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INSTRUMENTATION AND CONTROL OF INDUSTRIAL WASTEWATER TREATMENT PROCESSES

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Requirements for treated wastewater are becoming increasingly more stringent. This, in combination with increasing loads, and limited availability of resources, calls for efficient methods of wastewater treatment processes.
At present, the most widely used biological treatment process for industrial wastewater is activated sludge. This paper describes devices used for on-line measurement and monitoring of wastewater together with analyses used to characterize wastewater, as well as options available for control of the wastewater treatment process. Expert systems, fuzzy logic, and neural networks are discussed and introduced to be concerned with dynamic features, nonlinearities, not clearly stated control goals and the use of qualitative information about these processes. Potential benefits of thermophilic aerobic digestion, a promising technology of wastewater treatment, are also discussed.

Keywords: Activated sludge, thermophilic, aerobic, biological treatment, control, wastewater, artificial intelligence

Introduction

Development of industry plays an important role in consumption of water. It leads to a great increase in water usage. New water supplies all over the world are being searched for, and methods for recycling and re-using the already existing ones are developed. When practically applicable, biological processes are preferred because of economical considerations [1]. Biological processes are generally classified as either aerobic or anaerobic. Aerobic systems tend to be more resilient in being able to handle a larger variety of waste streams and more difficult-to-degrade waste streams, whereas anaerobic systems produce much less sludge and have lower energy requirements because they do not require aeration.

At present, the most widely used biological process for industrial wastewater treatment is activated sludge. It refers to a continuous or semi-continuous aerobic method for industrial wastewater treatment. In the presence of adequate nutrients and oxygen, a high rate of microbial growth and respiration is achieved, causing high rate removal of biodegradable organics and other contaminants. In addition, the treatment system is required to produce a good clarifying and settling sludge by well flocculation and control of proliferation of filamentous organisms.

Wastewater treatment plant

At present time, unit operations and processes are grouped together to provide primary, secondary, and advanced (tertiary) treatment [2]. In primary treatment, physical operations such as screening and sedimentation remove the floating and settleable solids found in wastewater. In secondary treatment, biological and chemical processes remove most of the organic matter. Microorganisms themselves are removed afterwards by sedimentation under aerobic conditions. Part of the settled sludge is recycled to the aeration basin to maintain a high concentration of microorganisms; the rest is drawn off as waste. In advanced treatment, additional combinations of unit operations and processes remove other constituents (nitrogen, phosphorus) not reduced significantly by secondary treatment (*Fig.1*).

The important contaminants of concern in wastewater treatment are listed in *Table 1*. The analyses used to characterize wastewater vary from precise quantitative chemical determinations to the rather qualitative biological and physical determinations.

Table 1 Important contaminants in wastewater [2]

Contaminants	Reason for importance
Biodegradable organics	Composed principally of proteins, carbohydrates, and fats, biodegradable organics are measured traditionally in terms of BOD and COD. If discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen resources and the development of septic conditions.
Suspended solids	Suspended solids can lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment.
Pathogens	Communicable diseases can be transmitted by the pathogenic organisms in wastewater.
Nutrients	Both nitrogen and phosphorus, along with carbon, are essential nutrients for growth. Discharged to the aquatic environment they can lead to the growth of undesirable aquatic life. Discharged in excessive amounts on land they can also lead to the pollution of groundwater.
Priority pollutants	Organic and inorganic compounds selected based on their known or suspected carcinogenicity, mutagenicity, or high acute toxicity.
Refractory organics	These organics tend to resist conventional methods of wastewater treatment. Typical examples include surfactants, phenols, and agricultural pesticides.
Heavy metals	Heavy metals are usually added to wastewater from commercial and industrial activities.
Dissolved inorganics	Inorganic constituents such as calcium, sodium, and sulphate are added to the original domestic water supply as a result of water use.

