FRAMEWORK FOR A CONTROL STRATEGY OF IN-MILL BIOLOGICAL TREATMENT USING ON-LINE SENSORS AND DYNAMIC MODELLING

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Abstract

Closure of paper mills implies recirculation and reuse of process water. However, increased internal recycling leads to accumulation of soluble organic substances and salts. The build-up of organic matter in the system may cause a number of serious problems, for example, microbial growth within the papermaking process. Biological in-mill treatment of whitewater is a potentially efficient and cost-effective way of reducing the amount of recycled soluble organic substances. A problem with treating whitewater biologically is that nutrients must be added since there is deficiency of these in relation to the high content of organic substances. The main challenge in controlling the biological treatment is to obtain a high reduction of organic matter without releasing nutrients into the whitewater system where they could promote microbial growth. In this paper, a framework for controlling biological in-mill treatment of whitewater is discussed. The control objectives and available control handles are outlined and a number of feasible control structures, ranging from traditional feedback to model-based control, are presented. Finally, a control strategy to ensure robust operation of the treatment system while minimising the effluent nutrient concentrations is proposed.

Keywords: closure; control; in-mill treatment; nutrients; papermaking, whitewater

INTRODUCTION

As one of the most water-consuming industries, paper production leads to significant impacts on aquatic ecosystems and demands on producers in terms of water charges and obligations in meeting statutory effluent limits. Considering the world-wide production of organic water pollutants by industries, the pulp and paper industry represents the second largest producer (10-20% of total industrial impact) surpassed only by the food and beverages industry (World Bank, 2001). Consequently, intensive efforts are made to reduce the fresh water demand and reuse process water.

In papermaking the whitewater from wire and presses is collected. It contains fibres, fillers (if used) and chemicals. For a better utilisation of the raw materials and to reduce the heat losses from the papermaking process, part of the whitewater is generally recycled and used instead of fresh water for diluting the pulp, cleaning of the wire, etc. However, the remaining excess whitewater (wastewater) contains valuable raw material, chemicals and heat. To recover the raw material, the wastewater is led to a separation unit, often a disc filter, before being discharged for external wastewater treatment. A significant part of the fibres and to some extent the fillers are separated and recycled to the paper machine. However, there are still losses, and they increase with increased amounts of generated wastewater, which also rises with a higher intake of fresh water. Therefore, there are strong economical incentives to increase the recycling of whitewater in the process and decrease the fresh water consumption and wastewater discharge. In addition, there are significant environmental benefits by eliminating wastewater discharge, which may also serve as a sales argument for marketing the final paper products.

However, increased internal recycling of whitewater leads to accumulation of soluble organic substances and salts. Soluble organic material enters the paper mill with the pulp and more is generated in the refining of pulp. The build-up of organic matter in the system may cause a number of serious problems, for example, microbial growth within the papermaking process, resulting in negative effects on paper quality, production rate and the working environment (e.g. Barnett and Grier, 1996; Gudlauski, 1996; Mallouris, 1996). As a result, the demands for robust and efficient systems for in-mill treatment of whitewater are increasing. A multi-disciplinary research project (acronym CLOSEDCYCLE) within the European Union Fifth Framework Programme – including expertise in papermaking technology, practical operation of paper mills, biological treatment, separation technology, automation and control, analytical chemistry and microbiology – is currently addressing these issues and aims at developing in-mill treatment systems for effluent-free, yet cost-effective, paper production.

IN-MILL BIOLOGICAL WHITEWATER TREATMENT

As the degree of water closure is increased the amounts of dissolved organic solids, suspended solids and inorganic matter in the whitewater will increase. Unacceptable levels will be reached if the closure is not accompanied by more efficient treatment of the whitewater. There is a tendency within the industry to rely on mechanical/physical/chemical treatment, such as sedimentation, flotation and filtration techniques as well as evaporation, whereas in-mill biological treatment is not so common although it has been tested (e.g. Habets *et al.*, 1997; Norris, 1998). Evaporation and chemical treatment are costly processes and membrane filtration often suffers from fouling problems, which decrease the efficiency and increase operating costs (Nuortila-Jokinen, 1999). To limit problems related to microbial growth, it is common to dose biocides to the whitewater, which means handling of toxic chemicals and potential negative effects in the receiving waters as biocides are discharged with the wastewater. However, biological treatment is probably the most efficient and cost-effective way of removing dissolved organic matter from the whitewater as well as being the most environmentally friendly method. Reduction levels of 90-95% are common. To accomplish a similar degree of reduction of dissolved biodegradable COD (Chemical Oxygen Demand), which represents the majority of COD in whitewater, extreme filtration (nanofiltration/reverse osmosis), chemical treatment or evaporation would be required. A drawback of biological treatment is its higher sensitivity to unforeseen disturbances, such as toxic spills, which may inhibit the process for a long time. Moreover, substantial reactor volumes are required and discolouring of the water due to the biological treatment may also present a problem.

