An instrument for the direct determination of oxygen utilisation rate

EW Randall[1]*, A Wilkinson[2], GA Ekama[3]
University of Cape Town, Rondebosch 7700, South Africa
[1]Dept of Chemical Engineering
[2]Dept of Electrical Engineering
[3]Dept of Civil Engineering

Abstract

An instrument which completely automates oxygen utilisation rate (OUR) determination in aerobic biological reactors is described. It controls the dissolved oxygen (DO) concentration between specified upper and lower limits with an on-off solenoid valve in the air supply line and computes with a microprocessor the OUR from the DO versus time curve during the air-off period. In addition to operating as a stand-alone DO meter or DO controller/OUR meter, it can be linked to a host computer (PC) for transfer of the accumulated OUR data for further processing or complete control of the instrument via PC software.

Introduction

The oxygen utilisation rate (OUR) is an important indicator of biological activity in activated sludge reactors; indeed in research at the University of Cape Town, the OUR has formed the primary parameter for delineating the kinetics of the activated sludge process (Dold *et al.*, 1980; Dold and Marais, 1986; Ekama, 1988).

Johnston and Buhr (1982) developed a simple electronic DO controller instrument which simplified OUR measurement in aerobic biological reactors. The electronic controller unit coupled to a DO meter with probe controlled the air supply with an on-off solenoid valve in such a way that the reactor was aerated intermittently to control the dissolved oxygen concentration (DO) between specified upper and lower limits. A DO versus time trace was made on a strip chart recorder connected to the DO meter and the rate at which the DO decreased with time during the air-off periods gave the biological oxygen utilisation rate (OUR); this was calculated manually from the slope of the DO-time trace. [This method gives accurate estimates of the biological OUR only for reactors with long actual hydraulic retention times (>3 h); for short actual hydraulic retention time reactors (<1 h) e.g. the contact reactor of the contact stabilisation system or aerobic selectors, the DO concentration-time slope needs to be adjusted to take account of the gains and losses of DO in the influent and effluent flows to obtain the biological OUR (Ekama and Marais, 1979)].

This paper describes an instrument that completely automates OUR measurement. The calculated OUR values may be viewed on a digital display and are stored in a memory. The instrument may be optionally linked to a personal computer (PC) to transfer the stored data to disk files. The PC may also control the instrument's input/output (I/O) functions in order to implement alternative OUR determination algorithms.

Instrument capability

The instrument is based on the same principle as that of Johnston and Buhr. It comprises a DO and a temperature probe and an electronic unit consisting of a DO meter and controller, a crystal, a microprocessor for computing the OUR, a memory, a key pad for receiving instructions and a liquid crystal display (LCD) for displaying the results. The DO probe, meter and controller components serve to control the DO concentration between selected upper and lower DO set points in the same way as that of Johnston and Buhr. With the aid of the microprocessor, which is driven by a specially written program, the OUR is determined by collecting DO and time data pairs from the DO probe and crystal respectively at a preselected time interval (10 s) during the air-off period (~5 to 10 min) and performing a statistical linear least-square regression analysis on the accumulated data pairs. The LCD displays the current DO concentration and reactor temperature and the current OUR (calculated from the DO-time data pairs collected from the last time the air supply was switched off) together with its corresponding correlation coefficient.

With the aid of the key-pad various instructions can be given to the instrument, such as changing the high and low DO set points or, recalling up to 9 previous OUR readings and their respective correlation coefficients from the previous 9 air-off cycels, for viewing on the LCD. The memory is sufficiently large to retain information on 200 OUR readings which, for the usual activated sludge operating conditions [40 mgO/(ℓ.h)], would span over a period of about 36 h.

Besides operating as a stand-alone DO meter, controller and OUR meter as described above, the instrument can be connected to a host computer e.g. a personal computer (PC). With special programs written for the PC, the data stored in the OUR meter can be transferred to the PC for storage on disk and for further processing on the PC. This may be done with user written programs or with spread sheets which enable high quality plots to be easily produced. In addition, the instrument can be completely controlled from the specially written PC control programs, e.g. adjusting the high and low DO set points and the DO-time data collection time interval, or requesting and transferring to the PC the DO-time and OUR data. The PC control programs make the OUR meter-PC combination a powerful DO and OUR data logging system. The programs allow automatic data transmission from the instrument to the PC as a background task i.e. while the PC is being used for some other function such as word-processing or computation.