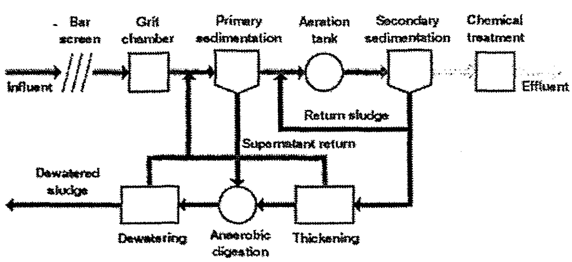

Fig.1 A common layout of a wastewater treatment plant [2]

Instrumentation and control

When properly designed and operated, the activated sludge process is capable of high-quality performance, including the removal of nitrogen and phosphorus. However, it has the reputation of being difficult to operate and can exhibit gross process failure such as sludge bulking, foaming or the loss of nitrifying ability. Therefore, the first objective of the control system must be the prevention of process failure. This is especially important for the activated sludge process since a substantial amount of time (weeks) may be required to fully recover from process failure. Excessive pollution of the receiving water thus takes place not only during the failure period but also during the recovery period.

Once satisfied that the control system is protected against failure, the major concern then becomes high quality effluent in order to satisfy the permit requirements. Only after these two objectives are attained, becomes a third objective, minimization of costs, a matter of concern [3].

Although a plant has many measurements and manipulated variables, most of control loops can be decoupled. It is usually not necessary to apply complex multi-input/multi-output controllers, instead a large number of local control loops keep the plant running. In its basic configuration the secondary treatment, process consists of an aerated tank and the settler (*Fig.2*).

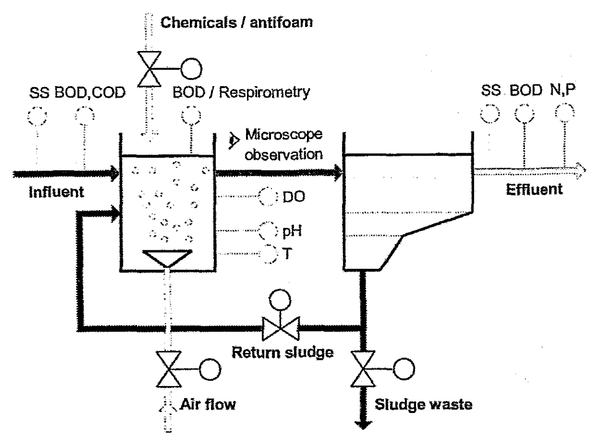

Fig.2 Basic control mechanisms in the activated sludge process

For the control of an activated sludge system, it is necessary to understand which measurements to make and how they relate to the process behaviour. Important types of measurements are biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon, phosphorus fractions, nitrogen in ammonia, nitrite and nitrate, pH, suspended solids (SS) in different units, alkalinity, temperature, dissolved oxygen (DO) in different locations, flow rates between different plant units, air flow rates and air pressure, sludge levels and sludge flow rates. Further, we shall discuss the most important and novel types of process measurements and also typical mechanisms used in control of the activated sludge process.

Biochemical oxygen demand

The most widely used parameter of organic pollution applied to wastewater is the five–day BOD (BOD_5). Unfortunately, the BOD_5 is unsuitable for control purposes, as it requires a five days lasting analysis.

Therefore, methods enabling the continuous measurement of the BOD for monitoring purposes have been developed. These methods yield a short-term BOD (BOD_{st}), which is a more valuable variable for control purposes. The BOD_{st} monitoring methods are classified into three categories [4]: state estimation from a model of the activated sludge, BOD probe method, and respirometric method.

A BOD probe consists of immobilized living cells, a membrane and a dissolved oxygen electrode. A signal of the probe is a measure of the substrate concentration in the water. The linear range of BOD probes is below the BOD_{st} of most wastewaters, so that samples have to be diluted, which is unsuitable for continuous measurement.

BOD measurement is often used in control of the sludge distribution over the process. There are basically three control variables for the sludge inventory in an activated sludge system. The waste activated sludge flow rate controls the total sludge mass in the system and the sludge retention time can be kept at a desired level. The sludge distribution within the system is controlled by the step feed flow distribution (where step feeding is possible) or the return sludge flow rate. The former can dynamically redistribute the sludge within aerator while the latter can shuffle sludge between the settler and the aerator [3].

Respirometry

Respirometry is the measurement and interpretation of the biological oxygen consumption rate under well-defined experimental conditions. Because oxygen consumption is directly associated with both biomass growth and substrate removal, respirometry is one of the most important means of modelling, monitoring and operation of the activated sludge process.

All respirometers are based on measuring the rate at which biomass takes up DO from the liquid [5]. This can be done directly by measuring DO or indirectly by measuring gaseous oxygen. Most techniques based on the measurement of oxygen in the liquid phase use an electrochemical DO sensor. DO mass balance over the liquid phase is used to determine the respiration rate of the biomass.

