

Automation strategies for dissolved oxygen control in real activated-sludge plants

H. Alvarez, R. Lamanna and S. Revollar

Abstract—This paper presents the main characteristics of the activated-sludge treatment plants focusing on dissolved oxygen control as a key condition for successful water treatment. Particularities of current strategies used for dissolved oxygen control are mentioned and compared with a somewhat improved control scheme. Some simulation results are presented in order to point out certain advantages of the new approach to dissolved oxygen control.

I. INTRODUCTION

WATER treatment is one of the main topics in process engineering since water resources, after their use at industrial processes or domestic activities, must be returned to rivers or lakes. Official regulations in most countries state very restrictive rules regarding water quality, and therefore, any user of water resources is advised about environmental responsibility. Hence, water treatment processes must be designed and implemented in order to decrease the contaminant load of used water.

Several processes for wastewater treatment are being developed and applied around the world. Each treatment impacts in different ways the contaminants contained in the wastewater. The activated-sludge process is one fundamental part of the majority of Wastewater Treatment Plants (WWTPs). Being a complex bio-chemical system, its adjustment and process control must be carefully carried out to ensure the desired effluent water conditions. In this work, the main characteristics of the activated-sludge treatment plants are exposed. The focus is on dissolved oxygen (DO) control as a key condition for successful water treatment.

An important number of contributions can be found in the literature regarding the application of advanced control strategies for regulation of DO content in the activated-sludge-process aerobic reactors. See for instance applications of predictive control MPC in [1], [2], [3] and [4]; or fuzzy controllers for DO in [5] and [6]; or

comparisons between different advanced control strategies for reactor process as a whole in [7].

In many applications, the typical single loop structure controlling DO by “manipulating” the global oxygen transfer coefficient $K_L a$ is proposed. A few contributions consider more complex control schemes, for example, cascade control in [8] or cascade plus feed-forward in [9], where the typical cascade configuration considers an external loop for nitrate level control manipulating the DO concentration, this is, defining a set point for the internal DO loop. However, the control handle for the DO concentration, which lies in the aeration system used, is generally taken directly as “ $K_L a$ ” without considering that $K_L a$ is not a unique variable and cannot be directly manipulated.

Only a few authors include in their designs the actual manipulated variables needed for DO control, but are suitable only for the particular aeration systems used. For instance, a complete model of an aeration process is developed in [10] including blowers, diffusers, throttling valves and collector pipes, to support a lower-level controller devoted to the aeration system of the Kartuzy Wastewater Treatment Plant (WWTP) in Northern Poland. In reference [3] a system where surface aeration is provided by two-speed motors is considered. The manipulated variable is an average power that is subsequently translated into the pulse sequence needed to obtain a corresponding average speed in the aeration motors. Likewise in [4] a specific aeration system is described, constituted by turbines with fixed speed motors, and a control system is designed where DO is regulated by the optimal on-off sequence.

The aeration system of an aerobic reactor is actually a complex dynamical process in itself. It has to be considered in the control system design to allow the use of typical, tangible handled variables (valve positions, motors speeds, power usage, etc.) that provide the desired $K_L a$. Furthermore, it is advantageous to achieve the separated command of the two components of the oxygen transfer process, namely the mass transfer coefficient K_L and the bubble-transfer area a , which is seldom considered in the literature.

In this work, we propose a complete DO control scheme which takes into account the aeration system, consisting of two loops handling separately the flow-rate and the input pressure of the air supply to the spargers. The performance of the control strategy is analyzed with simulations, while considering the detached effects on the K_L and a parameters. The paper contains an introduction to the wastewater treatment problem in section II, followed by a qualitative

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description on the activated-sludge process in section III. Section IV and V are devoted to the DO concentration control system and the simulation results of the application. Conclusions are outlined in section VI.

II. WATER TREATMENT

The main objective of the wastewater treatment plants is to remove, by transformation and separation processes, the nutrients and organic matter contained in the water to return an effluent that meets the environmental standards imposed by the law. The type of treatment depends on the characteristics of the wastewater, the desired effluent quality and other environmental factors.

