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Respirometric kinetic parameter calculations of a batch jet loop bioreactor treating leachate and oxygen uptake rate estimation by DTM

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Abstract

A novel circulating jet loop bioreactor adapted for organic matter oxidation has been designed and constructed. In this study, the input was leachate samples collected from Kemerburgaz Odayeri waste landfill site located on the European side of Istanbul. Controlling the jet loop bioreactor to realize high rates of purification depends on maintaining the appropriate loadings and operating conditions. This requires collecting various system data to estimate the dynamics of the system satisfactorily with the aim of keeping certain parameters within the specified range. The differential transform method (DTM) based solution of the state equations reveals the current state of the process so that any deviation in the system parameters can be immediately detected and regulated accordingly.

The respirometric method for kinetic parameter calculations for biodegradation has been used for some time. In many studies, the respirometer was designed separately, usually in bench-scale. However, when a separate respirometer is used, the scale effect and parameters that affect the hydrodynamic structure of the system should be taken into consideration. In this study, therefore, the jet loop reactor itself was used as a respirometer. Thus, the kinetic parameters found reflecting the characteristics of microorganisms used for biodegradation would be more realistic. If the main reactor, here the jet loop reactor, would be used as the respirometer, the kinetic parameter changes can easily be monitored in the long run. Using the bioreactor as a respirometer, the most important kinetic parameters, K_s, k_d and μ_{max} were found to be 11,000 mg L^{-1}, 0.019 day^{-1}, and 0.21 day^{-1}, respectively. The stoichiometric coefficient, Y, was found to be 0.28 gr gr^{-1} for the present system.

Keywords: Respirometric kinetic parameters; Jet loop bioreactor; Leachate treatment; Differential transform method

1. Introduction

As it is known, landfills are the mostly preferred option for storing municipal wastes and to some extent for industrial wastes in Europe on the contrary to reuse by recycling, incineration or composting. The Turkish Statistical Institute announced that around 1.6 million m^3 leachate was produced in the 13 landfill sites in whole Turkey in 2005 [1]. Eighty-five percent of leachate is treated on-site, and the rest is discharged directly to the sewer system. Unfortunately, the reported volume of the leachate produced could not be properly treated to meet the stringent wastewater discharge limits. Therefore, there is an urgent need to develop novel systems to reduce the adverse impact of leachate.

The treatability of landfill leachate depends on its composition and characteristics, the biodegradability of the organic matter present, BOD_5/COD ratio, as well as the age of the landfill. Different technologies such as biological technologies including aerobic and anaerobic systems, physico-chemical treatment methods, advanced oxidation processes or natural systems have been used for leachate treatment [2].

Biological treatment, both aerobic and anaerobic treatment (suspended or attached systems), is generally preferred when treating leachate. However, most of the time biological treatment itself is insufficient for the treatment of mature leachate, due to refracter organics present in the wastewater. Therefore, physico-chemical treatments, such as chemical precipitation, activated carbon adsorption, ion exchange or membrane filtration are needed to support the biological treatment [2].

The characteristics of leachate change over time as the landfill ages, therefore the system should also be flexible in adapting itself to changing BOD_5/COD ratios in leachate over time.

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Nomenclature

C	dissolved oxygen concentration under working conditions (mg L^{-1})
C_e	dissolved oxygen concentration at endogenous phase (mg L^{-1})
COD	chemical oxygen demand (mg L^{-1})
DO	dissolved oxygen (mg L^{-1})
k_d	decay coefficient (day^{-1})
K_La	overall oxygen transfer coefficient (min^{-1})
K_s	half saturation rate constant (mg L^{-1})
OUR	oxygen uptake rate (mg O_2 L^{-1} h^{-1})
Q	flow rate (m^3 h^{-1})
r_e	substrate respiration rate (mg L^{-1} min^{-1})
r_s	sludge respiration rate (mg L^{-1} min^{-1})
R_e	specific substrate respiration rate (g g^{-1} day^{-1})
R_s	specific sludge respiration rate (mg L^{-1} min^{-1})
S	substrate concentration (mg L^{-1})
V	volume (m^3)
X	biomass concentration, MLSS (mg L^{-1})
Y	yield ratio (produced microorganism mass per utilized unit organic matter/substrate mass) (g MLVSS g^{-1} COD)

