Computer optimization of the performance of an anaerobic filter used for purification of highly polluted wastewater from a sugar refinery

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Summary. An anaerobic filter system with a volume of 11 l fed with wastewater from the Swiss sugar refinery in Frauenfeld was established on a laboratory scale. It provided a filter performance of over 8 kg COD $\cdot$ m^{-3} $\cdot$ d^{-1} with an efficiency of at least 70%. A 600-l pilot plant system in the factory gave a degradation efficiency of 70% when fed with 28 kg COD $\cdot$ m^{-3} $\cdot$ d^{-1} and yielded 0.34 m^3 methane/kg COD, demonstrating that the scaling-up of the anaerobic filter had been successful. The rapidly-varying concentrations of organic materials in the wastewater required the constant control of the wastewater flow to the system. A control program was developed for a small computer using an empirical model simulating the operator. By varying the influx rate of the wastewater to the anaerobic filter the computer kept the system at an optimal organic load. The results obtained were equivalent to those obtained by permanent control of the system by an operator.

Key words. Anaerobic filter; computer control; optimization; sugar refinery.

Introduction

Since the end of the last century, when the first large-scale biogas producing tank was constructed for sludge treatment in the English town of Exeter, the technology of wastewater and sludge treatment has achieved a sophisticated standard whereby wastewater treatment plants can operate practically without any supply of external energy[4, 7]. In contrast, anaerobic treatment of organic wastes other than municipal wastewater, e.g. in the food industry, has not attained a wide distribution, due to the low cost of primary energy, high investment costs, and problems with process stability[8].

Our knowledge of the interactions between microbes during anaerobic degradation of organic substances has increased greatly during the past decade, and many new methanogens have been described and biochemically characterized, which is an absolute prerequisite for the control and optimization of the process of anaerobic degradation.

A key factor in continuous processes with methanogens is their slow growth with the consequence that they tend to be washed out. Since population density and activity determine to a large extent both the yield of methane and the simultaneous reduction in organic materials in the wastewater, various systems have been developed to reduce the loss of biomass during the process, such as the upflow anaerobic sludge bed reactor[6], the stationary fixed film reactor[11], the fluidized bed reactor[5] or the anaerobic filter[12]. In the latter the reactor is filled with solid support material which allows the bacteria to form stable biofilms and furthermore increases the separation of the gases formed from the waste water. Anaerobic filters are well suited for wastewaters rich in soluble organic material and a low content of solid materials and particles. So far only few commercial plants are in operation and research concentrates mainly on new support materials for the microorganisms.

A sugar refinery, such as the one in Frauenfeld, Switzerland, produces daily over 100 000 l of highly polluted wastewater with a COD of up to 30 g/l; an organic load which cannot be treated by the communal wastewater treatment plant. At present the wastewater is fed into a pond where the organic material is degraded and mineralized during several months. Later, the partially degraded wastewater is transferred in portions to the communal wastewater treatment plant. Calculations suggest that the energy content of the wastewater of the sugar refinery could supply up to 5% of the process energy of the plant if the raw wastewater were to be treated by an efficient anaerobic digestion for methane production instead of being digested in this open air pond.

The goal of the present work was to improve the laboratory-scale anaerobic filter described earlier[9, 10], to scale it up to pilot plant size, and especially to establish a method for computer-control of the process, where the rate of inflow of variably loaded wastewater could be determined from on-line data such as pH, gas production and gas composition.

Materials and methods

The wastewater was obtained from the sugar refinery in Frauenfeld. For the laboratory experiments the material was kept in the cold room until use. The pilot plant anaerobic filter was situated in the sugar refinery and directly connected to the wastewater system of the factory.

Chemical analysis gave the following major elements (concentration given in mg/l): Na (510), Ca (336), Fe (103), P (66), K (65), Mg (29), Si (8.9), S (7.4), Mn (4.5), Al (3.6) and traces (less than 1 mg/l) of Zn, Pb, B, Sn and Ni. Other elements were present in concentrations less than 0.05 mg/l. Total N during the sugar beet harvest 1983 averaged 110 mg/l, total carbon 4.6 g/l, giving a COD of 7.6 g/l.