The treatment processes are physical, chemical or biological, and can be used in many different combinations. Physical treatment involves sedimentation, flotation, filters and membrane techniques. Chemical treatment involves coagulation and flocculation of colloidal and suspended matter as well as precipitation of some dissolved matter, such as phosphorous. Typical chemicals used in this treatment are ferrous, ferric and aluminum salts as well as lime. To further increase the efficiency of the process, coagulation aids such as polymers are often used [11].

In biological treatment, the microorganisms are used to remove the organic matter present in the incoming wastewater. The organic pollutants serve as food and energy sources for the microbiological culture as it grows. In the aerobic processes, dissolved oxygen is used by microorganisms in the conversion of organic wastes to biomass and CO_2 . In the anaerobic processes complex organic wastes are degraded into methane, CO_2 and H_2O through three basic steps: hydrolysis, acidogenesis including acetogenesis and methanogenesis, in the absence of oxygen. The excess sludge created in the biological process is removed and treated for stabilizing and dewatering. Stabilization of sludge makes it biologically safe and often usable as fertilizer. The reduction of organic matter in a biological treatment plant is typically 90% or more [12].

Water treatment processes can be divided into two major families: treatments for industrial water and treatments for domestic water. The characteristic of industrial wastewaters is highly variable and directly related with the field of industrial production. For example, aerobic biological processes are commonly used in the treatment of organic wastewaters to obtain high degrees of treatment efficiency. Concerning anaerobic processes, considerable progress has been done in anaerobic biotechnology for waste treatment based on the concept of resource recovery and utilization while still achieving the objective of pollution control.

In general, aerobic systems are suitable for the treatment of low strength wastewaters (concentrations of biodegradable material less than 1000 mg/L) while anaerobic systems are suitable for the treatment of high strength wastewaters (concentrations over 4000 mg/L).

The activated sludge process is an appropriate technology

for municipal and industrial wastewaters from several major industrial sectors. However, when treating high organic strength industrial wastewaters, aerobic or anaerobic treatment alone do not produce effluents that comply with effluent discharge limits [12].

III. TYPICAL CONFIGURATION OF ACTIVATED SLUDGE TREATMENT PLANTS

The activated sludge process is an appropriate technology for municipal and industrial wastewaters from several major industrial sectors. In the simplest type of activated-sludge wastewater treatment system, the microorganisms degrade the content of organic matter in the wastewater aerobically, i.e. when air is supplied to the biological reactor. To retain the sludge in the system, the biological reactor is followed by a sedimentation unit that separates the clear effluent wastewater from the sludge (see Fig. 1). The important variables are: aeration (Dissolved Oxygen DO), sludge outtake and sludge recirculation. These variables should be controlled to ensure a suitable treatment efficiency of the process, which includes maintaining a correct amount of sludge in the system.

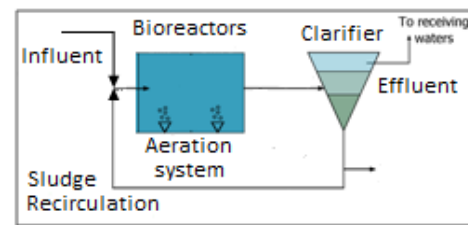


Figure 1. Sludge-process for organic-matter-removal

The nitrogen removal process requires both aerobic and anoxic conditions, and is therefore fairly more complicated. In the anoxic stage instead of dissolved oxygen in the water, there is nitrate available. A simplified diagram of the whole process can be seen in Figure 2. The first step is an aerobic nitrification process where nitrifiers (i.e. microorganisms able to perform nitrification) convert ammonium to nitrate. This is followed by an anoxic process, known as denitrification, where nitrate is converted to free gaseous nitrogen, which leaves the water through the surface into the air. For this process, the denitrifying microorganisms use easily biodegradable organic matter.

Several types of wastewater treatment plants can perform the nitrogen removal processes [13]. One of the most common plant designs is the pre-denitrification system, which is depicted extremely simplified, in Figure 3. To satisfy the need for easily degradable organic matter the denitrifying reactor is located so that it can use the organic matter in the influent wastewater, and the nitrification reactor is placed following it. An internal recirculation from the second reactor to the first one ensures the presence of nitrate in the denitrification reactor. The main input variables that can be used to control the process are: internal

recirculation, sludge outtake and sludge recirculation, and particularly the aeration, which regulates the water oxygen-content (dissolved oxygen DO).