In order to realise the potential for biological treatment of whitewater it is important not to consider only conventional biological treatment (e.g. activated sludge) operating in normal biological conditions (< 40 °C, neutral pH). It is essential to design processes specifically for whitewater and papermaking conditions, which can operate at high temperatures and low/high pH. Several recent studies have shown that biological treatment at elevated temperatures is possible and can be acclimated to a wide range of environmental conditions (e.g. Pauly and Kappen, 1999; Malmqvist *et al.*, 1999). Consequently, new possibilities for cost-effective biological treatment of whitewater are becoming available.

For successful implementation of an in-mill treatment the goal is not simply to remove as much COD as possible. The characteristics of the whitewater and its quality requirements may vary significantly depending on the type of pulp used, the quality of the paper products produced, etc. The treatment process operates in close interaction with the paper production and an integrated approach of whitewater treatment and papermaking is required to achieve an optimal result and avoid unforeseen problems. The overall goal of the treatment process is to produce and maintain a whitewater with optimal characteristics as defined by the paper production process. Consequently, the paper machine and the whitewater treatment should be regarded as an integrated system and considered as a unit in terms of design, production planning and operation. The need for such integration by means of dynamic modelling is also discussed in Tenno and Paulapuro (1999). For the reasons stated above, a variety of treatment processes may be required for different implementations and it is important to identify the most cost-effective solution that will give satisfactory results for each type of paper production and avoid overkill in terms of whitewater treatment complexity.

Within the CLOSEDCYCLE project a number of treatment processes are investigated. In Figure 1, a schematic description of the different processes is given allowing any flow combination, whereas any real implementation would certainly be more limited. Biological treatment is used to remove the bulk of organic material from the whitewater in one or two stages. The primary stage is a fluidised anaerobic reactor. Although anaerobic treatment is generally slower than aerobic treatment it has advantages in terms of low sludge production, possible biogas production and suitability for treating influent waters of high COD concentrations. In mills using a large portion of kraft pulp, anaerobic treatment may not be suitable due to high sulphur content in the whitewater. The secondary stage is an aerobic process with suspended carriers for microbial growth. Suspended carriers with a high effective area (500-1000 m^2/m^3) allow high concentrations of biomass in the system with limited risk of washout during periods of process disturbances as well as a high biomass retention time. Moreover, the need for a sedimentation unit and sludge recirculation is eliminated. Using a combination of these two processes is considered the best solution for a zero-discharge paper mill. A layout of the proposed in-mill biological treatment is shown in Figure 2, including available sensors and control handles. The different organisms occupying anaerobic and aerobic environments may certainly complement each other in terms of COD removal and capability to attenuate various disturbances. A secondary aerobic treatment should also effectively eliminate odours from organic acids and sulphide, which may appear in an anaerobic system. In order to achieve high removal rates in a biological treatment system for whitewater it will generally be necessary to add nutrients. However, dosing of nutrients in excess leads to nutrients entering the whitewater system with the recycled water. As microbial activities in the whitewater are normally nutrient limited, an increased supply of nutrients may lead to increased growth of microorganisms and an enhanced problem of slime production in the paper machine, rather than a decrease, which is the overall purpose of the biological treatment system (Malmqvist *et al.*, 1999). As the conditions in the paper mill and the load to the biological process vary, in combination with an adaptive microbial system, the need for automatic, on-line nutrient control becomes imperative. A control system for balanced dosing of nutrients for a combined anaerobic/aerobic treatment process is the focus of this paper.