The main advantage of measuring oxygen in the gas phase is elimination of possible difficulties, like formation of sludge film on the sensor. Oxygen is one of the few gases that show paramagnetic characteristics, so it can be measured quantitatively in a gaseous mixture. However, in addition to the mass balance on the liquid phase, a balance on the gas phase must be also considered.

Respirometric data obtained with effluent sample are often used to adjust both return sludge flow rate and waste sludge flow rate to maintain the sludge concentration at a level desired for quality of wastewater remediation. Although the incoming wastewater flow cannot be manipulated at will, some possibilities may exist where detention basins are available. A feed-forward strategy based on respirometric measurements of the incoming wastewater may be used to alert and handle the situations concerning the toxic or high strength wastewater inflow. It is also possible to combine the respiration rate of the incoming wastewater with the respiration rate of the return sludge to calculate the return sludge flow rate necessary to handle the organic matter.

Chemical oxygen demand and suspended solids

On-line measurement of UV absorption and turbidity can be used to estimate the actual level of COD and SS in the wastewater. The relationship between COD and UV absorption, and between SS and turbidity are linear [6]. SS data may be used to estimate actual biomass concentration or to evaluate effectiveness of capturing suspended particles in settling tanks.

Dissolved oxygen control

Common DO sensors are normally used to obtain data on dissolved oxygen concentration in different plant units. The choice of the optimal DO setpoint is a crucial question for the control of the process. In order to obtain high effluent quality, the sludge needs to have a combination of good clarification and thickening properties. This can be reached by use of a mixed population model having two competing organism types, floc-forming and filamentous organisms. A time-varying DO concentration controlled according to a time-varying setpoint can lead to the co-existence of both population types thus resulting in sludge with ideal settling properties.

However, even the static DO setpoint control involves several difficulties. The DO dynamics is both nonlinear and time-varying. Moreover, considering the long time constants and random influent disturbances, any tuning of a conventional controller becomes tedious. Using cascade control with secondary measurement of gas flow and secondary feedback controller of gas flow the dynamic response to load changes may be greatly improved [3]. A disadvantage of conventional feedback control or cascade control is that the correction for disturbances does not begin until the process output deviates from the setpoint. Feedforward control using measurement of disturbances offers large improvements in this case. The use of the adaptive controllers (KO et al. [7]) should also be considered.

Foaming control

Filamentous microorganisms are responsible for the foam formation in most cases. The application of toxicants is effective for all foam-formers. The control of foam-forming microorganisms by toxicants has to be accompanied by a regular microscopic examination of the consortium of both foam and mixed liquor to avoid overdosing.

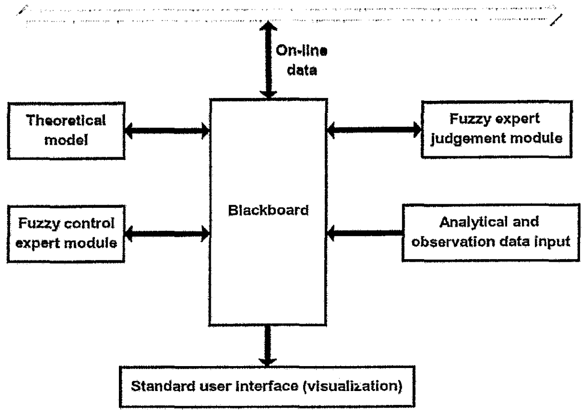

Fig.3 Blackboard concept

An expert system may be used to simplify this rather complex problem so that someone with minimal microbiological training can identify the general health of the biological reactor and process data from microscopic observations [8, 9]. Methods for the on-line image processing are also used [10] to monitor conditions of the activated sludge process.

The application of antifoam agents is a rather costly and uncertain method. That is why foaming is also addressed by the use of mechanical foam breakers [11].

Dosage of chemicals and pH control

Dosage control of chemicals is often based on feedback, such as flow rate. In some cases the dosage rate may be adjusted to the water quality obtained in lab tests or on-line measurements. Possible approach may be the dosage adjusted from historical data and regularly corrected by off-line quality tests [3].

The pH control is important for cell growth rate in biological systems. However, pH control has difficulties due to its nonlinearities and time-varying properties. LEE et al. [12] propose the use of the titration curve to transform the measured pH value to the total ion concentration. Then the PI controller is used to control the total ion concentration value rather than the pH value.