Instrument description

A schematic diagram of the instrument configuration is given in Fig. 1.

*To whom all correspondence should be addressed.

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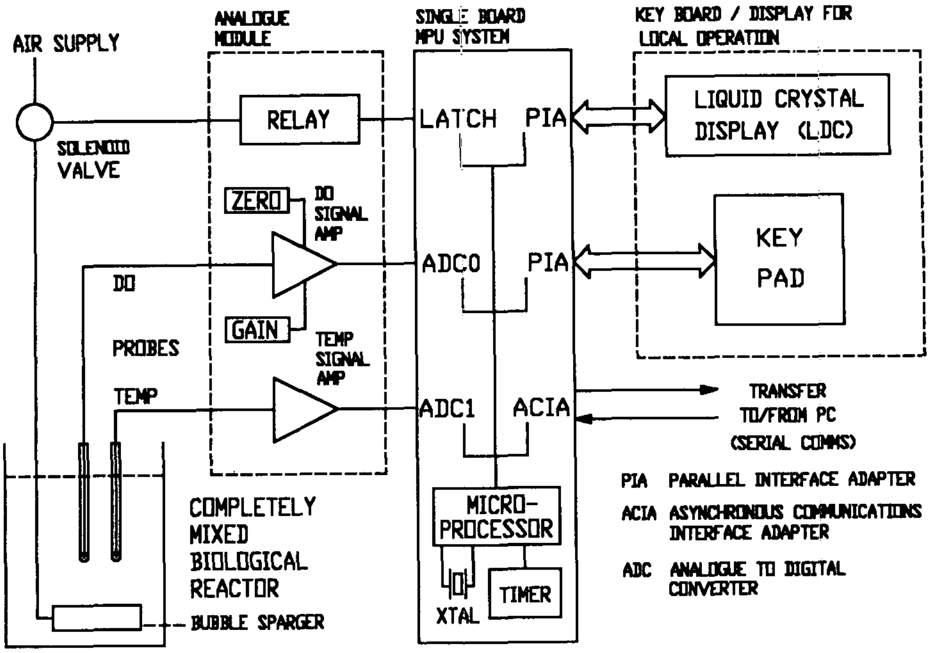

Figure 1

Schematic set-up and layout of the oxygen utilisation rate (OUR) meter, showing the completely mixed biological reactor with bubble aeration and solenoid valve air supply, the dissolved oxygen (DO) and temperature probes, the analogue module for amplifying the DO and temperature signals and relay for controlling the solenoid valve, the single board microprocessor unit with crystal (XTAL), analogue to digital converters (ADC) and adapters (PIA and CIA) for communication with the keyboard and display (for local operation) and personal computer (PC) for remote operation.

System hardware

The instrument consists of an analogue module and a single board microprocessor system. The analogue module incorporates the amplifiers for the DO and temperature probes as well as the relay for control of the air supply solenoid valve. All the timing and data processing functions required for the OUR determination are performed by the microprocessor unit. A schematic layout showing the various components of the instrument is shown in Fig. 1.

A simplified schematic diagram of the DO signal amplifier is shown in Fig. 2. This is essentially a high stability amplifier with facilities for zero and gain adjustment which are required for calibration. The output range of this amplifier is 0 to + 1V which corresponds to a DO concentration of 0 to 10 mg/ℓ. A second amplifier channel is provided on this board for a temperature sensor (National Semiconductors LM35DZ). The temperature, as calculated from this is also displayed, and can be used for temperature correction of the DO signal if non-internally compensated probes are used. With a suitable display device (e.g. a digital panel meter) this circuit can function as a self standing DO meter.

The solenoid valve control relay required for switching the air supply on and off in accordance with the upper and lower DO set points, is located on the DO meter circuit board.

The microprocessor unit is an in-house design, details of which have been published by Randall and Flach (1985) and Randall and Dold (1988). This is essentially a singleboard computer and is supported by standardised memory resident software routines (EPROM). These routines provide input/output (I/O) functions such as reading the analogue to digital converters (ADCs) (DO and temperature signals), reading the key-pad, writing to the LCD and communicating with the host PC. Utilising these routines simplifies the development of application specific tasks such as those required for the OUR meter.