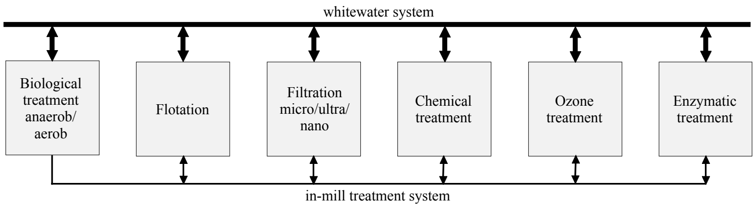

Figure 1. Schematic description of investigated in-mill treatment processes.

In many situations, the biological treatment must be complemented with various types of post treatment although any extra treatment should be kept to a minimum to promote cost-effective solutions. Within the project, processes such as flotation, micro/ultra/nano-filtration, ozone treatment, enzymatic treatment and chemical treatment are investigated in various combinations for post treatment. Accumulation of salts in the whitewater represents one problem, which may require post treatment. Nanofiltration removes salts in the range 40-85% (Tenno and Paulapuro, 1999). An organic fraction that may be difficult to remove completely in a biological process is lignin. Lignin darkens considerably in biological treatment and may increase the colour of the whitewater to an unacceptable level for certain paper qualities. For removal of colour and possibly odour, polishing of the whitewater with minimal dosage of ozone or by enzymatic treatment may be required. Separation technologies may also be needed for removal of biosolids after the biological treatment. However, the possible post treatment systems will not be further discussed in this paper.

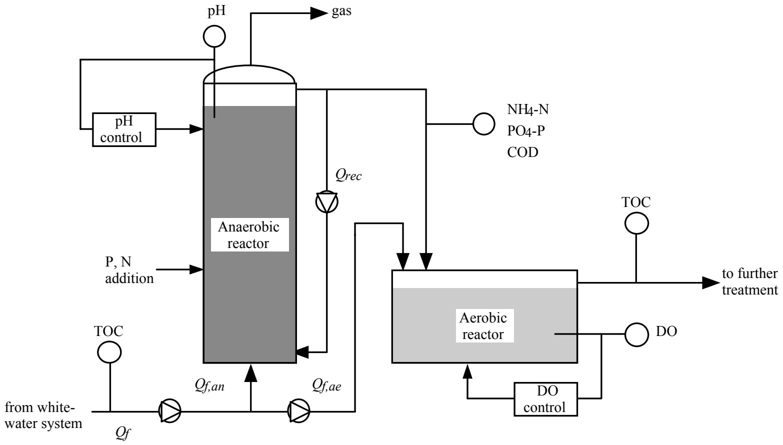

Figure 1. Layout of in-mill biological treatment. The location of sensors may vary depending on the chosen control strategy.

MOTIVES AND CHALLENGES FOR CONTROL

The overall goal of the in-mill treatment of the whitewater is to reduce the COD concentration to avoid biological fouling in the whitewater system. This goal is achieved through efficient treatment without compromising the requirement of low concentrations of nutrients in the whitewater system. However, since the added nutrients are a necessity for biological treatment, the balance between the efficient dosing and overdosing of nutrients call for automatic control.

Motives

Since most of the organic reduction occurs in the biological processes the resulting concentrations in the whitewater is a function of the size and efficiency of the anaerobic and aerobic reactor and at what rate the whitewater is treated. To reduce the size of the reactors, the biological processes should be operated as efficiently as possible. Stability and reliability of the processes are essential as failures may seriously disturb the overall paper production.

In the anaerobic reactor, the degradation involves many different types of microorganisms and in the last step methane-producing bacteria convert acetic acid into methane. If this production is reduced due to inhibition caused by the presence of toxic compounds or other disturbances, organic acids could accumulate in the reactor, causing a decrease in the pH. This would further affect the anaerobic reactor and prolong the time it takes for it to recover from the inhibition. During its recovery, the anaerobic effluent with low pH could also affect the next step in the treatment sequence, the aerobic reactor. Therefore, both the anaerobic and the aerobic reactors should be equipped with pH control, in order to adjust the pH in case of disturbances. The fluidisation of the contents in the anaerobic reactor is obtained by recirculation of the fluid in the reactor. This flow must be controlled so it remains in the right operating range. In the aerobic reactor, air is released at the bottom of the reactor and this fulfils two requirements. Partly, the air provides oxygen to the degradation process and partly the addition of air provides mixing of the carriers.