Greek letters

μ	specific growth rate (day^{-1})
μ_{max}	maximum specific growth rate (day^{-1})

Therefore, the use of jet loop bioreactors can be an alternative to the classical biological treatment methods, since, these systems have become bulky and obsolete, as they need large areas to be built. Jet loop bioreactors, which are developed in parallel to the progresses in bioengineering, can treat wastewaters efficiently and relatively cheaper compared to the conventional treatment technologies [3–5]. These novel bioreactors have some advantages such as having an uncomplicated structure, operation simplicity, well-defined flow regimes, better dispersion impacts, lower power consumption, lower sludge production, improved quality of treated water with low turbidity and high mass transfer [5–8]. One of the most significant features these reactors possess is to achieve high dissolved oxygen concentration by means of the turbulence created throughout the reactor homogenously. It was reported that by means of these features high removal efficiencies were obtained for high strength wastewaters [5]. Therefore, leachate, with complex and unstable compositions, can be treated by this new technology.

In this study, the treatment of leachate collected from a waste landfill site located on the European side of Istanbul, which has been in operation since 1995, was studied using a jet loop reactor. The efficacy of the jet loop bioreactors can be affected by the changes in several parameters during operation. Data on biodegradation kinetics is, therefore, essential for the performance evaluation. Additionally, it is important to understand the system kinetics and dynamics properly, in order to detect sudden upsets and impending failures, and then compensate for them. It is also crucial from the point view of energy save to adjust on–off times of the compressor for the aeration process by getting use of the monitored system dynamics.

Consequently, the aim of this paper is to determine the kinetic parameters of the system using respirometric analyses and to solve nonlinear equations related to the process using differential transform method (DTM) so that it could be possible to determine the oxygen uptake rate (OUR), which gives information directly on the microbial population and therefore biological activity of the process. This will lead to increase process efficiency by means of supplying correct amounts of dissolved oxygen (DO). The results obtained are expected to provide valuable information for further studies.

2. Materials and methods

2.1. Leachate characteristics and effects on activated sludge

Leachate used in this study was collected from a waste landfill site located on the European side of Istanbul, which has been in operation since 1995. Since leachate characteristics is important in reflecting the biodegradation properties [9], and since the characteristics of landfill leachate might vary dramatically with time, the physical and chemical characteristics of the leachate used was monitored throughout the study and presented in Table 1.

The pH value of leachate was in the range of 7.4–8.1. The mean values of COD and BOD_5 of leachate were 12,225 and 3789 mg L^{-1}, respectively. In general, BOD_5/COD ratio represents the proportion of biodegradable organics in leachate. A large portion of the organic matter in young leachate consists of volatile fatty acids, which are easily biodegradable. Therefore, the BOD_5/COD ratio during this phase is generally 0.4–0.5 or even higher [10]. As the landfill gets older, the BOD_5/COD ratio decreases to almost zero [11]. This is due to the decomposition of most of the organics present in leachate over time. In this study, the mean BOD_5/COD ratio of landfill leachate was found to be 0.31. Total ammonia concentration was found to be quite high, ranging between 2000 and 2500 mg L^{-1}.

When the results obtained from biochemical tests such as catalase oxidase, were evaluated according to the *Bergey's Manual of Systematic Bacteriology* [12], it was proved that there was no *Nitrosomonas* in the mixed liquor taken from the reactor. It was also stated in the literature, that the reason

Table 1
Physical and chemical characteristics of the leachate used

Parameter	Range (mg L^{-1})[a]
pH	7.4–8.1
COD	9800–13025
BOD_5	3150–4500
TSS	1320–1840
TKN	2850–3500
Org N	625–750
Total ammonia	2000–2500
Total P	7.0–8.5

[a]Concentration unit, except pH.