The operation of all the input/output (I/O) devices of the OUR meter, which are shown in Fig. 1, is controlled by the microprocessor unit under program control. The DO and temperature signals from the analog section are connected to two channels of the National Semiconductors ADC1205. This ADC gives a 12-bit resolution, i.e. 1 part in 4095. The input range is set from 0 to 4,095V thus giving a resolution of 1 mV/bit or 0,01 mg/ℓ DO per bit. An output latch is used to control the air supply solenoid valve via an external relay. A parallel interface adapter (PIA) is used to drive the LCD and key-pad. A serial communication port (asynchronous communications interface adapter, ACIA) provides the link to a host computer, such as a PC.

Microprocessor software

The main program is coded in the Pascal language with calls to the standard low level routines for performing I/O functions. Program development was done on a PC and finally compiled for installation on the microprocessor unit. To test the program logic before installation, procedures were written which emulated all I/O functions of the OUR meter.

A flow sheet, indicating the major program sections and the sequence in which they are called, is shown in Fig. 3. After the initialisation sequence, the program cycles through one of two

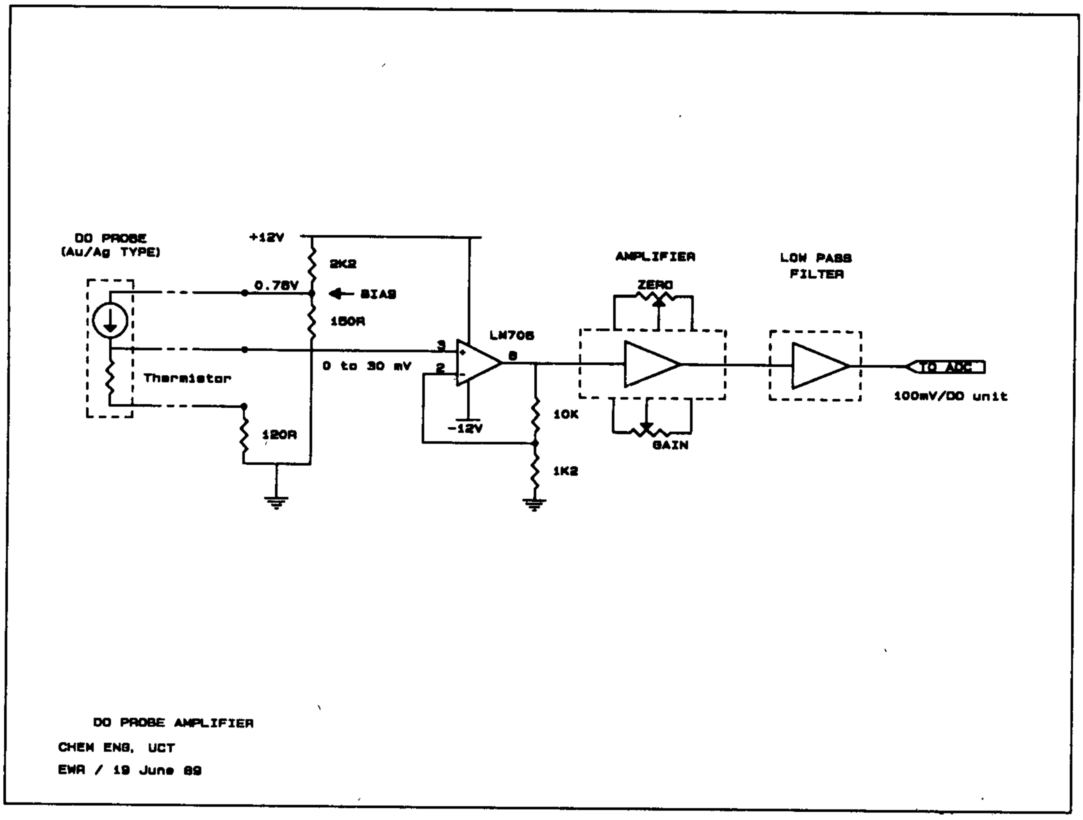

Figure 2
Schematic layout of the circuit diagram for amplifying the dissolved oxygen probe signal.

endless loops, depending on the operating mode selected (Mode A or Mode B). Each loop contains the required numerical procedures, key-pad scan and LCD update routines, and a routine to respond to instructions from a host PC.

Statistical functions

To facilitate the regression analysis of the collected DO-time data pairs the following statistical functions were written for the variables time (X) and DO concentration (Y):

ClearSigma - Clears all variables at start of each curve-fitting procedure.

UpdateSigma - Calculates running totals of X, Y, XY, X^2, Y^2 and N (the number of data points collected).