Since the whitewater normally is deficient in nutrients, it is important to supply such substances to both the anaerobic and the aerobic reactor. The term nutrients refers to all essential elements except oxygen and carbon but normally it is only nitrogen and phosphorous that are limiting the process since they are required in larger amounts. However, since they are essential to the microorganisms it is also important to prevent the nutrient concentration in the effluent to exceed specified limits, as this will cause microbial growth in the whitewater system. Apparently the nutrient addition must be controlled.

It is possible to distinguish between two different operational modes: stable operation with no production changes and only minor disturbances and transient mode when the treatment is affected by significant disturbances (start-up, production changes, toxicity, etc.). In stable operation, the objective is to maintain the concentrations of COD and nutrients at desired levels. However, in transition phases the control objective may shift to, for example, keep the biological process alive, controlling the COD concentration in the whitewater to a new target or maintaining the COD concentration but under significantly different circumstances.

Challenges

Anaerobic treatment is in some regards a sensitive process. An anaerobic system will take longer time than its aerobic counterpart to recover if it is disturbed. Also, anaerobic digestion involves a greater number of steps and is therefore not only more complex but also generally more sensitive to unfavourable conditions.

An important prerequisite for reduction of organic compounds is the addition of nutrients. In principle, the control task to add just enough nutrients so that they are assimilated by the biological growth should be simple. However, as it is important that only extremely low amounts of nutrients are returned to the whitewater system, i.e. basically no nutrients in the treatment effluent, the control problem becomes more difficult and analogous to controlling non-measurable variables. Modelling of the effluent nutrients must be done, either in form of rules or as a mathematical model.

A problem associated with basically all wastewater treatment applications is that the degree of control authority is relatively limited. The limitations may be of an economic nature but often they are intrinsic functions of the process itself. Most control handles are macro variables, whereas the controlled mechanisms generally are on the micro level. The mechanisms are often coupled, which requires combinations of control actions to obtain a certain control objective. Also, the fact that what is normally considered a harmful component in the water is at the same time a necessity for the reduction of other harmful components. This is especially emphasised in in-mill treatment when nutrients must be added to obtain a reduction of organic compounds. The balance between overdosing and, thus, retaining nutrients in the effluent and underdosing resulting in non-efficient reduction limits the ability to control the process.

It is well known that long time constants, i.e. the time it takes for a change to propagate through and affect the system, make the control of a system more challenging. In biological processes, most of the time constants associated with the biological activity are in the range of hours to days and even weeks. This has some implications on the control system. An advantage is that the system cannot be considered time critical. There is sufficient time to measure (with the delays related to actual sensor techniques), to process data and calculate control actions. However, a drawback of the delays is that feedback control is difficult. Methods to deal with time delays in control systems generally involve models and they are seldom easy to come by. As an implication of this, the controller gain has to be set relatively moderately resulting in a slow controller.

CONTROL FRAMEWORK

The control framework presented here is based on the specific control objectives necessary to address in the operation of in-mill treatment of whitewater. Control objectives, control variables, measured variables and control structures will be discussed from an in-mill application point of view. Possible control strategies within the framework are presented in a later section.

Control objectives

The main control objective for the biological in-mill treatment is to keep the concentration of COD in the whitewater system at an acceptable level. This must be achieved without releasing nutrients into the whitewater system. To fulfil the control objective, a number of subordinate objectives can be determined: controlling the COD concentration in the biologically treated water, controlling the nutrient concentrations in different locations in the biological processes, controlling the pH and recirculation flow in the anaerobic reactor and controlling the dissolved oxygen (DO) concentration in the aerobic reactor.

Control variables

In the treatment scheme discussed above, there are several manipulated variables: pH and recirculation flow rate in the anaerobic reactor, DO concentration in aerobic reactor, feed flow rate and nutrient addition (i.e. phosphate and ammonium). Biomass concentration cannot be controlled, at least not in a direct way, since both the anaerobic and aerobic treatment are biofilm processes. One could argue that temperature is a control variable, but as the whitewater temperature is assumed to assure thermophilic conditions the need for heating or cooling is not discussed here.

pH should be controlled so that suitable conditions are obtained in the anaerobic reactor. In stable operation this may involve no or little control action. During disturbances or other transient phases, the pH may have to be controlled in a more active way to ensure suitable conditions for the microorganisms. The recirculation flow rate in the anaerobic reactor should be controlled so that proper fluidisation and mixing are obtained.