for not encountering any nitrifying bacteria was due to several parameters including, quite high total ammonia concentrations (2000–2500 mg L^{-1}), high pH values (9.4–9.6) and the selectivity of jet loop reactors to microorganism strains. As it is known, free ammonia (FA), which is formed at high total ammonia concentrations, has an inhibitory effect on nitrification. The FA can easily be calculated by an equation proposed by Ford et al. [13,14]. As known, NH_3–N has an inhibitory effect on *Nitrobacter* when the concentrations exceed 0.1–1.0 mg NH_3–N L^{-1} and on *Nitrosomonas* when the concentration is above 10–150 mg NH_3–N L^{-1} [15,16]. Therefore, for the reactor used the high total ammonia concentrations led the FA concentration to be around 1300–1625 mg FA/L which was higher than the threshold value for *Nitrosomonas*. It should also be noted that nitrifying bacteria can retain metabolic activity at certain pH values ranging between 4 and 9. The optimum value for nitrifiers was reported to be 7.5–8.0 [17]. Therefore, in order to prevent the possible nitrification, addition of an inhibitory substance was not required.

2.2. Equipment, instrumentation and operational procedure

A jet loop bioreactor was designed and constructed in Gebze Institute of Technology, Department of Environmental Engineering. The cylindrical reactor (outer tube) and the draft channel (inner tube) were made of plexiglass with a conical bottom (height 113.5 cm, inner diameter 15 cm) with a height to diameter ratio of about 7.5:1, as depicted in Fig. 1a. As the name implies, the jet was formed by the jet head where the wastewater and air, at various ratios, introduced through a nozzle [8,18–21]. A detailed schematic of the nozzle used is presented in Fig. 1b.

In jet loop reactors, circulation is achieved by a liquid jet drive. Liquid is injected into the reactor with a high velocity, causing a fine dispersion of liquid and gaseous phases [7]. Due to the momentum of the liquid jet, the liquid and the gas inside the draft tube flow downwards and after reflection at the bottom of the reactor, the mixture rises between the wall of the reactor and the draft tube. At the upper end of the draft tube, a part of the fluid is recycled into the draft tube by the sucking action of the two-phase jet resulting in a homogeneous dispersion of the bubbles and the biomass produced in the biological reaction [6]. The biomass concentration was around 3800 mg L^{-1} during the experiments.

2.3. Calculation of kinetic and stoichiometric parameters by respirometric methods

Determining specific kinetic parameters of the batch jet loop bioreactor process for treatment of leachate is an important issue in establishing a viable mathematical model in designing effective control strategies. The most important parameters required for biological removal process include the stoichiometric parameter Y, and the kinetic parameters K_s, k_d and μ_{max}.

The stoichiometry between the organic substrate consumed and microorganisms produced can be expressed as:

$$\frac{dX}{dt} = Y\frac{dS}{dt} - k_d X \quad (1)$$

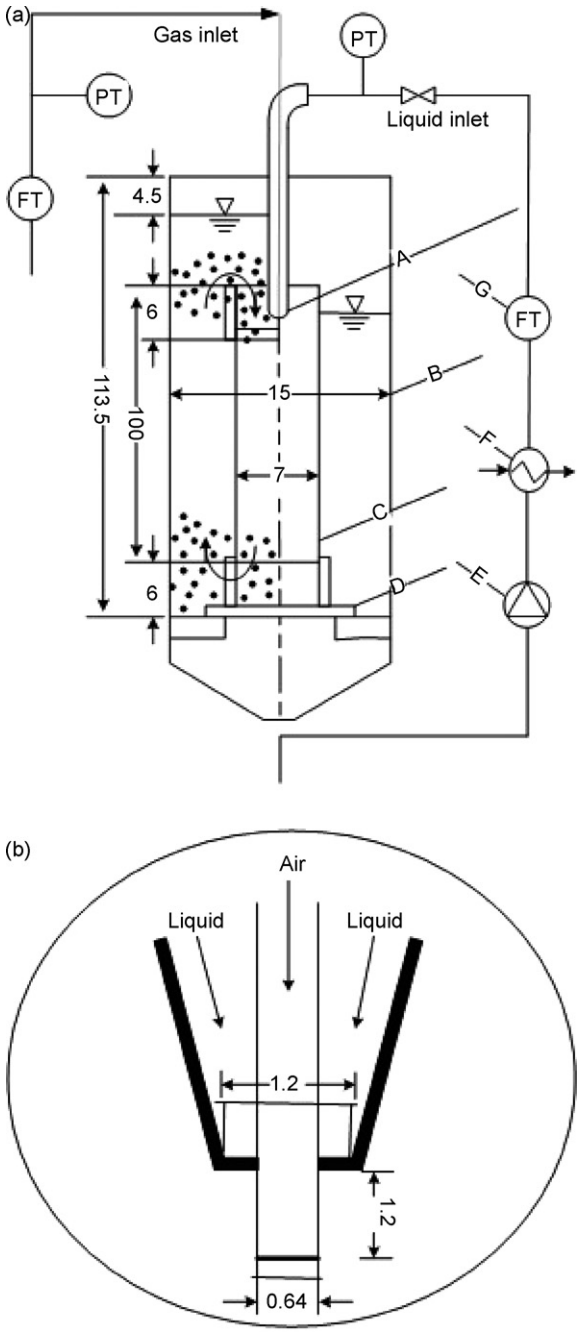

Fig. 1. (a) A schematic of the experimental setup (dimensions are given in cm): (A) nozzle head; (B) reactor; (C) draft tube; (D) impact plate; (E) circulation pump; (F) multimeter (to measure dissolved oxygen, pH and temperature). (b) A detailed schematic of the nozzle.

The first term of the right-hand side of the equation indicates the growth rate of bacterial culture, while the second term shows the endogenous decay. The growth rate of microbial mass can also be expressed as the specific growth rate, μ, multiplied by the biomass concentration, X. The growth rate, μ, is a function of the substrate type (degree of oxidation), substrate concentration and microorganism species.

Many approaches for the determination of biodegradation kinetic parameters of batch experimental systems can be found in literature. These include respirometric approaches whereby

oxygen consumption is used as a surrogate measure of biodegradation. In this study, for the determination of kinetic parameters, respirometric measurements were carried out, since the dissolved oxygen concentration was higher compared to classical activated sludge systems. Additionally, the dissolved oxygen was dispersed homogeneously within the reactor leaving no dead zones. Therefore, the jet loop bioreactor was used as a respirometer, where all the hydrodynamic parameters were kept the same as normal operational conditions. Respirometric experiments were conducted according to [22]. The activated sludge was cultivated for about 2 months in the aforementioned reactor, in which leachate was treated. After the system was reached to the endogenous phase and the determination of K_La was carried out, a known quantity of substrate was added into the respirometer reactor. The sample was aerated intermittently using an air compressor. The temperature was maintained at $25 \pm 2\,^{\circ}C$ during the experiments by circulating tap water through a heat exchanger immersed in the feeding tank. Different volumes of leachate sample were added into the respirometer. Leachate was fed from a feeding tank. Both the air and liquid flows were measured by flow-meters. The pH in the respirometer was continually recorded (Hach Lange) and it was observed that the pH values were between 9.4 and 9.6. The reason for high pH values was because the produced CO_2 was scrubbed from the system by the continuous air flow. Likewise, the dissolved oxygen concentration (DO) was measured with an oxygen sensor continually (Hach Lange, LDO). For the control of the system a programmable logic controller (PLC, Phoenix Contact ILC 350 IB) was used, and data acquisition and visualization was carried out (WinCC, Siemens). The aeration was controlled automatically by means of the PLC. The raw data was transferred to MS Excel to generate respirograms.

The overall oxygen transfer coefficient, K_La, is a necessary parameter for the further calculations of kinetic parameters. Therefore, K_La was determined experimentally using activated sludge, and was found to be $0.27\ min^{-1}$. For this purpose, a nonlinear least-squares based curve fitting program (Sigma Plot 9) was used.