Application of artificial intelligence

It is obvious that overall modelling of wastewater treatment system by a single knowledge representation is almost impossible, since biological wastewater treatment processes have very characteristic features that must be considered [13]: nonlinearity, unsteadiness, complexity of the process, poor process understanding and dependence on empirical knowledge, lack of kinetic information on bacteria and the change of control objectives under irregular conditions.

Mathematical dynamic model can describe the unsteady, complex, and nonlinear nature of the target system. On the other hand, linguistic representation,

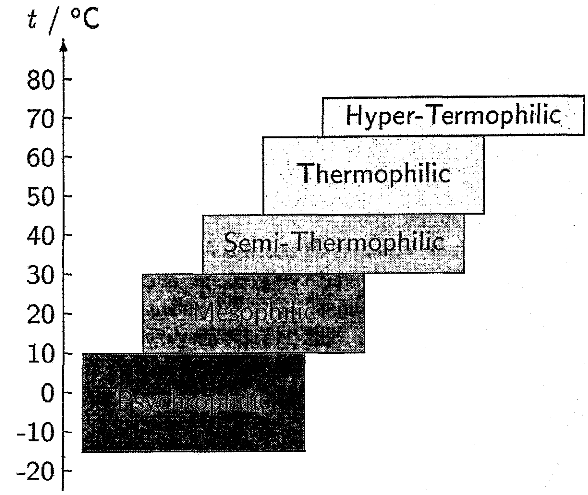

Fig.4 Classification of biological processes according to the temperature

such as an expert system, is necessary to describe the bulking phenomenon and to judge circumstances that may require a change in control objectives. A fuzzy controller is very useful to incorporate the rules of thumb of operators. The applications of communities of such modules, which interact by cooperation, coexistence or competition, are discussed in several publications [14, 15] and are used in creating so called knowledge-based control systems.

In this context the blackboard architecture [8, 13] is adopted to organize various knowledge representations, data manipulation methods, and modelling methods. The blackboard concept is a widely used control metaphor in the field of artificial intelligence, where multiple software agents must contribute collaboratively to achieve system objectives. Based on this concept all reusable data are stored in abstract database and used in the knowledge-based control system (*Fig.3*).

Expert systems are intended to solve those aspects of problems that are traditionally solved using expert human judgement and experience. Both on-line and off-line expert systems are used to operate wastewater treatment process. The on-line system recognises process failures from on-line signals and immediately starts the diagnosis and gives proper advice. The off-line systems are used for the diagnosis of process upsets and solving of simulated plant problems as well as the choice of control parameters [16].

As mentioned above, the activated sludge process is characterised by a lack of relevant instrumentation, the use of qualitative information in decision making, poorly understood complex biological behaviour mechanisms, and control goals that are not always clearly stated. As such it appears to be an ideal candidate for fuzzy control [17, 18]. Recent approaches seem to focus on gaining learning capability using neural nets in hybrid architecture with fuzzy control and fuzzy expert methodologies [8, 19], where the artificial neural network is used as a fuzzy rule extraction method. Proposed system of fuzzy rule acquisition method demonstrated better performance than the conventional fuzzy system.

Thermophilic aerobic treatment systems

According to the growth temperature biological processes are classified as psychophilic, mesophilic, semi-thermophilic, thermophilic and hyper-thermophilic (*Fig.4*). Thermophilic aerobic degradation systems combine the best features of both anaerobic and aerobic processes, because they have the kinetic resilience of conventional aerobic systems while having the low sludge production characteristics of anaerobic systems. The higher temperatures employed in thermophilic systems tend to facilitate the biodegradation of waste streams that contain components more soluble at higher temperatures (e.g. fats, oils, and grease wastes). Moreover aerobic thermophilic processes are able to deal with waste streams with high salt concentrations that are problematic for anaerobic systems [1]. Thermophilic aerobic systems are very similar to the activated sludge systems. However, thermophilic aerobic digestion also presents it's own difficulties. First of all, it is difficult to transfer oxygen in high temperature fluids because of the reduced saturation value for oxygen at higher temperatures.