DO concentration could be argued a control variable for the aerobic reactor of the treatment process. This is true in many biological treatment processes when DO concentration is associated with an operating cost and, thus, limited. However, in this application the energy cost is subordinate to the requirements of robust operation and the DO concentration is consequently controlled to a level assuring not only no-limiting conditions but also sufficient mixing of the suspended carriers.

Adequate pH, recirculation flow rate and DO control are prerequisites for achieving the main control objective rather than powerful control handles. Instead, focus has to be on nutrient addition and feed flow rate (or in fact the load of organic matter) to control the process. By increasing or decreasing the addition it is possible to maintain the desired effluent concentrations despite disturbances in influent organic load. If nutrients are only added to the anaerobic reactor the addition should also meet the aerobic demand of nutrients. An important point is that, if possible, the phosphate and ammonium additions should be separated to ensure and improve the operability of the process.

The feed-flow rate can be used as a control variable to control the removed mass of COD. However, its authority is limited by the maximum removal capacity of the biological processes. Thus, feed-flow rate is closely linked to the effluent concentration of COD, since an increase is bound to yield decreased removal efficiency if the capacity of the processes is already fully utilised. Caution must be taken to avoid negative effects on the subsequent treatment steps introduced by too high feed-flow rate. The adequate choice of feed-flow rate is, consequently, subject to optimisation. Related to the feed rate is the possibility to use step-feed. This can be used to increase the COD load on the aerobic reactor to ensure an abundance of organic compounds in the reactor.

On-line sensors and control implementation

The control strategies discussed in this paper require a number of on-line sensors. Some of the sensors are since many years established as standard sensors in wastewater treatment industry, such as dissolved oxygen and pH, and do not require further discussion. Others are at the forefront of new commercial sensor applications. These sensors include total organic carbon (TOC), COD, phosphate and ammonium. Sensors are available from a number of suppliers and based on different measuring mechanisms. A survey (Alexandersson, 2003) shows that most of the ammonium sensors work in the concentration range of 0-20 mg NH_4-N/l and with a lower detection limit of approximately 0.05-0.1 mg NH_4-N/l. Phosphate sensors generally measure in a range of 0-10 mg PO_4-P/l with a lower detection limit of 0.01-0.05 mg PO_4-P/l. Both ammonium and phosphate sensors are afflicted with response delays of 5-15 minutes. TOC and COD on-line sensors can be used to *estimate* the COD concentration in the water stream. The measurement range for TOC sensors is generally 0-20000 mg/l. Only two COD sensor were studied and the capacity of the two differed significantly.

For use within the CLOSEDCYCLE project, ammonium, phosphate, COD and TOC sensors from different suppliers were chosen based on the results of the survey. Special care was taken to the fact that the sensors will operate in conditions of high COD and low nutrient concentrations. Thus, sensors believed to suit in-mill treatment were chosen. Currently, a PC-based control system is being implemented using the LabView software as the operator interface and for communication with sensors and actuators whereas Matlab is used for on-line model simulations, parameter estimation, etc. Data acquisition from the sensors is achieved by a distributed system of 16-bits analogue-digital converters, which communicate with a central networking module using the FieldPoint bus. Communication between the PC and the networking module is based on a high-speed Ethernet network. The same principle is used to transmit control signals from the PC to the actuators in the system. The aim is to a have a robust yet flexible control system, where new control strategies can easily be activated, new sensor signals included, sensor locations changed, actuators added and so forth without having to reconfigure and rewire the system. Remote access and control of the process from any computer on the same network (or possibly the Internet) are feasible.

CONTROL STRUCTURES

A number of possible control structures can be applied for in-mill biological whitewater treatment. However, due to some of the challenges discussed above, simple feedback control may be complemented by more sophisticated methods. Below, a discussion on the most common control structures and their applicability to in-mill treatment is presented. Possible control strategies will be discussed in the next section.

pH and DO control

The control of pH and DO in the anaerobic and the aerobic reactors, respectively, are in principle not problematic and must be regarded as common knowledge in the wastewater treatment industry.