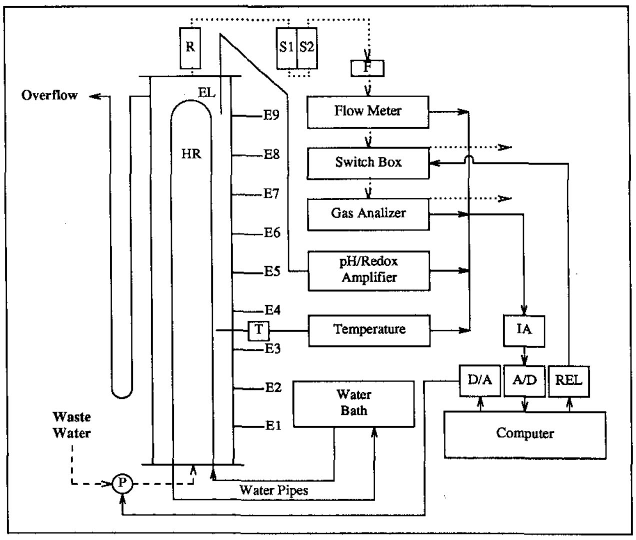

Figure 1. Scheme of the laboratory system of the anaerobic filter with the controls for collecting the input parameters necessary for the optimization procedure.
A/D, analog-digital converter; D/A, digital-analog converter; E1 to E9, valves for sampling; EL, combined pH and redox-electrode; F, hydrophobic membrane filter; HT, heating tube; IA, input amplifier; P, pump for substrate addition, controlled by the computer; R, reflux cooling system; REL, relais board; S1, drying tube with $Fe_2O_3 \cdot n\,H_2O$; S2, drying tube with $CaCl_2$ and silica gel; T, thermosensor (Pt 100).

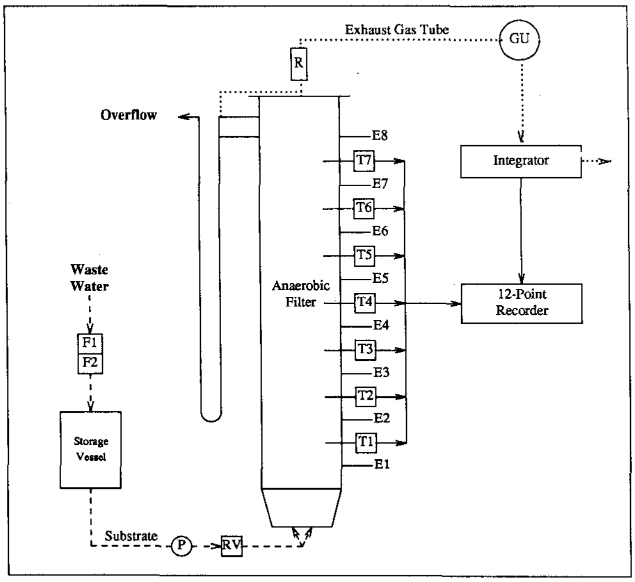

Figure 2. Scheme of the 680-l pilot plant in the sugar refinery.
E1 to E8, valves for sampling; F1 and F2, filters; GU, gas meter; P, pump; R, reflux cooling system; RV, valve to prevent back flow; T1 to T7 thermosensors (Pt 100).

The inoculation material for the anaerobic filter was obtained from digested sludge of the wastewater treatment plant in Zumikon (Switzerland).

The original laboratory scale anaerobic filter[9, 10] was slightly modified to provide better temperature control. The pH and the redox potential were measured continuously at the outlet. Gas flow was determined with a Tylan mass flow meter after drying the gas with $CaCl_2$ and silica gel and elimination of the hydrogen sulfide by absorption on solid iron hydroxide. The whole system is described in figure 1.

The pilot plant fermenter was a steel cylinder of 48 cm in diameter and 380 cm in height. Seven glass-covered holes situated along the cylinder made it possible to observe the flow of the wastewater through the filter and to take solid samples at different sites, and through eight mobile tubes liquid could be removed between the wall and the center of the filter. The temperature was measured along the axis at 7 sites by Pt100 sensors. Gas formed left the anaerobic filter at the top; its volume was measured by a gas meter after it had passed through a reflux cooling system to remove the water. The filter was fed from the bottom by a peristaltic pump (Watson-Marlow 601), as given in figure 2. Both the laboratory and the pilot-plant anaerobic filters were filled with spheres of porous clay of a diameter of 5–10 mm and 10–20 mm, respectively.