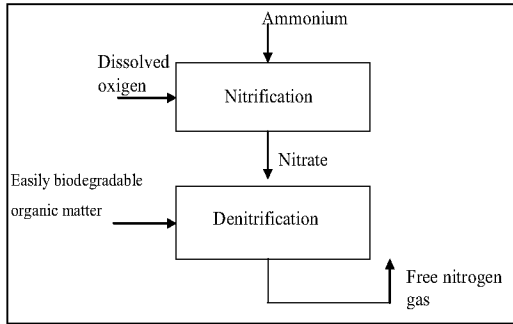


Figure 2. Nitrogen removal process.

Phosphorous removal can be performed biologically or chemically, however, the most widely applied procedure is by chemical precipitation. The process consists of dosing of a chemical (typically an iron or aluminium salt) that binds phosphate molecules and forms flocs that can be removed by sedimentation. Hence, the phosphorous is removed via a chemical sludge.

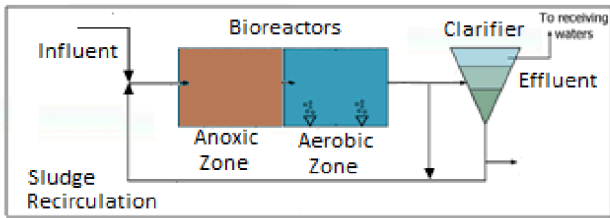


Figure 3. Pre-denitrification plant design.

A number of models have been developed for the activated sludge process (biological reactor), the most generally known is the ASM1 developed by the International Association on Water Pollution Research and Control (IAWPRC). The model considers 13 state variables and it describes the elimination of the organic carbon and nitrogen. The same working group extended the model afterwards by adding the biological process of eliminating the phosphorus, and named this model the Activated Sludge Model 2 (ASM 2). Two other improved versions of the ASM2, named ASM2d and ASM3 appeared. In order to study the aeration system dynamics and replicate the behavior of the proposed control strategies, the Benchmark implementation of model ASM1, namely BSM1 is used here for simulations. BSM1 is displayed in Figure 4.

The activated sludge plant modeled by ASM1 contains two reactor units in the anoxic zone and three units in the aerobic zone. The complete description of the plant, its mathematical model and physical parameters, can be found in [14].

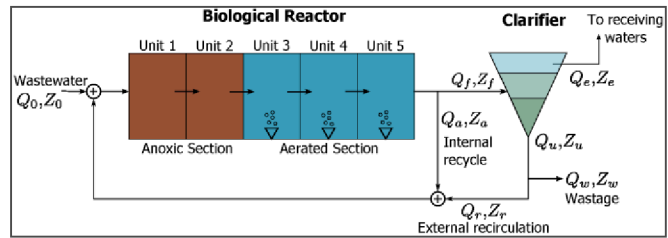


Figure 4. Benchmark activated sludge plant layout.

IV. DISSOLVED OXYGEN CONTROL

As it is evident from the previous discussion about activated-sludge treatment plants, oxygen availability is a key condition for successful water treatment.

Taken into account the versatility and precision of current dissolved oxygen sensors, it is possible to check the knowledge about oxygen-water interaction. Two key aspects are related to DO in water treatment, the organic content of the water vs. the oxygen demand and the biochemical oxygen demand [15]. Both help to state the oxygen requirements in order to fulfill government regulations about the water after treatment.

However, control structures currently used for Dissolved Oxygen (DO) control too often lack efficiency, due essentially to the deficient attention given to the mass transfer (oxygen) phenomenon involved.

In order to understand the mechanism of the oxygen mass transfer, a simple model can be stated using the typical gradient format:

$$N = K_L A (C_S - C_L) \quad (1)$$

where:

N is the total mass transfer rate (kgO_2/s),
 K_L is the liquid film coefficient in $\text{kgO}_2/(\text{m}^2\text{-s}-(\text{mgO}_2/\text{m}^3))$,
 A is the total interfacial transfer area (m^2),
 C_S is the saturation concentration of oxygen (mgO_2/m^3), and
 C_L is the concentration of oxygen dissolved in the liquid (mgO_2/m^3).