Both control loops can be implemented as single-input, single-output (SISO) systems and standard methods, for instance feedback control using a PID controller, are normally sufficient. Specific difficulties associated with the practical implementation may occur, but will not be discussed further.

Feedback control

In principle, separation of the control problem into three separate feedback control loops should be possible. This implies that phosphate and ammonium additions are based on the measurement of effluent PO_4-P and NH_4-N concentrations, respectively, and that feed-flow rate is based on the measurement of effluent COD concentration. This strategy has some important shortcomings, which makes it less feasible. Firstly, the detection limits on PO_4-P and NH_4-N measurements are not sufficiently low for use in the effluent water. Secondly, it is at this point not clear what the response delay between nutrient addition and effluent nutrient concentration is. If significant it would make a strict feedback system slow, as small controller gains must be used to ensure stability. Thirdly, decoupling of the control loops does not take the internal relationships into account and this may have severe effects on the control performance. However, the situation can be improved by locating the PO_4-P and NH_4-N sensors in the way depicted in the Figure 2. In this case the nutrient concentrations will be sufficiently high to measure. Such a control structure is illustrated in Figure 3.

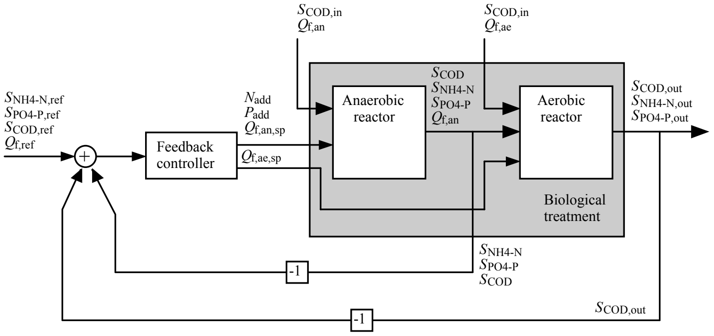

Figure 3. Feedback control of the in-mill biological whitewater treatment.

Feed-forward with corrective feedback

It is likely that the delay in the biological process will make a controller based only on feedback information too slow. By introducing a feed-forward component in the controller, the control performance can be significantly enhanced if a sufficiently good model of the process is available. The forward term in the controller provides in the short time scale a control action that will yield the desired process output if the model is correct. However, a perfect model is not attainable. The error in the model can then be corrected by the feedback term in longer time scale. A feed-forward controller with corrective feedback is depicted in Figure 4.

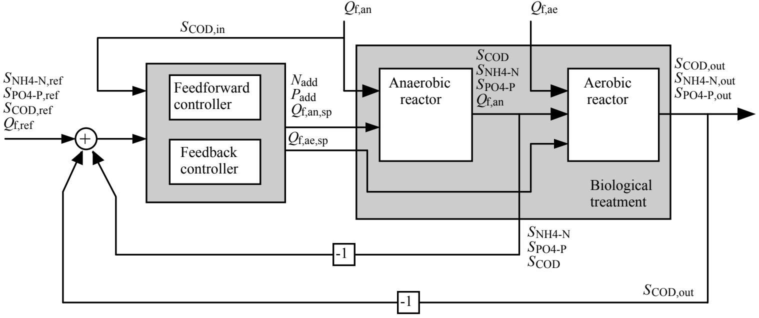

Figure 4. Feed-forward control with corrective feedback for in-mill biological treatment.

Model-based control

To better utilise the information available through on-line measurements, a model-based controller can be applied (Figure 5). In such a controller, dynamics and mutual relationships can be represented by, for instance, deterministic modelling (differential equations) or rule-based reasoning (heuristic information representation). The output of such a model is not only dependent on the influent flow characteristics but also on the process states, measured or estimated. Of course, the model becomes more complex than in the feed-forward case but the information incorporated may yield significant improvements in the controller performance.