A foaming tendency also exists because of two combined factors. The first factor is that thermophilic aerobic biological treatment systems are usually operated at high biomass concentrations (10 to 30 g/l of suspended solids). The maintenance of high solids concentrations results in the accumulation of relatively high levels of microbial surfactants, which are foaming agents. This situation along with the fact that relatively high levels of air are introduced into a thermophilic aerobic biological reactor creates the potential for foaming and associated operational problems.

Also high reactor temperatures in thermophilic aerobic systems alter the physical, chemical and biological characteristics of the treatment process. All this means that the knowledge base for conventional activated sludge operations no longer directly applies and has to be adapted along with control methods themselves.

Conclusions

The paper describes an essential part of a preliminary background research concerning measurement, modelling and control of the activated sludge wastewater treatment process with the aim to apply these methods for control of relatively new and promising thermophilic aerobic digestion process for industrial (mainly food) wastewater remediation. Theoretical problems of measurement, modelling and control of these processes and practical aspects of the creation of an appropriate knowledge-based control system using artificial intelligence methods are discussed as well.

Thermophilic processes as a kind of biological processes have all their typical characteristics as complexity, nonlinearity and time-dependence. That is why it is supposed that different knowledge representations and artificial intelligence control methods will be of a great importance for solving control task and will be mainly applied. On the other hand, despite automation, the role of a human supervisor is still very important. His ability of sensual perception of many phenomena and his reasoning is superior to any sensor. A combination of automatic control and computer assistance for the operator seems to be a powerful tool for better operation.

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SYMBOLS

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
N	Nitrogen
P	Phosphorus
SS	Suspended Solids
T	Temperature

REFERENCES

1. ROZICH A. and COLVIN R.: Design and Operational Considerations for Thermophilic Aerobic Reactors Treating High Strength Wastes and Sludges. Purdue Industrial Waste Conference, West Lafayette, USA, 1997
2. TCHOBANOGLOUS G. and BURTON F.: Wastewater Engineering: Treatment, Disposal and Reuse. McGraw-Hill, New York, NY, USA, 1991
3. ANDREWS J.: Dynamics and Control of the Activated Sludge Process, Technomic Publishing, Lancaster, PA, USA, 1992
4. SPANJERS H., OLSSON G. and KLAPWIJK A.: Wat. Sci. Tech., *1993*, 28(11-12), 401-414
5. SPANJERS H. and VAN ROLLEGHEM P.: Respirometry in Control of the Activated Sludge Process: Principles. Scientific and Technical Report No. 7, IAWQ 1998
6. RUBAN G., MARCHANDISE P. and SCRIVENER O.: Wat. Sci. Tech., *1993*, 28(11-12), 67-78
7. KO K. Y., MCINNIS B. C. and GOODWIN G. C.: Automatica, *1982*, 18(6), 727-730
8. PATRY G. and CHAPMAN D.: Dynamic Modelling and Expert Systems in Wastewater Engineering. Lewis Publishers, Boca Raton, FL, USA, 1989

9. ICHIKAWA M. and SIMIZU K.: Wat. Sci. Tech., *1993*, 28 (11-12), 231-238
10. WATANABE S., BABA K. and YODA M.: Wat. Sci. Tech., *1993*, 28(11-12), 325-332
11. WANNER J.: Activated Sludge Bulking and Foaming Control, Technomic Publishing, Lancaster, PA, USA, 1994
12. LEE B. K., SUNG S. W., CHUN H. D. and KOO J. K.: Wat. Sci. Tech., *1998*, 37(12), 141-148
13. OHTSUKI T., KAWAZOE T. and MASUI T.: Wat. Sci. Tech., *1998*, 37(12), 77-85
14. BAEZA J., GABRIEL D. and LAFUENTE J.: Environmental Modelling & Software, *1999*, 14(5), 383-390
15. PARASKEVAS P. A., PANTELAKIS I. S. and LEKKAS T. D.: Knowledge-Based Systems, *1999*, 12(7), 355-361
16. LADIGES G. and KAYSER R.: Wat. Sci. Tech., *1993*, 28(11-12), 157-164
17. TONG R. M., BECK M. B. and LATTEN A.: Automatica, *1980*, 16(6), 695-701
18. TSAI Y. P. and OUYANG C. F.: Wat. Sci. Tech., *1993*, 28(11-12), 355-367
19. ENBUTSU I. and BABA K.: Wat. Sci. Tech., *1993*, 28(11-12), 333-340