Values for oxygen saturation concentrations C_S are tabulated for distilled water at standard conditions and at different temperature. However, saturation values C_S for real wastewater must be determined from current wastewater properties, normally through laboratory tests. In general, all the mass transfer characteristics of the wastewater-oxygen system must be calculated as a function of water solids content, temperature of water and air, superficial area for liquid-gas contact (bubble quantity and size), and other less significant variables.

Dividing equation (1) by the total system volume V , yields:

$$N_C = K_L a (C_S - C_L) \quad (2)$$

with N_C the specific mass transfer rate in $\text{kgO}_2/(\text{m}^3\cdot\text{s})$ and a the interfacial transfer area per system volume unit (m^2/m^3).

Due to the admitted difficulty to determine A or a , it is common to use the $K_L a$ as an overall coefficient, but the effect of interfacial area must be considered as a key variable for process control.

Generally, the manipulated variable in DO control loops is air flow but the Final Control Element (FCE) used changes from one treatment plant to another. However, several aspects of the real effect of air injection over DO are directly related to the FCE used. As it was discussed above, overall mass transfer coefficient $K_L a$ expresses two effects: *i*) the mass transfer phenomenon K_L and *ii*) the influence of area for mass transfer $a = A/V$ (directly related to the bubble size).

Normally, wastewater treatment plants use spargers (drilled tubes or porous elements) or injectors for dosing air into the water. Both kinds of air dosing elements produce a bubble curtain with a bubble size depending on the air supply pressure-temperature and water density. Bubble size is an important variable never considered explicitly into DO control loop design.

V. RESULTS OF ALTERNATIVE CONTROL STRATEGIES

In this section the typically used DO control scheme and a novel proposal are simulated. The BSM1 simulation protocol is used for testing the two different DO control strategies, in order to illustrate control difficulties, drawbacks and advantages. The novelty consists in a double control loop seeking an effective DO regulation by manipulating the separated effects over K_L and a . In this alternative, a first control loop is dedicated to maintain air flow, directly influencing K_L , and the second one regulates air pressure, directly affecting bubbles size and therefore the interfacial transfer area A (and a).

The proposed control strategies are conceived for a real wastewater plant, considering the real aeration equipment and the habitual operation procedures, even though they are evaluated in a Benchmark protocol. The Salamanca's wastewater treatment plant, with an average influent flow of $117500\text{m}^3/\text{d}$, has been used as reference plant.

The Salamanca's WWTP includes primary treatment (removal of suspended solids), secondary treatment (activated sludge process) for removal of nitrogen and organic matter and sludge treatment. The activated sludge process consists of six independent activation basins divided into anoxic, facultative and aerobic zones. The aeration system is made of three arrangements of 1300 to 600 diffusers in series, the driving machine is a turbine, which provides between 9000 and 20000 m^3/hr of air [16].

In a real wastewater treatment plant, this assembly will be as displayed in Figure 6.

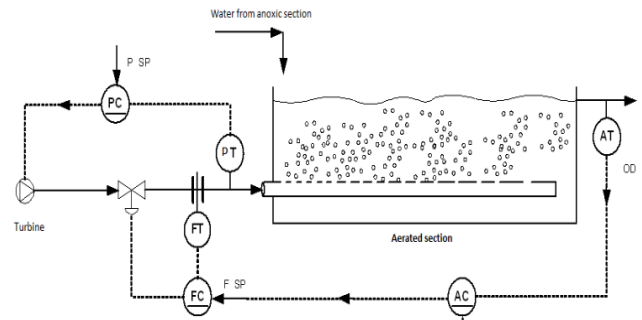


Figure 6. Multiple-loop control scheme for the aerated reactor.

A direct signal from the analysis (DO concentration) control loop, which acts as a master loop, is included as the flow-rate setpoint to the air-flow controller (internal loop). On the other hand, the pipeline pressure (sparger pressure) reference is manually set in accordance with DO performance. Normally, a human operator adjusts the air pressure setpoint taking into account the last hour plant performance and inherent characteristics of the air driving machine.

Due to sparger typical operation, when air flows through the pipe, the pressure drop produces different point to point pressure and different bubble size. In addition, it is a common practice to connect two or more air pipes (spargers) from the same air driving machine output. As a result, the air flowrates in the different pipelines are not the same even when the unique flow control valve is open to the same degree.