2.4. Determining dynamic behavior of the system

The fundamental way to maintain optimum operating conditions of a wastewater treatment system is to have a well acquaintance with the dynamic behaviors of the process. Controlling the jet loop bioreactor to achieve high rates of purification possible depends on maintaining the appropriate loadings and operating conditions. This requires collecting various system data to estimate the system's dynamics satisfactorily with the aim of keeping certain parameters within the specified range. Primary operating conditions of main concern include dissolved oxygen concentration, temperature, pH and wastewater to air ratio. The general acceptance in literature suggests that optimum performance is obtained at a temperature of 23 °C with a maximum variation of 1 °C per day and at pH values between 6.5 and 7.3 [23]. The PLC and SCADA-based control, automation and monitoring system could maintain the pre-specified requirements of the process under usual loading conditions. However, the desired pH and temperature values of the process may deviate from their tolerable ranges due to the unexpected or sudden variations in the inlet variables such as substrate and biomass concentrations. These deviations may cause some undesirable conditions, which cannot be noticed until the end of the complete process, since most of the parameters are measured off-line, i.e. titration based measurements in the laboratory. Therefore, a well-defined mathematical model of the process together with the on-line measured parameters can be very useful from the point view of observing and estimating some of the parameters, which give information on the state of the process and any impending failure. Besides, this will automatically adjust the flow rate of the air to be fed to the process leading to treatment efficiency and energy save. The mathematical solution carried out herein will give OUR information, which is related to the required DO value. The difference between this value of DO and the actual value measured by DO sensor is compensated by means of adjusting on–off time of the compressor. This is generally realized by pulse width modulation (PWM) as reported in [24].

The following nonlinear state equations, which are based on well-known Monod's biomass growth rates, describe the dynamic behavior of the process. As the Monod equation states, the specific growth rate is;

$$\mu = \frac{\mu_{\max} S}{K_s + S} \tag{2}$$

Since the system of interest is a batch reactor, the state equations are,

$$\frac{dX}{dt} = \mu X - k_d, \quad X\frac{dS}{dt} = -\frac{\mu X}{Y} \tag{3}$$

The oxygen uptake rate, OUR, is estimated by [5]

$$\frac{dOUR}{dt} = \frac{1 - Y}{Y}\mu X \tag{4}$$

In the solution of linear or nonlinear state equations such as Eqs. (3) and (4), differential transform method (DTM), which was introduced by Zhou [25] and applied to various engineering problems by Arikoglu and Ozkol [26,27], emerges as a convenient procedure. It is a semianalytical numerical technique based on Taylor series, which gives quite accurate results or exact solutions for the differential equations dealt with. Also, it can be conveniently coded and implemented for real time process control applications.

2.5. Differential transform method (DTM)

The transformation of the kth derivative of a function with one variable can be written as,

$$F(k) = \frac{1}{k!}\left[\frac{d^k}{dx^k} f(x)\right]_{x=x_0} \tag{5}$$

and the inverse transformation to get the original function is defined by:

$$f(x) = \sum_{k=0}^{\infty} F(k)(x - x_0)^k \tag{6}$$

The theorems derived from the definition of DTM, given in Eqs. (5) and (6), are presented in Appendix A. The state equations describing the process are solved by using the related theorems and demonstrated in the following section.

2.6. DTM based solution of the state equations

The state equations given in Eqs. (3) and (4) have a nonlinear structure and need to be solved by iterative numerical methods. Here, DTM as given in Eqs. (5) and (6), is used to find biomass, X, and substrate, S, concentrations and oxygen uptake rate (OUR). Using the DTM theorems presented in Appendix A, the solutions of the state equations are found.

Substituting Eq. (2) into Eq. (4)

$$\frac{\mathrm{dOUR}}{\mathrm{d}t} K_\mathrm{s} + \frac{\mathrm{dOUR}}{\mathrm{d}t} S = -k_\mathrm{y} S X \tag{7}$$

where k_y is defined as

$$k_\mathrm{y} = \mu_{\max} \frac{1 - Y}{Y} \tag{8}$$

Applying the related DTM theorems to Eq. (7),

$$K_\mathrm{s}(k+1)\mathrm{OUR}(k+1) + \sum_{k_1=0}^{k} S(k_1)(k - k_1 + 1)\mathrm{OUR}(k - k_1 + 1) = -k_\mathrm{y} \sum_{k_1=0}^{k} S(k_1) X(k - k_1) \tag{9}$$

Starting the iterative procedure from the initial values,

$$K_\mathrm{s}(k+1)\mathrm{OUR}(k+1) + S(0)(k+1)\mathrm{OUR}(k+1) + \sum_{k_1=1}^{k} S(k_1)(k - k_1 + 1)\mathrm{OUR}(k - k_1 + 1) = -k_\mathrm{y} \sum_{k_1=0}^{k} S(k_1) X(k - k_1) \tag{10}$$