Analysis of the gas formed was performed either manually on a Carle 111 gas chromatograph equipped with either a MS5A or CSS column (Supelco), or automatically on a GOW-MAC gas chromatograph with a timer-controlled pneumatic injection loop on a Carbosieve B120/140 column. Methane was determined continuously with an IR gas analyzer (Horiba). Volatile fatty acids were determined from 1-ml samples after drying with 50 µl 1 N NaOH and solubilization in formic acid by gas chromatography (Shimadzu GC-7) on 60/80 Carbopac C, 0.3 % Carbowax 20 M, 0.1 % phosphoric acid column (Supelco) with He as carrier gas.

Hardware

The measuring and control system was based on a VME-bus computer unit equipped with the following boards:

- VEX-111 CPU (Eltec, Mainz, FRG) with the 68000 microprocessor from Motorola, 2 MB of memory and 8 V24 serial interfaces.
- A/D converter board MPV 901 (Burr Brown Ltd., Livingstone, Scotland) with 32 single-ended channels and 12 bit resolution.
- D/A converter board MPV 904 (Burr Brown Ltd.) with 15 output channels (0–10 V) and 12 bit resolution.
- Digital output board TSVME 401 (Thomson Semiconducteurs, Velizy, F) with 32 real outputs.
- Graphic controller Graz3 (Eltec) with a resolution of 5.12×256 pixels.

Additionally all signals from the different probes and analytical devices to the computer system were galvanically separated with buffer amplifiers.

Operating system

The VME-bus system was running with the OS9-68K, a real time, multi-tasking and multi-user operating system (Microware, Des Moines, Ill., USA).

Software
The basic software package used for the data collection, setpoint control and data analysis was the PCS 68 000 (developed by K. Schneider). This extremely versatile program includes a large number of interface functions allowing a controlled access to all internal data of the PCS 68 000. The whole of the software was written in C.

Results and discussion

Experiments on the laboratory scale

For comparison with the performance of the anaerobic filter the results from a homogeneously mixed fermentor of similar size are given in figure 3. With a hydraulic retention time of 120 h at a load of 1.5 kg COD $\cdot$ $m^{-3} \cdot d^{-1}$ a methane production of 0.92 m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$ was achieved. The retention time could be reduced to 57 h, which resulted in a load of 3.6 kg COD $\cdot$ $m^{-3} \cdot d^{-1}$ and a methane production of 1.61 m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$. When the retention time was reduced further, to 43 and 34 h, the specific methane production dropped and the whole fermentor became acidified due to accumulation of lower fatty acids. With a 43-h retention time butyric acid was found in the efflux, whereas with 34 h high concentrations of acetic and propionic acids were detected (50–60% of influx value). When the retention time was changed from 43 to 34 h the reduction of the COD dropped from 74 to only 9%.

In a similar experiment with the laboratory scale anaerobic filter (fig. 4) the results were completely different. A reduction in retention time down to 22 h, leading to a load of 8.9 kg COD $\cdot$ $m^{-3} \cdot d^{-1}$, resulted in a continuous increase in methane production up to 4 m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$. The reduction in COD was still 68% compared to 80% at the retention time of 44 h. Twice-concentrated wastewater at a retention time of 45 h and a load of 8.4 kg COD $\cdot$ $m^{-3} \cdot d^{-1}$ resulted in a methane production of 4.3 m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$ and a COD reduction of 71%. The concentrations of free fatty acids remained low at all retention times tested (around 1% of the influx concentration).

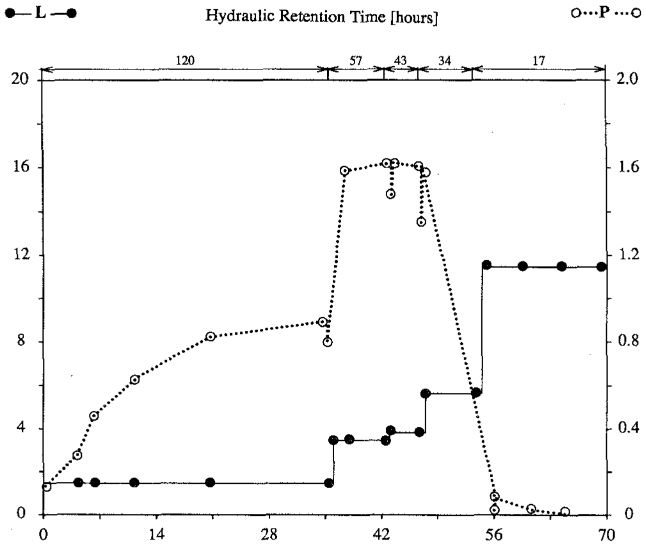

Figure 3. Time course of load L (kg COD $\cdot$ $m^{-3} \cdot d^{-1}$) and specific methane production rate P (m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$) in a homogeneously stirred laboratory fermentor as a function of time and hydraulic retention time.