A. Control Strategy

The proposed structure is simpler than the hierarchical configuration used in [10], hence it is better suited for real implementation without a high computation burden.

A Non Linear Model Predictive Controller (NLMPC) is applied for the control of the dissolved oxygen (DO) according to the control scheme described in figure 6. The NLMPC provides the appropriate flow-rate reference to an internal PI controller, and a simple feedback control loop with a PI is used to regulate the sparger pressure (See figure 7). Such a structure resembles a master-slave or multi-loops cascade control.

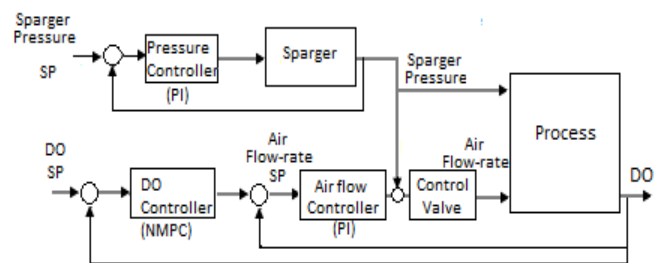


Figure 7. Control strategy blocks diagram

In the typical MPC algorithms the optimal control actions are calculated by solving an optimization problem where the process model is used to predict the future outputs of the plant at each time step. The NMPC proposed here, uses directly the nonlinear plant model and it solves the optimization task using Restricted Enumeration Optimization (REO) over a discrete set of possible control actions [17], [18], [19]. The method takes advantage of the Final Control Element (FCE) characteristics, building a restricted set of possible control actions (u) represented by a grid centered into current control action. The control actions with erroneous directions in accordance with error sign and the control actions out of operative limits of FCE are discarded from the grid. The optimization of FCE future position proceeds as an enumerative search over that set.

Two simulations are performed using the BSM1 with a Nonlinear Model Based Predictive Control (NMPC) for the DO concentration control loop (master loop). Controller tuning parameters were manually adjusted looking for the best performance. The parameters finally used were: sampling time=0.001hour (1.44min), prediction horizon=8, control horizon=1.0 (condition of REO), FCE span for REO=15.8%, error gain into MPC cost function=1200, FCE changes gain into MPC cost function=10. Air flow and air pressure controllers where PI-type and manually tuned.

B. Simulation Results

DO closed loop responses using the conventional control option and using the double control loop proposed here, are compared. Conventional control option uses the same Nonlinear MPC previously described but without modeling the real air flow and air pressure behaviors. Three days of operation are simulated with the input flow-rates and concentrations given in the benchmark. DO setpoint is adjusted to 2.0 g/m³. Figures 7 and 8 show the DO response and FEC movements with conventional K_La control loop when air pressure disturbances are included during the first half of day at days 1 and 2. Wastewater flows to be treated were taken directly of BSM1 file. As it was previously mentioned, this control strategy uses only the air flow regulation as FCE to achieve the DO requirement. No action on the air pressure is implemented.

As can be seen, setpoint values are reached only occasionally due to faults in air pressure over the sparger. Conventional single loop control (in spite of being NMPC) moves air flow while letting air pressure go free depending of the air supply. Obviously, embedded pressure control of driving machines is a general purpose control loop. Therefore, its performance is not good enough to guarantee bubble size distribution. The effects of air pressure faults are evident from Figure 8, which displays K_La values obtained with the conventional control loop.

Alternatively, Figure 9 and 10 show the DO response and the K_La obtained with the combined control actions when the proposed two control loop strategy is applied. In this case, pressure set point is fixed at the sparger-provider value and the DO controller acts as a master to the air flow control

loop. As can be seen, DO content is near its setpoint value of 2.0g/m³ during almost all the simulation time. In addition, high K_La values are achieved when air pressure is maintained in spite of high air flow requirements (additional disturbances at the beginning of days 1 and 2). In this sense, bubble size is nearly constant, instead of the variable bubble size typically observed when air pressure is not controlled.