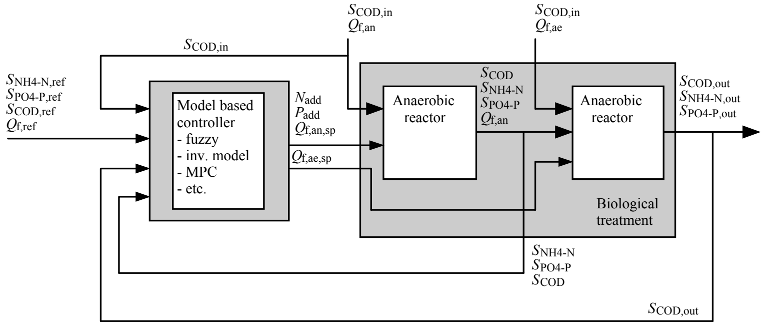

Figure 5. Model-based controller structure for in-mill biological treatment.

A number of different model-based control methods can be employed, for instance, rule-based control, inverse model-based control and model-predictive control. A short description of the different approaches is given below. For more information on model-based control, see control textbooks, e.g. Glad and Ljung (2000) or Åström *et al.* (2001). In rule-based control, the rules are often defined as "if…then…else" rules. Information on the behaviour of the system is represented in sets of rules and an inference engine is used to draw conclusions from data. It is frequently desired to design a controller that allows for more gradual implementation of the rules. This is the justification for fuzzy logic, in which the result of a rule can be softened or fuzzified. Fuzzy control is today a well-known concept in the control community and there are several examples of commercial and industrial implementations. An important advantage with rule-based control is that it is generally intuitive; the controller mimics human thinking in the way it derives control actions. In inverse model-based control, a model is used to calculate appropriate control actions to obtain a desired process output. Such an approach requires a good process model. However, even if a good model can be obtained, it is not guaranteed that it is possible to find its inverse. Model-predictive control (MPC) is an approach that can be described as utilising a process model to predict future process outputs as a function of future control actions. An optimisation routine is used to find the best set of future control actions to obtain desired future process outputs. An appealing feature of MPC is its ability to incorporate constraints on the variables. This is, for instance, important if it is suspected that limitations in the control variables will be significant or when a process is operated close to its physical boundaries. It is also natural to include control action cost in the optimisation, which makes MPC an excellent tool for increasing the operational efficiency.

DISCUSSION

Monitoring

Regardless of what control structure is implemented, the need for monitoring the process and the control performance is vital. To be able to early detect and isolate deviations in process performance does not only save time in correcting the fault, but also money in terms of increased production time. Process monitoring and fault detection have gained importance during the last decades and today, a variety of different methodologies are available. Statistical process control

(SPC) and multivariate statistical process control (MSPC) are used in many industries for process surveillance. The basic idea behind these methods is that the process behaviour is compared with historical behaviour from periods of known process performance. If the behaviour deviates from known "in-control" behaviour, an alarm is triggered and the operator is notified. The signals used for process monitoring are often the same as used by the control system. However, additional measurements may be necessary to provide a complete picture of the current process state. More information on SPC and MSPC can be found in, e.g. Box and Luceno (1997), Wise and Gallagher (1996) and MacGregor and Kourti (1995).

Measurement collection

The relatively slow dynamics of the system implies, as discussed before, that measuring and data processing (including control) is not time critical. This allows for the sensors to be used in a more elaborate and efficient way. For instance, the sensors can periodically sweep over several locations in the process, allowing for an enhanced information acquisition. This is appealing from an economical point of view. The sweeping is achieved by locating the sensors in central position with side streams from all vital locations in the treatment system. The additional cost for such an arrangement should be marginal.

Control strategies

A possible control strategy, facilitated by the design of the treatment plant (Figure 2), is to apply a constant load to the anaerobic process and letting the aerobic treatment handle the variations in the influent load. There are some immediate benefits in doing this. Firstly, anaerobic treatment is less robust to disturbances than aerobic treatment and the step-feed decimates the effect of disturbances. Secondly, anaerobic treatment is more resource efficient than aerobic treatment and by applying a constant load the optimisation of the treatment is simplified.