CalcStat - Calculates the following statistical parameters based on the current values of the running totals, average and standard deviation of X and Y values, slope of the line (i.e. the OUR) by linear least square regression, the Y intercept of the line, and the correlation coefficient.

OUR determination

The method of OUR determination is best explained by considering a complete cycle of operation as the DO changes from maximum (high set point) to minimum (low set point) and back to maximum during an on-off aeration cycle. The saw-tooth waveform of the DO concentration-time trace obtained with on-off aeration is shown in Fig. 4.

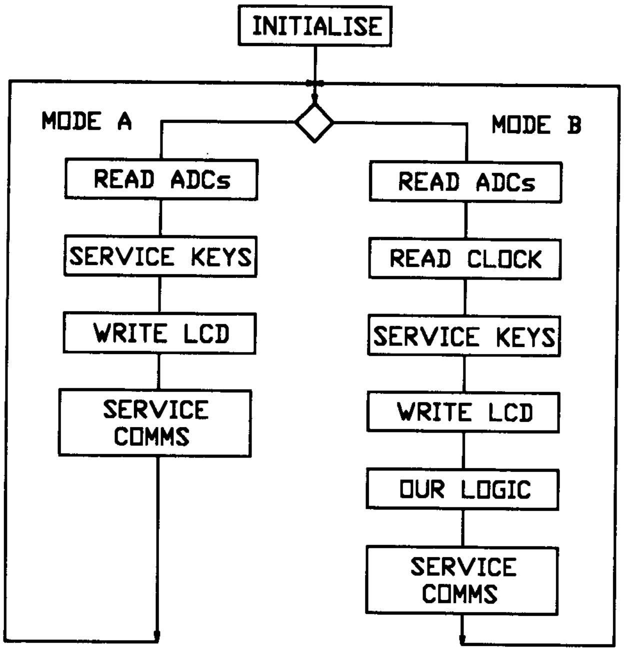

Figure 3
Flow diagram of the OUR meter program indicating operations when functioning as a DO meter (mode A) or as an OUR meter (mode B).

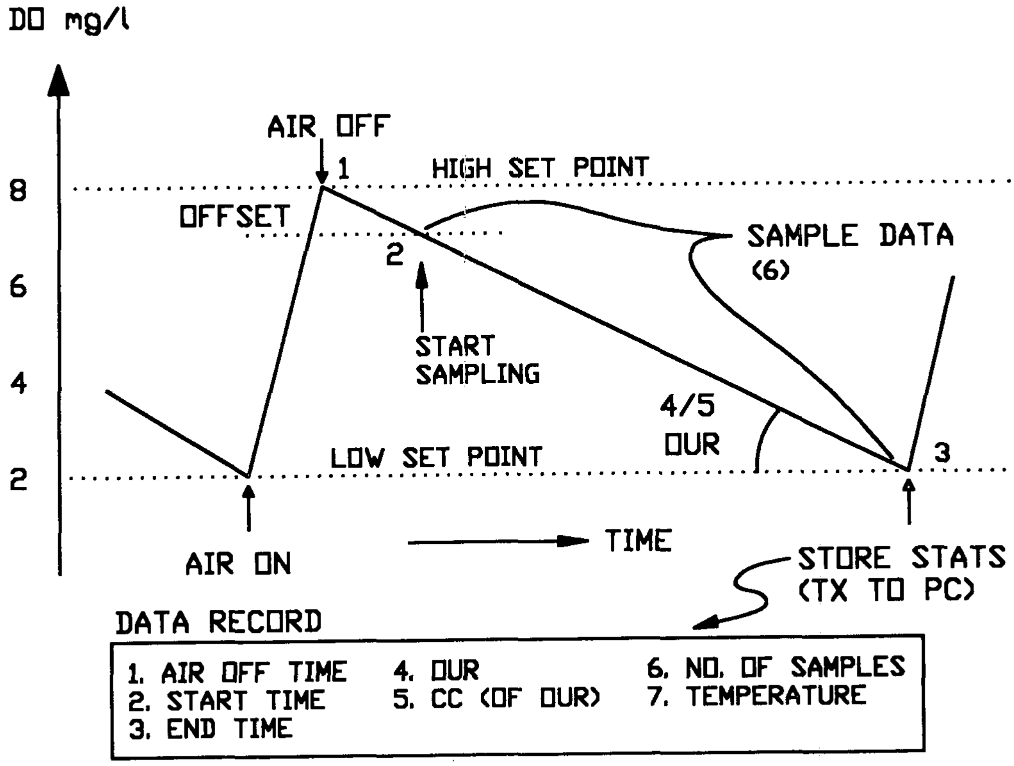

Figure 4
Dissolved oxygen (DO) versus time trace for one air-on air-off cycle when DO concentration is controlled between 2 (low DO set point) and 8 mg/ℓ (high DO set point) showing the region of DO-time data collection (sample data) and the 7 items of information that are stored by the OUR meter at the air-on time.