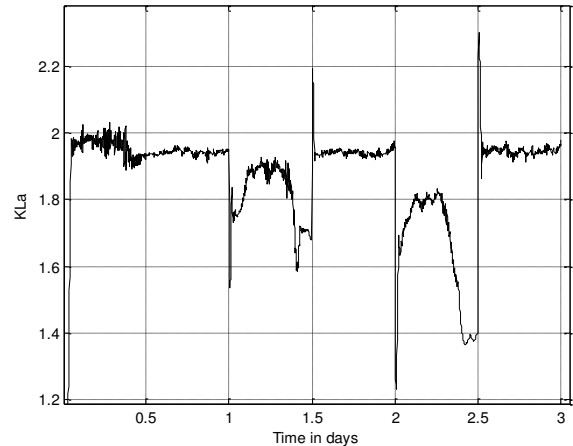


Figure 7. DO response with conventional K_La control.

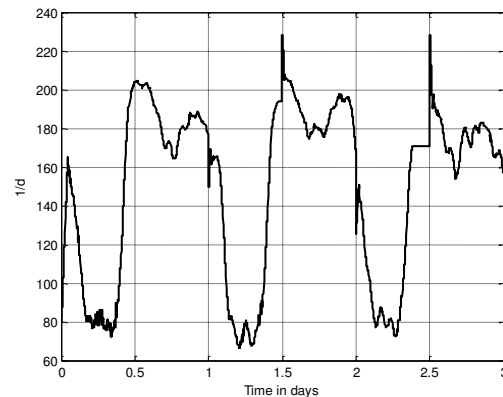


Figure 8. Single control action K_La using one control loop.

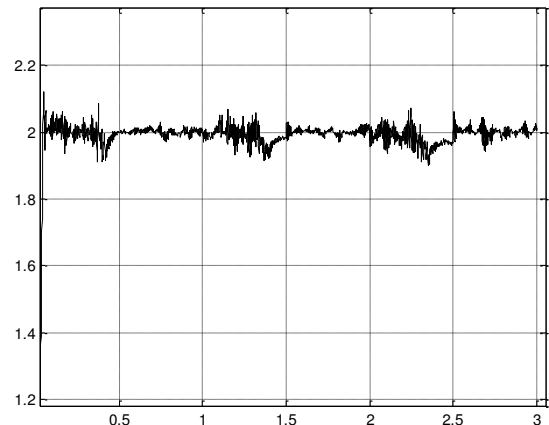


Figure 9. DO response using the proposed two control loops.

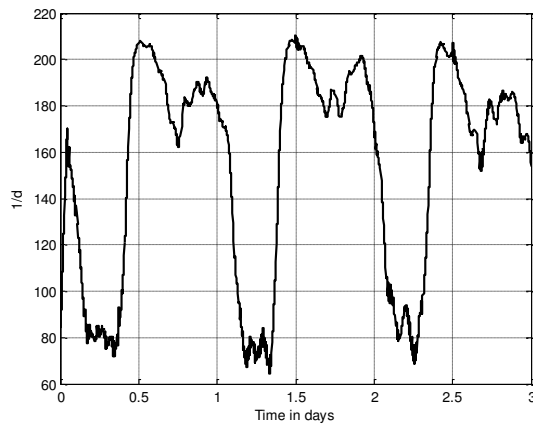


Figure 10. Combined control action $K_L a$ using two control loops.

VI. CONCLUSIONS AND FUTURE WORKS

In this work, a double-loop DO control scheme is proposed, considering the particularities of the oxygen mass transfer mechanism to operate the aeration system. Namely, the mass transfer coefficient K_L and the bubble-transfer area a are manipulated through two separated control loops, one for the air-flow and the other for the air-input-pressure respectively. The main controller is a Nonlinear MPC.

Some simulations, realized with the BSM1 benchmark, allow to conclude that an improvement over the DO response is obtained when using an additional PI control loop (on the air pressure of the aeration system), compared with conventional $K_L a$.

Eventually, the obtained DO response improvement can be further increased if a most complex control structure is implemented converting air Pressure in a tracking variable instead of a regulatory one. This can be done through a simple signal loops interaction, avoiding heavy process models as the used in NMPC. A right tuning of both control loops must be executed looking for smooth master to “slave” command.

In the same line of model based actions, future works should develop a phenomena-based semiphysical model for implementing a model-based $K_L a$ action. Such model will act as a signal splitter instead of being a model for optimizing. In this way the real required values of K_L and a can be estimated, hence providing the air pressure and the air flow control loops with enough information to act within a coordinate and more effective approach.

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