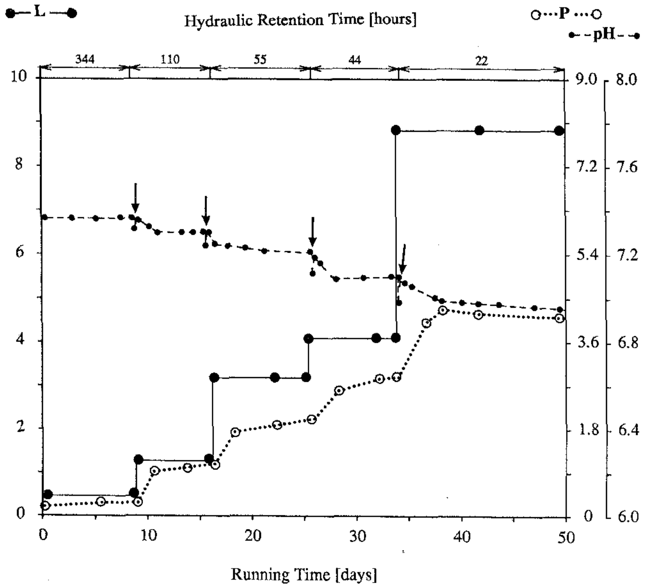

Figure 4. Time course of load L (kg COD $\cdot$ $m^{-3} \cdot d^{-1}$), specific methane production rate P (m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$) and pH in the laboratory anaerobic filter as a function of time and hydraulic retention time.

In the homogeneously mixed fermentor COD reductions of more than 70% were only achieved with retention times of more than 40 h. This agrees with the retention times of large plants, e.g., for the Anamet process a minimal retention time of 48 h is a prerequisite[2]. When the retention time drops to less than 40 h, biomass – in particular the methanogenic organisms – is washed out; this results in a smaller COD decrease and a lower specific methane formation rate.

It is clear that the anaerobic filter is much more stable towards changes in load and reduction of retention time than the homogeneously mixed fermentor, and retention times as low as 22 h gave still a COD reduction of about 70% with the anaerobic filter. However, a remarkable difference between measured and calculated retention time was observed, especially at low flow rates, indicating that the substrate does not flow homogeneously through the packing material but prefers channels and pores, as earlier described by Genung[3]. In a system in which the pH was not controlled the minimal retention time could not be determined owing to the fact that massive acidification led to an inhibition of the methanogenic organisms; however, with pH control and diluted substrate the retention time could be lowered even to 10 h without reaching the critical dilution rate where the organisms are washed out from the filter.

Experiments on the pilot plant scale

Experiments with the pilot plant size anaerobic fermentor in the sugar refinery plant at Frauenfeld during the harvesting periods in 1981, 1982 and 1983 yielded results for the performance of the pilot plant system similar to those for the laboratory system. Technical problems occurred frequently, e.g. increase of pressure due to clogging of the filter material. Special care had to be taken to prevent small particles being present in the filter material. Figure 5 shows the successful full-time performance of the system 1983. After a first phase in which a specific bacterial population was allowed to develop, a retention time of 23 h and later one of 17 h could be reached. Even with a filter load of 20 kg COD $\cdot$ $m^{-3} \cdot d^{-1}$ the COD reduction was as high as 73% and the specific rate of methane production reached 10.9 m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$. The profile of the volatile fatty acids demonstrates that at 23-h retention time with a high load the main COD reduction occurs mostly in the lower part of the filter which demonstrates the stability of the anaerobic filter. The results show that scaling-up by a factor of 60 can be easily achieved. Problems which occurred were mostly of a technical nature, and concerned especially the filling of the filter with carrier materials and the inoculation procedure. Spheres of porous clay could not be used to lower the retention time to less than 17 h owing to the limited surface available for biofilm formation. With better filter support materials the filter load could possibly be increased from the observed 30 up to 100 kg COD $\cdot$ $m^{-3} \cdot d^{-1}$ as previously demonstrated by Aivasidis[1].