After the high DO setpoint is reached the air supply is switched off and the DO starts to decrease due to the biological uptake of oxygen. To ensure that at the time of aeration cessation no transient values affect the slope (OUR) calculation, the statistical routines are activated only at a specified value (default 0,5 mg/ℓ) of DO (offset) below the high DO setpoint. At this point the ClearSigma procedure is called, thereafter UpdateSigma is called at the specified DO and time data collection frequency (default 10 s). Data collection continues until the low setpoint is reached, at which point CalcStats is called and the air supply is switched on. Upon completion of CalcStats, the following information is stored:

- OUR;
- its correlation coefficient;
- number of DO-time data pairs collected;
- air-off time;
- start data collection time; and
- stop data collection (air-on) time.
- water temperature

The internal memory of 4K bytes RAM is sufficient to store the data from 200 operating cycles, which is equivalent to about 36 h of operation under typical activated sludge system operating conditions [~40 mg O/(ℓ.h)].

Operating modes

The instrument can be controlled locally (in which case instructions are given to it via the key-pad on the instrument) or remotely (in which case instructions are given to it via a host PC). Under local or remote control, the instrument has two operating modes: as a DO meter (mode A); and as a DO meter/controller/OUR meter (mode B).

Under local control, in mode A, the current DO and temperature are displayed on the LCD. Via the key-pad, three instructions can be given to the instrument, viz: (1) switch air supply on; (2) switch air supply off; and (3) select mode B. In mode B, the current DO and temperature and default high and low DO set points are displayed on the LCD. Via the key pad, six instructions can be given to the instrument, viz: Instructions (1) to (4): increase and decrease high and low DO set points; (5) select mode A; and (6) display current and historical OUR/correlation coefficient data. The current OUR and its correlation coefficient are based on the DO-time data collected up to the particular time in the current air-off cycle. Up to 9 historical OURs with their respective correlation coefficients, from the 9 previous air-off cycles, can be recalled and viewed on the LCD. When viewing OUR/correlation coefficient data on the LCD via key-pad instruction, these replace the current high and low DO set point values, until the key pad button is released, whereupon the DO set-points again appear on the LCD.

Under remote control, the instrument is given instructions via the host PC. In mode A, the same three instructions can be given to the instrument as under local control via the key-pad, i.e. (1) switch air supply on; (2) switch air supply off; and (3) select mode B. Additionally, the PC can request from the instrument the current DO and temperature readings and the mode currently in operation. In mode B, the instructions that can be given to the instrument are not only those that can be given via the key-pad in mode B viz., (1) select mode A; (2) specify DO set points; but also

6 additional instructions that make the instrument-PC combination a powerful OUR data logging system. Via the PC, the 6 additional instructions ((3) to (8) below) that can be given are:

(3) specify DO-time data collection time interval;
(4) specify DO concentration offset from high DO set point at which DO-time data collection commences;
(5) set or (6) clear flag for automatic OUR data transfer to PC and;
(7) set or (8) clear flag for automatic transfer of DO-time data.

The PC logging programs were specially written so that the automatic data transmission instructions, when set (Instructions 5 and 7) operate as a background task on the PC i.e. the PC receives the transmitted data while it is being used for something else completely unrelated to the data logging e.g. word processing or computation. The automatic OUR data transfer (Instruction 5) occurs after each slope calculation, i.e. when the DO reaches the low DO set point [typically every 5 to 10 min at an OUR of 40 mgO/(ℓ.h)] and the data that are transferred are the seven items that are stored in the instrument's local memory (see Fig. 4). The automatic DO-time data transmission (Instruction 7) also occurs when the DO reaches the low DO set point; at this time all the DO-time data collected during the air-off period are transferred. This operation occurs in addition to the instrument calculating the OUR and storing the seven parameters as normal. The transfer of the raw DO-time data allows alternative OUR calculation techniques to be implemented on the PC. For example, in short actual retention time reactors (< 1 h) linear DO-time traces are not obtained because the DO in the reactor effluent contributes in decreasing amounts to the OUR as the DO decreases and needs to be taken into account to determine the biological OUR correctly (see **Introduction**).