The subsequent values of OUR can be found using,

$$\mathrm{OUR}(k+1) = \left[-\sum_{k_1=1}^{k} \mathrm{OUR}(k_1)(k - k_1 + 1) S(k - k_1 + 1) - k_\mathrm{y} \sum_{k_1=0}^{k} S(k_1) X(k - k_1) \right] \times [[K_\mathrm{s} + S(0)]\,(k+1)]^{-1} \tag{11}$$

3. Results and discussion

3.1. Kinetic and stoichiometric parameters

As known, cell culture systems involve extremely complex structures having many inputs and outputs. Unlike most chemical systems, the cell culture systems themselves are self propagating. Therefore, in order to understand quantifying cell culture systems, mathematical models are often used. Among these models, the most frequently applied one is the Monod model, which describes the effect of growth limiting nutrient, i.e. substrate, on specific growth rate. The use of a respirometer is a very useful tool in determining the bio-kinetic growth constants.

The important kinetic and stoichiometric parameters required for biological removal process performance, namely the Y, K_s, k_d and $\mu_{\max}$ were calculated from the respirometric experiments. Thus, modeling parameters for both the composition of the influent wastewater and for biological processes including maximum growth rates of microorganisms can be determined. Using Eqs. (1)–(5), maximum specific growth rate, $\mu_{\max}$ and K_s, Y and k_d were calculated and presented in Table 2.

A change can be observed in the oxygen consumption when a known amount of substrate is added to a system, which is in endogenous phase. If the oxygen change is plotted against time, "a respirogram" can be obtained [22]. In the calculations of respirometric kinetic parameters, the knowledge of $\mathrm{K_La}$ is very important [28]. The $\mathrm{K_La}$ of the system was determined to be $0.27\,\mathrm{min}^{-1}$ via a non-steady state aeration procedure. The related respirometric equations can be found elsewhere [22,28,29].

3.2. Determination of μ, μ_{max} and K_s

The substrate respiration rate after the addition of substrate to the activated sludge suspension can be calculated using Eq. (12) [22]. As it can be seen from the equation, the r_e and μ values are equal to each other, likewise, the maximum substrate respiration rate ($r_{\mathrm{e}_{\max}}$) would be equal to $\mu_{\max}$. When different amounts of substrate is added to the system, different μ values can be obtained. In order to obtain the $\mu_{\max}$ value, sufficient substrate addition and sufficient number of trials should be carried out within the reactor of interest [22].

$$r_\mathrm{e} = \mathrm{K_La}(C_\mathrm{e} - C) - \frac{\mathrm{d}C}{\mathrm{d}t} = \mu \tag{12}$$

The r_e values obtained are then divided to the mean biomass concentration in order to determine the R_e values which corre-

Table 2
Kinetic coefficients obtained

Kinetic parameter	Value
$\mu_{\max}$, max. specific growth rate day^{-1}	0.21
Y, yield ratio gr gr^{-1}	0.28
k_d, decay coefficient day^{-1}	0.019
K_s, half saturation rate constant (mg L^{-1})	11,000

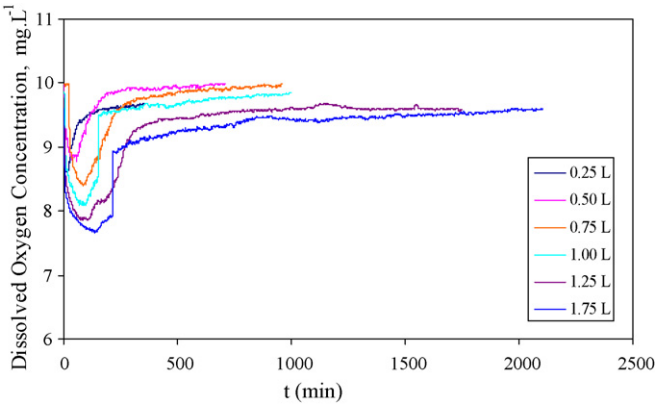

Fig. 2. Respirograms obtained by different amount of leachate added to the reactor.

spond to the maximum specific growth rate, Eq. (13).

$$R_e = \frac{r_e}{X}, \quad (1/T) \tag{13}$$

In Figs. 2 and 3, the respirograms obtained and r_e diagrams can be found. As it was mentioned above, when the endogenous phase was reached, that is dissolved oxygen concentration is constant during constant aeration, a known amount of substrate was added to the respirometry. In this case, 0.25, 0.50, 0.75, 1.0, 1.25 and 1.75 L of substrate were added. The respirograms for each addition is given in Fig. 2. According to Eq. (12), the r_e diagrams (Fig. 3) were plotted. As it can be seen, due to the size of the reactor, additions 0.25, 0.50, 0.75 and 1.0 L were insufficient. However, when 1.25 and 1.75 L of substrate was added, the μ_{max} values were almost identical. Therefore, for the system in question, the μ_{max} values obtained were accepted to be the system's μ_{max} value, 0.21 day^{-1}.

