a second oxygen sensor in the first part of the aeration basins will improve the controllability and the process behaviour. Simulations in Matlab/Simulink verify this. By comparing this strategy with the control strategy applied today, a more even distribution of the oxygen concentration is achieved, and hence excessive aeration in the latter zones can be avoided. Results are displayed in Figure 4.

While still achieving the same nitrification result, a control strategy with two oxygen sensors would result in an aeration energy reduction of 15 %. With the current energy price applied at Himmerfjärden WWTP, an annual saving of 450,000 SEK would be achieved.

Energy balance

In addition to process optimisation, the usage of internally generated energy should be investigated. At Himmerfjärden WWTP today, approximately 40 % of the produced digester gas is combusted in a torch. This, of course, is a large waste of energy which could be utilised for more cost effective purposes. By developing an energy balance simulator, different strategies for internal heat energy and digester gas usage could be evaluated. The energy balance simulator gives the user the possibil-

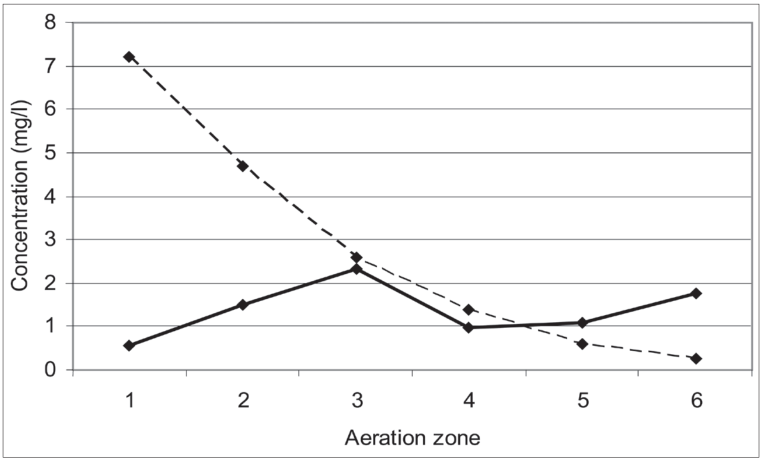

Figure 4. *Oxygen concentration (continuous line) and ammonium concentration (striped line) achieved by simulations in Matlab/Simulink when controlling with two oxygen sensors located in zone 2 and in zone 5.*

ity to change and evaluate different operation strategies for the WWTP. Offering instant feedback with both economical and energy related results, the energy balance simulator is a useful tool.

The results archived when running simulations with the energy balance simulator suggests an optimal operation strategy involving combustion of digester gas in a motor for replacing a part of the electrical drive of the aerating compressors. By offering the possibility to change motor power and efficiency in the energy balance simulator, an optimal motor size can be established. Furthermore, sale of excess digester gas for upgrade to vehicle fuel, and installation of heat pumps would result in a more optimal energy balance. At Himmerfjärden WWTP, an optimisation of the usage of internally generated energy would imply a considerably better energy situation, resulting in economical savings of 3–5 MSEK annually.

Summary of results

One of the most significant results from the energy conservation project is the low efficiency of the current operation of the aerating compressors in the biological treatment process. By rather simple and low-cost measures, a control strategy involving two oxygen sensors in each basin instead of one could be implemented. Running computer simulations in Matlab/Simulink showed an energy usage reduction of 15 % by controlling in this manner. With today's energy price, this corresponds to an annual cost reduction of 450,000 SEK. In addition to a more efficient energy usage, more suitable conditions for the microorganisms would be achieved due to a more even oxygen distribution, resulting in an increased sludge quality.

Furthermore, the analysis of the fluidised beds indicated a potential in operative change resulting in a more energy efficient process. Since there is a rather large overcapacity in the operation of the fluidised beds, a shutdown of one of the four beds would be possible. Calculations showed that a shutdown during eight months per year would be possible, without exceeding the demands stated regarding the annual average total nitrogen effluent. This would result in an annual energy usage reduction of approximately 292 MWh, i.e. 155,000 SEK with the current energy price. Furthermore, the action would result in a decreased need for an organic source corresponding to 1,110 kg/day. The annual saving due to this would correspond to 1.1 MSEK/year.

A reduction of the power demand may be possible, resulting in a decreased power demand cost. Usage of a power demand safeguard would secure the power demand being kept below the limit. A suggested new power demand limit when using a power safeguard is 3.5 MW, resulting in a lowered power demand cost of 124,000 SEK/year. However, the cost reduction should be put in relation with the possible negative process consequences and the investment costs involved.

Development and implementation of a maintenance plan would secure a situation where the processes involved in the treatment operation are working in an adequate manner. Regular maintenance of electrical motors, pumps, sensors and other equipment is essential for making sure no excessive energy usage occurs due to wear or poor calibration.

However, the most evident result achieved when conducting the energy conservation project was the inefficient usage of the internally produced energy, mainly digester gas and heat energy from the waste water. By changing the operation of the WWTP for better usage of this energy, large financial savings can be made.

General conclusion

A very important objective of this master thesis is that it should work as an eye-opener. Excessive energy usage due to inefficient treatment methods and a somewhat old-fashioned way to look at the energy aspect is a problem when dealing with today's energy situation. Energy is no longer a product that can be spent lavishly without circumspection, but should be considered as a product acting as a load, both from an economical and an environmental point of view. Hence, conducting an energy conservation project is not only essential because of the obvious economical advantages it may entail, but also because of the environmental issues. Potentials for a more energy efficient wastewater treatment definitely exist, and should thus be aimed at.

The master thesis can be downloaded from Internet at: http://www.iea.lth.se/publications/MS-Theses/5215_full_document.pdf

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