Under remote control in mode B, the PC can be used to make five requests to the instrument, the responses to which are displayed on the PC screen, (1) mode: give instrument mode of operation (A or B); (2) instrument status: give information such as current high and low DO set points, DO-time data collection interval, DO offset at which DO-time data collection commences and mode; (3) DO and temperature: give current DO and temperature; (4) transfer DO-time data: give the DO-time data collected during the current air-off cycle; and (5) transfer historical OUR data: give all the OUR data stored in the instrument memory. Request (4) and (5) of course are not relevant when the instrument has been instructed to auto-transfer OUR or DO-time data (Instructions 5 and 7).

A summary of all the instructions and requests in local and remote control with the instrument operating in modes A or B, is given in Table 1.

PC software

Three Pascal (Borland's Turbo Pascal Version 5) programs (DOLOG, DOTSR and DOBUF) were written for the host PC computer that performs all the remote control and data logging instructions outlined above and summarised in Table 1.

- DOLOG implements all the "command" and "request" functions, listed in Table 1. When automatic transfer of data is disabled i.e. flag cleared for automatic transfer of OUR and DO-time data (Instructions 6 and 8 in Table 1) the data returned to the PC by the requests are printed on the screen and if required, are written to disk file for subsequent analysis by other user written programs or by spread sheets. This program is normally run every 24 h to extract the OUR data from the OUR meter (i.e. Request - OUR history).
- DOTSR and DOBUF allow background logging of data automatically transmitted by the instrument i.e. when automatic transfer of data is enabled (Instructions 5 and 7 in Table 1). The DOTSR program consists of an initialisation section and an interrupt driven routine which reads characters from the communications port and stores them in ring buffer. After completion of the port initialisation and setting up of the ring buffer, control is returned to the operating system. The inter-

TABLE 1
INSTRUCTIONS THAT CAN BE GIVEN TO OUR METER VIA KEY-PAD (LOCAL CONTROL) AND VIA THE PC (REMOTE CONTROL)

Operating mode	Local control key-pad	Remote control-PC communications Instructions	Requests
A	1)Air on	1)Air on	1)DO and temp.
	2)Air off	2)Air off	2)Mode
	3)Sel mode B	3)Sel mode B	
B	1)Inc Hi set-pt*	1)Specify set-points	1)Mode
	2)Inc Lo set-pt*	2)Specify offset	2)Status
	3)Dec Hi set-pt*	3)Specify sample rate	3)Current DO and Temp.
	4)Dec Lo set-pt*	4)Sel mode A	4)DO-time data
	5)Sel mode A	5)Set auto-tx** OUR data	5)OUR history
	6)Display OURs (0 to 9)	6)Clr auto-tx** OUR data	
		7)Set auto-tx** DO-time data	
		8)Clr auto-tx** DO-time data	

*pt = point; **tx = transmit.

rupt routine, however, remains resident in the PC's memory and responds to characters arriving from the instrument. A program of this type is known as a TSR (terminate stay resident) and the Turbo Pascal compiler provides a means for setting these up. During data capture via this program the PC is free to perform other tasks such as word processing. The program DOBUF retrieves data inserted into the ring buffer by DOTSR. This is executed periodically and enables the collected data to be viewed or written to a disk file.

Results of operation

To demonstrate the usefulness of the instrument and ease with which it can be used to obtain reliable OUR data, the OUR results from two types of activated sludge experiments are shown in Figs. 5 and 6. In Fig. 5, the OUR data measured in the aerobic reactor of a constant flow and load (steady state) anoxic-aerobic long sludge age system are given. Without any operator intervention, the instrument automatically controlled the DO between 1 and 3 mgO/ℓ and measured and stored the OUR over a period of 11 h. The data accumulated in memory were transferred to a PC for inspection and plotting (see Fig. 5). The correlation coefficients of all the OUR data were between 0,99 and 1,00, indicating that all the DO-time slopes were very close to linearity, which in turn indicates that accurate OUR data were obtained. As expected for a steady state system, the OUR remained approximately constant, in this particular experiment between 31 to 32 mgO/(ℓ.h). In this steady state experiment, not only was the DO controlled between 1 and 3 mgO/ℓ, but also in doing so, an accurate measure of the steady state OUR was obtained.