The half saturation constant, K_s, value was found from the linearized Monod equation. For batch systems, K_s can easily be obtained, from the slope of $1/S$ versus $1/\mu$ plot. The K_s value was found to be 11,000 mg L^{-1} indicating, the leachate was difficult for biodegradation by microorganisms. As it is known, this parameter shows the affinity of microorganisms to substrate [30].

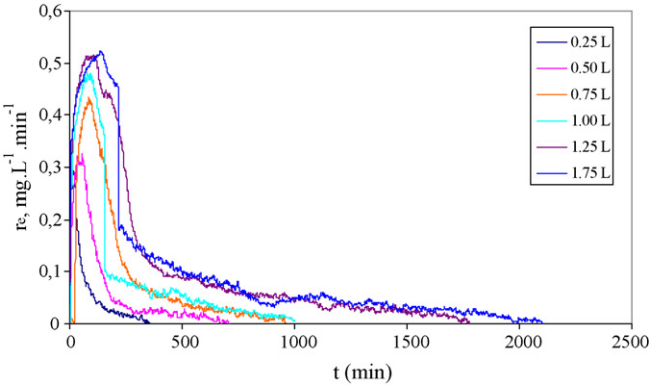

Fig. 3. r_e plots obtained by different amount of leachate added to the reactor.

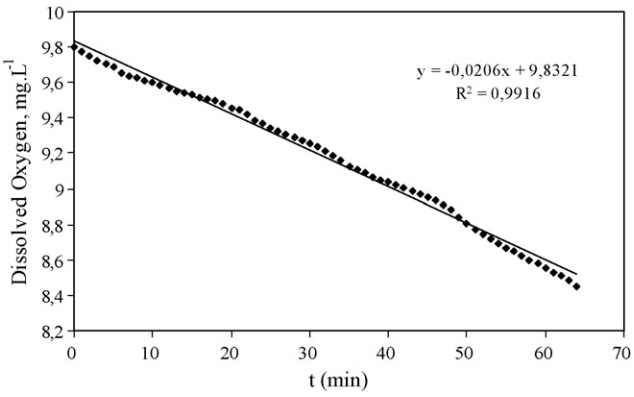

Fig. 4. Plot of specific endogenous oxygen uptake rate.

3.3. Determination of k_d

For the k_d measurements, the reservoir of the dissolved oxygen probe was used. During the experiments, activated sludge entrance from the main reactor to the DO probe reservoir was cut. Likewise, it was ensured that the reservoir was completely closed for any air leakages. As seen in Fig. 4, the air supply to the respirometer was discontinued after the endogenous phase has been attained. As reported by Suschka and Ferreira [31], a 4 h aeration time is usually sufficient for reaching the endogenous respiration conditions. It should be noted that in longer runs, a logarithmic curve would be obtained, and therefore, there is no single endogenous respiration rate for a specific system [31]. The k_d value would be expected to decrease over time. Thus, it is very important to understand the curve of endogenous respiration under examination. In this study, the endogenous oxygen uptake rate was calculated from the linear part of the DO versus time curve using Eq. (14) [22].

$$r_s = \left|\frac{dC}{dt}\right| (\text{mg L}^{-1}\,\text{min}^{-1}) \tag{14}$$

As seen in Fig. 4, from the slope of the linear graph which corresponds to approximately 1 h period right after the discontinuation of air supply, the R_s value can be calculated. The specific endogenous oxygen uptake rate was then calculated using Eq. (15) where R_s indicates the k_d value (Table 2).

$$R_s = \frac{1.44\, r_s}{X}(1/T) \tag{15}$$

3.4. Determination of yield coefficient, Y

For the determination of yield coefficient, Y, the method proposed by Roš [22] was followed, as given in Eq. (16).

$$Y = 1 - \frac{K_L a A}{BOD} \tag{16}$$

where, A indicates the area corresponding 1 L of substrate addition to the respirogram.