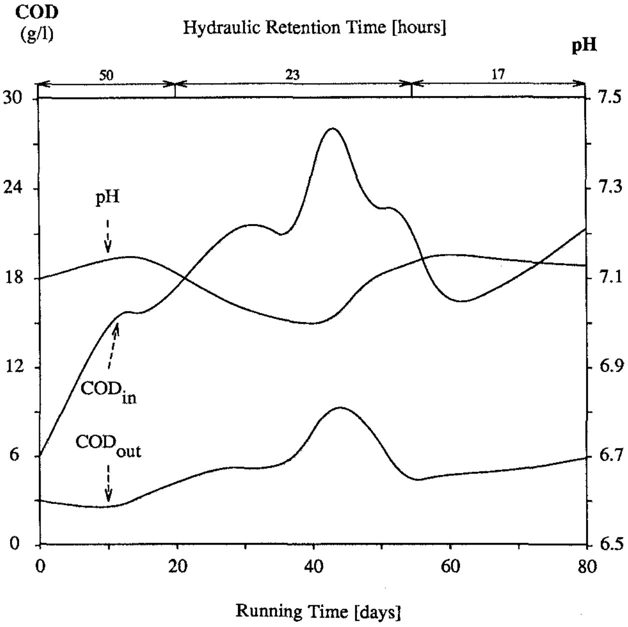

Figure 5. Time course of COD ($g \cdot l^{-1}$) in influx (COD_{in}) and efflux (COD_{out}) and pH of the pilot plant anaerobic filter as a function of time and hydraulic retention time.

Process optimization with a computer

For the optimization program a skilled operator was simulated, who adjusted the load of the filter by regulating the flow rate of the wastewater feeding on the basis of his knowledge of the processes going on in the filter. The experiments were performed with the laboratory scale filter. As input parameters the pH at the outlet, the rate of gas formation and the concentration of methane in the gas were measured on-line. Mean values of these inputs were calculated, and a graphics program produced all desired values on a color screen.

The flow diagram gives the details of the optimization program (fig. 6). The leading parameter used for the optimization program was the pH value, thus a careful analysis of the signal behavior over a long period and under different organic loads was a prerequisite for successful control. The pH value of the input (pH_{act}) was continuously compared with a critical pH given by the user (pH_{crit}). For safety, the substrate pump stopped when the pH_{act} dropped below pH_{crit} and restarted only after the pH had been restored (pH_{rest}). Since such breaks were only allowed in emergency cases pH changes had to be detected as early as possible. When the pH dropped at a rate greater than a defined critical value (δpH_{crit}) the pump rate was reduced by a value δP_2. This correction factor $\delta P_1 - \delta P_6$ was, furthermore, dependent on changes in the concentration of the methane (ΔCH_4 conc) and the methane flow (ΔCH_4 flow). Time intervals ($\delta_{T..}$) for time-dependent parameters could be determined by the user.

The main problem was the slow mixing of the liquid in the filter, leading to significant time delays between changes within the active volume of the filter and in the supernatant where the measuring probe was located. In addition the experiments showed that a frequent calibration of the pH probe (every 70–80 h) was a prerequisite for guaranteeing a fast and accurate response of the electrode. In a set of experiments all control parameters were adjusted to their optimal values such as critical pH value, critical pH change rate, control interval and changes in pump performance.

The continuous recording of the pH value in the upper reservoir of the filter is given in figure 7. The noise observed allowed only changes greater than 0.03 pH units to be used for calculations. A recalibration of the electrode every 70–80 h was necessary for an optimal regulation of the process. From an experiment similar to the one depicted in figure 4 the kinetics of the pH changes induced by switching the pump on and off were determined and used for the calculation of the time factor (T_{sleep}).

Figure 8 shows a typical filter start-up and performance over 155 h. The wastewater had an initial COD value of 7400 mg/l. The initial retention time was set to 110 h. In the following 140 h the optimization program decreased the retention time to 26 h. The COD value of the substrate was then changed to 8200 mg/l with glucose