In Fig. 6, the OUR results of a non-steady state experiment are shown. A volume of 1,3 ℓ of sludge was harvested from a steady state system like that described above and, after inhibiting nitrification by adding Allylthiourea, was placed in a batch reactor. The OUR meter was initialised and set to control the DO between 2 and 6 mgO/ℓ and it commenced to measure the OUR. Two hours after start-up, 1,7 ℓ of raw sewage was added to the batch reactor and thereafter the OUR meter continued to measure the OUR without any operator attention for a period of 26 h. The data accumulated in memory were transferred to a PC for inspection and plotting (see Fig. 6). The correlation coefficient of all the OUR data was between 0,99 and 1,00. This indicated that even though the OUR varied considerably over the 26 h period, the DO-time slopes all were very close to linearity, and consequently it was concluded that accurate OUR data were obtained.

Application

The instrument can be applied directly for automatic OUR measurement in biological reactors (1) with long actual hydraulic retention times (> 3 h); (2) where mixing and aeration are independent operations; and (3) where aeration is provided by a diffused air bubble aeration system. These 3 conditions need to be met because at short actual retention times the slope of the DO-time trace is not necessarily linear or equal to the biological OUR; good mixing needs to be maintained during the air-off (non-aeration) cycle so that representative DO-time data can be collected; and diffused air bubble aeration facilitates simple on-off air supply control. These conditions usually are met in laboratory or pilot-scale activated sludge systems.

In full-scale systems, one or more of the above conditions generally are not met; in particular condition 2 is not met because usually the aeration system provides mixing in the biological reactors. For full-scale systems, therefore, the OUR meter can be implemented only indirectly in a satellite reactor (say 200 ℓ) with independent mixing and diffused air bubble aeration. The simplest method is to pump mixed liquor at a continuous and constant rate from the particular point in the aeration basin where the OUR needs to be determined. This flow is discharged into the satellite reactor, where the OUR meter-solenoid valve-diffused air aeration system controls the DO concentration between the required high and low set points. The flow rate and volume of the satellite reactor should be selected so that the retention time is around 3 h; this retention time is sufficiently long that the DO concentration entering and leaving the reactor with the influent and effluent flows will not significantly influence the OUR obtained from the DO-time trace during the air-off cycle, and is sufficiently short (in terms of normal aerobic reactor retention times) to still give reasonably representative OUR readings for the point of mixed liquor abstraction. It should be noted that the abstraction flow need not be constant but the retention time should not change significantly from 3 h. It is likely that the flow rate will decrease due to progressive blocking of the suction end screens - if the retention time increases above 4 h, it is recommended that the suction end screens are cleaned. Alternatively, instead of the continuous flow method, the intermittent flow batch fill and draw method developed by Nicholls (1982) could be employed.

Conclusions

The oxygen utilisation rate (OUR) is an important parameter for assessing biological activity in, and developing the kinetics of, aerobic degradation reactions in biological reactors. To facilitate OUR determination, an instrument was developed which completely automates its measurement. It comprises a dissolved oxygen concentration (DO) and a temperature probe, an analog module for amplifying the signal from the DO and temperature probes, a microprocessor unit which performs the timing functions; reads the DO, temperature and time signals; and performs the data processing functions such as calculating the OUR. The instrument controls the DO between specified upper and lower set points with an on-off solenoid valve in the air supply line and computes with the microprocessor the OUR from the DO versus time trace during the air-off period by means of a linear least squares regression analysis. The instrument incorporates a local memory, wherein information on up to 200 OUR readings can be accumulated.

In addition to operating as a stand-alone DO meter and DO controller/OUR meter, it can be linked to a host computer such as a personal computer (PC) for transfer of the accumulated OUR data for storage on disk file or further processing and graph plotting; and for complete control of the instrument via PC control programs. The PC control programs make the instrument-PC combination a powerful OUR data instrument to the PC as a background task i.e. while the PC is being used for other duties e.g. word-processing or computation.

The instrument can be applied directly for automatic OUR measurement in biological reactors of laboratory and pilot systems where aeration and mixing are independent operations and aeration is by diffused air bubble aeration. In full-scale systems, where usually aeration and mixing are not independent, the instrument can be implemented on a satellite reactor which is continuously or batch fed from the full-scale biological reactor.