Assuming available measurements between the anaerobic and aerobic reactors (see Figures 3-5), control of nutrient additions may be carried out using a predefined target for the $S_{\mathrm{COD}}/S_{\mathrm{NH4\text{-}N}}/S_{\mathrm{PO4\text{-}P}}$ ratio. This target must be chosen according to a number of rules: (i) the S_{COD} must be available in abundance by controlling $Q_{\mathrm{f,ae}}$; (ii) the COD load (i.e. $Q_{\mathrm{f,ae}} \cdot S_{\mathrm{COD}}$) must not exceed the maximum capacity of the aerobic reactor; (iii) the set-point for $S_{\mathrm{PO4\text{-}P}}$ must provide a concentration of PO_4-P high enough to allow for all NH_4-N to be removed. Rule (i) is motivated by the fact that it is imperative that all nutrients are removed in the aerobic reactor. Rule (ii) assures that the reactor is not overloaded and rule (iii) implies that if there is a nutrient limitation, the limitation is access to nitrogen. Such a limitation results in effluent concentrations of $S_{\mathrm{PO4\text{-}P,out}} > 0$, while $S_{\mathrm{NH4\text{-}N,out}} = 0$. This is a better alternative than the opposite, since phosphate can be removed in subsequent treatment by chemical precipitation, whereas nitrogen cannot. Ongoing work within CLOSEDCYCLE aims at determining appropriate $S_{\mathrm{COD}}/S_{\mathrm{NH4\text{-}N}}/S_{\mathrm{PO4\text{-}P}}$ ratios for whitewater (Alexandersson *et al.*, 2003).

The strategy can be employed regardless of what control structure is chosen. If combined with a constant load strategy for the anaerobic reactor then feedback control of the nutrient additions should be sufficient. If the load to the anaerobic reactor is varying, a feed-forward control combined with corrective feedback control is probably a better choice. The feed-forward model would then be used to estimate the consumption of nutrients in the anaerobic reactor based on the influent COD concentration ($S_{\mathrm{COD,in}}$). Implementation of model-based control could yield better dynamic properties of the control.

It is stated in this paper that the overall control objective is to control the COD concentration in the whitewater system. So far though, the discussion has only covered control of the concentration in the effluent from the biological treatment. One could, of course, directly control the whitewater concentration by including a model of the subsequent treatment as well as the paper machine in the controllers in Figures 3-5. Another, and perhaps more feasible method, would be to include a supervisory control level, acting above the control structures discussed in this paper and controlling the whitewater COD concentration. Depending on the actual application and its dynamic properties, this supervisory level can be automatic or manual. It is likely that the dynamics of whitewater COD concentration are sufficiently slow to allow for manual control, which in an initial phase is probably the wisest choice. The monitoring output will in this case be vital, as it constitutes the basis for manual control actions.

Future work

A pilot plant is being commenced in accordance with the process structure of Figure 2 and control strategies discussed in this paper will be applied and evaluated. The on-line sensors and a fully computerised control system, based on software packages LabView and Matlab, will be used. The possible use of methods for parameter estimation and identification of non-measurable variables, such as biomass activity, will be investigated. In parallel, development of mathematical models both for control and for hypothesis testing of biological process mechanisms, based on the results from laboratory experiments (Alexandersson *et al.*, 2003), will be carried out. In this development, special effort will be made to incorporate the interaction between biological treatment and subsequent treatment as well as the paper machine itself.

CONCLUSIONS

As the biological treatment removes the bulk of soluble organic matter from the whitewater, it is imperative that the process operates efficiently. Balanced dosing of nutrients is generally required to achieve this and on-line control is needed for attenuating disturbances in the influent and within the process as well as ensuring the stability and robustness of the treatment process. The fact that effluent nutrient concentrations must at all times be kept extremely low to minimise consequent problems in the paper machine due to possible microbial growth is especially challenging. It defines the framework for appropriate control structures, suitable sensor locations and possible control strategies based on on-line measurements and mathematical modelling.

The control strategies differ depending on the characteristics of the process in terms of response delays, measurability of variables and operability of the process. It is believed that strict decoupled feedback control of nutrient additions and feed-flow rates will be less feasible, due to response delays and low nutrient concentrations. Instead, feed-forward control in combination with corrective feedback should be more appropriate to fulfil the control objectives of maintaining a desired COD concentration in the treatment effluent and the whitewater system. When adequate process models are available, model-based control strategies also constitute appealing alternatives for enhanced controller performance.

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