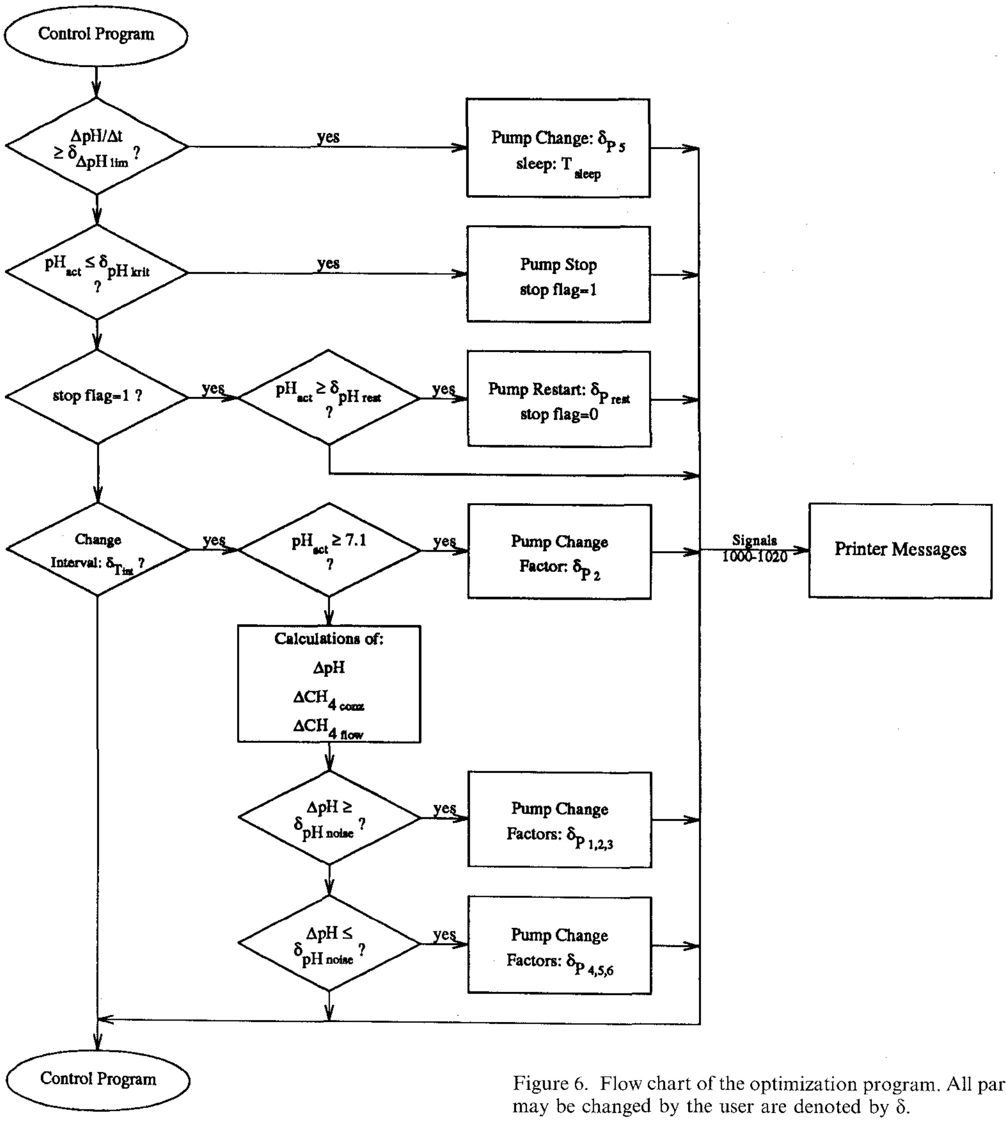

Figure 6. Flow chart of the optimization program. All parameters which may be changed by the user are denoted by δ.