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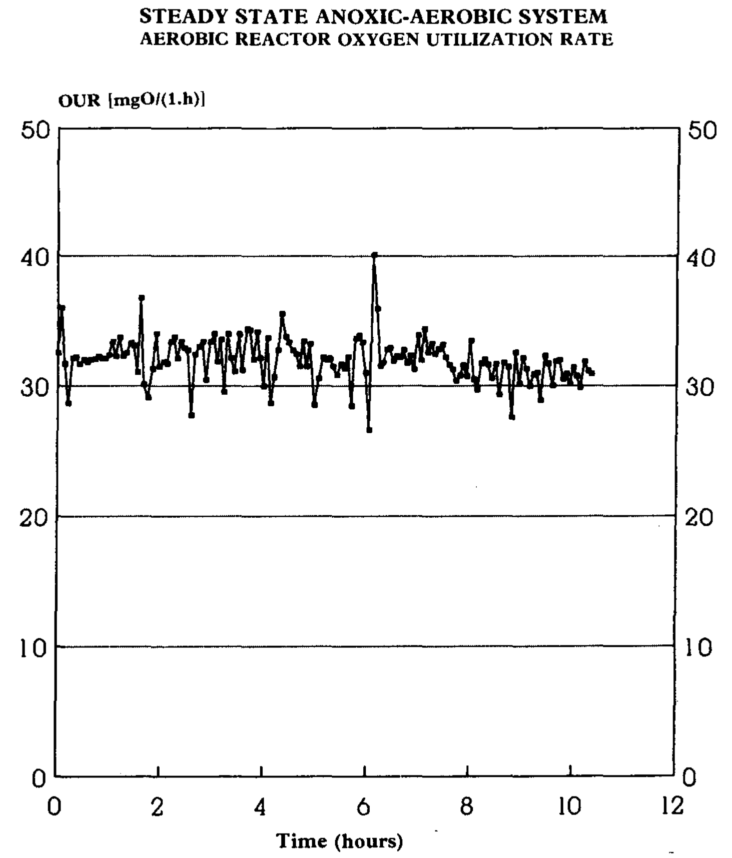

Figure 5
Oxygen utilisation rate versus time data measured and accumulated by the OUR meter in the aerobic reactor of a long sludge age anoxic-aerobic activated sludge system under constant flow and load conditions (steady state).

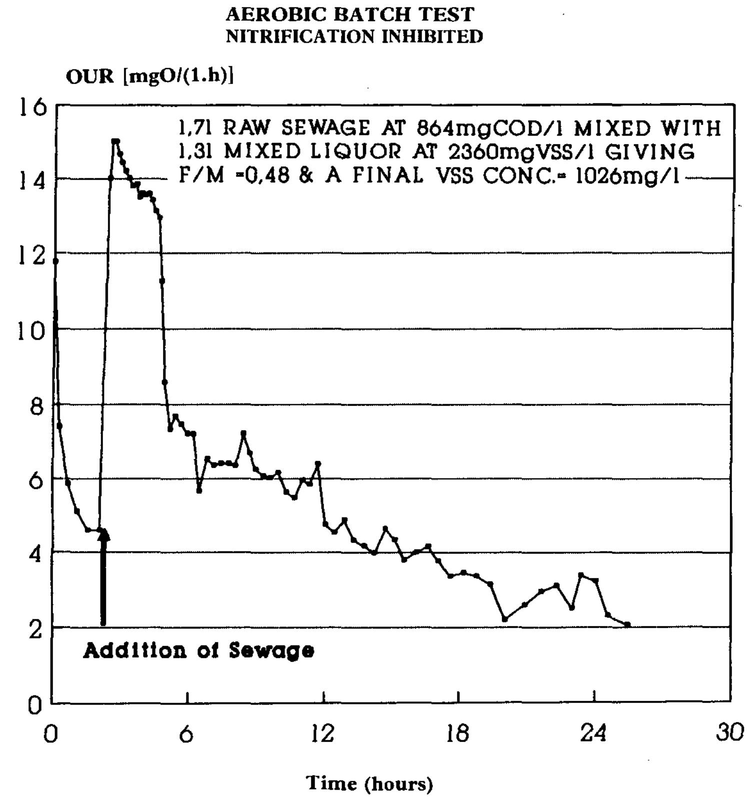

Figure 6
Oxygen utilisation rate versus time data measured and accumulated by the OUR meter in an aerobic batch test in which a slug of sewage was added to activated sludge and aerated for 24 h.

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