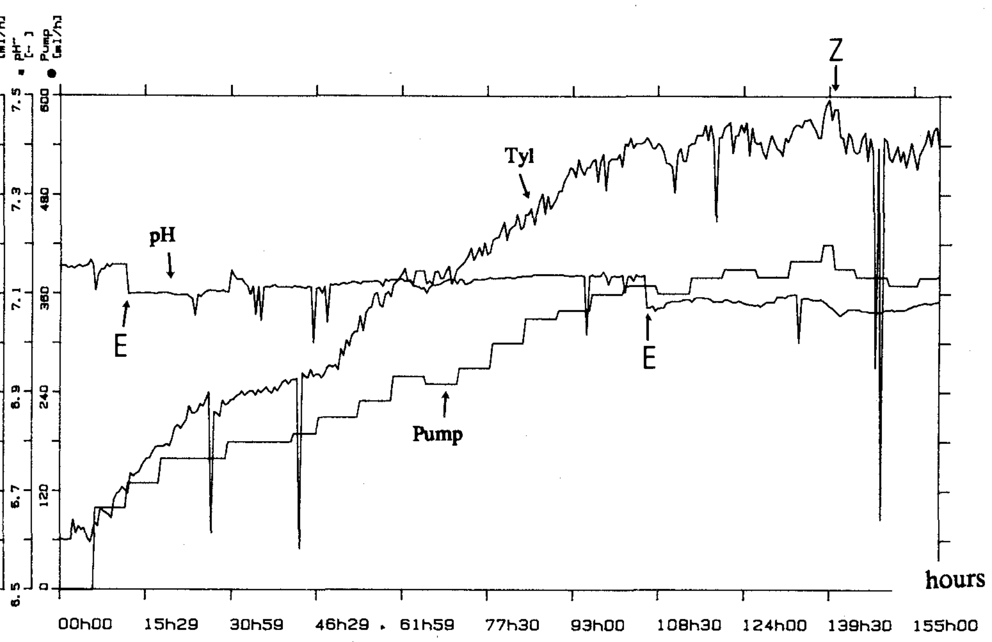

Figure 7. Time course of the actual pH signal. The load was 0.7 kg COD $\cdot$ m^{-3} $\cdot$ d^{-1}, the methane production 0.41 m^3 CH_4 $\cdot$ m^{-3} $\cdot$ d^{-1} and the dilution rate D 0.0045 h^{-1}.

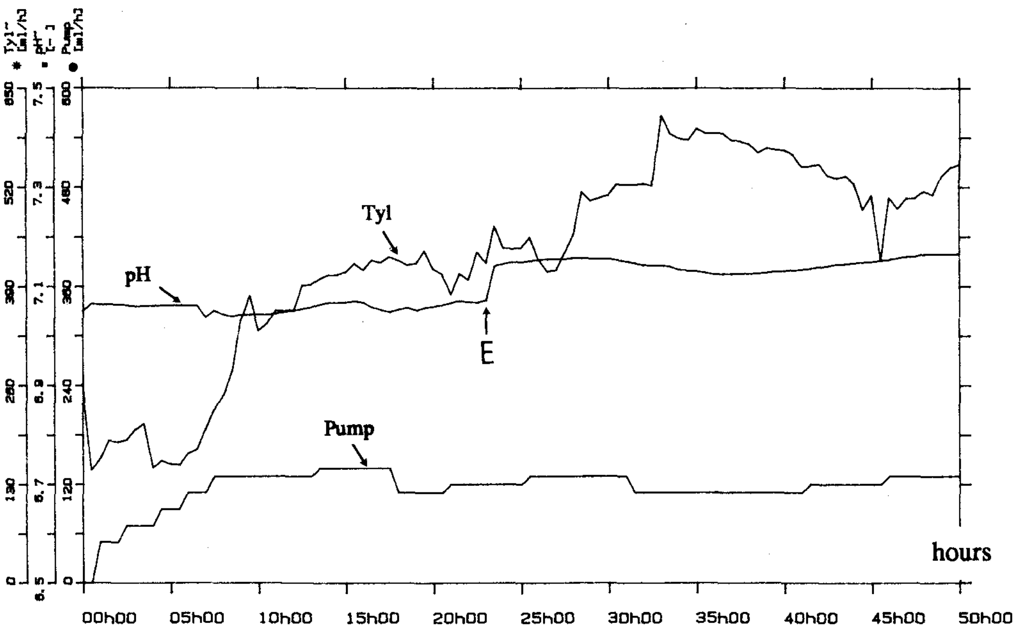

Figure 8. Time-course of the mean pH signal, gas flow (Tyl) (ml · h^{-1}) and pump rate (Pump) (ml · h^{-1}). Calibration at times denoted by (E).

to test the stability of the system towards a sudden increase of the organic load in the feed (marked with Z). After 2 h the methane concentration and after 3 h the pH value started to decrease. The optimization program reduced the pump rate and 15 h after the jump in concentration new stable conditions had become established, with a retention time of 29 h, an organic load of 7.8 kg COD · m^{-3} · d^{-1} and a COD-reduction of 72%. During this 155-h period the pH electrode was calibrated twice without disturbing the control program (marked with E).

The overall performance of the computer-controlled anaerobic filter was similar to that of a system controlled continuously by an operator. The maximal organic load was slightly lower but the COD reduction higher; on the other hand, the maximum performance was reached after only 6 days compared to the period of more than 2 weeks usually needed with manual operation.

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