It was observed that since the inert COD value of leachate was higher and leachate has a considerable amount of refractor organics, the maximum specific growth rate (μ_{max}), and yield

ratio (Y) parameters were lower than those cited in literature [5]. Likewise, the specific endogenous respiration rate (k_d) was lower. As it is known, μ_{max} and Y values are dependent on the microorganism type and the oxidation state of the organic matter in leachate. The main reason for low μ_{max} and Y values is that the leachate used in this study was obtained from a landfill site which has been operated a little more than 10 years, therefore the anaerobic conditions developed in the landfill caused the organic matter in leachate to reach the last oxidation state or close to it. However, the K_s value obtained was higher.

3.5. DTM solutions

The results obtained from the state equations by means of DTM are verified in MATHEMATICA using its "NDSolve" function, which is an interpolating function associated with a Runge Kutta based ODE solution method. OUR values were produced using Eq. (11). Substrate (S) and biomass concentrations (X) were calculated likewise. Then OUR against effluent COD concentration was plotted, as shown in Fig. 5. The oxygen uptake rate (OUR) can be used to evaluate the biological activity for the purpose of controlling and monitoring the treatment process [5]. Using the calculated OUR values and the effluent COD values can then be monitored easily, Fig. 5. This would prevent any disturbances caused by inhibition or other mechanical failures in the system. In Fig. 6a and b, the plots of biomass and substrate concentration variation with time obtained by DTM were presented. It should be noted that, here, only the degradable part of the organic matter was considered.

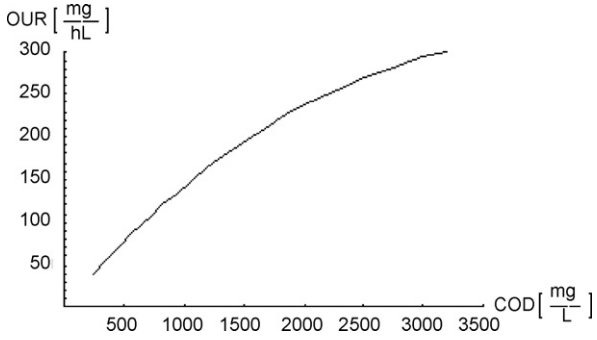

Fig. 5. The oxygen uptake rate with changing COD values.

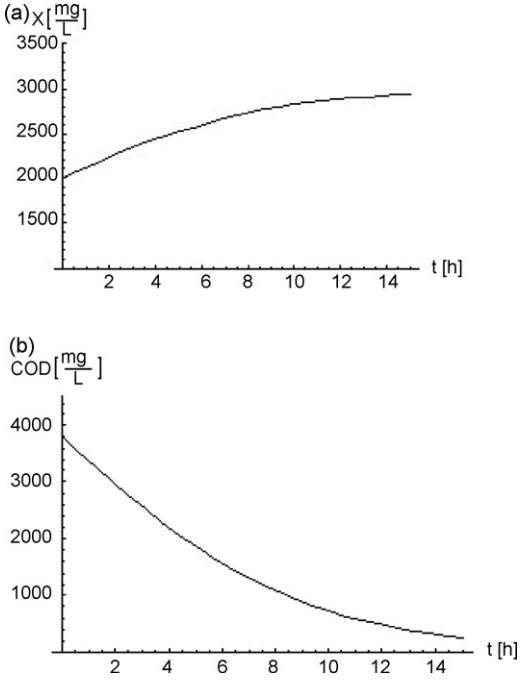

Fig. 6. (a) Microorganism concentration change with time and (b) effluent COD change with time.

4. Conclusions

The respirometric method for kinetic parameter calculations for biodegradation has been used for some time. In many studies, the respirometer was designed separately, usually in bench-scale, apart from the reactor in which the biodegradation is taken place. As it is known, when a separate respirometer is used, the scale effect and parameters that affect the hydrodynamic structure of the system, such as turbulence, the way of aeration and size should all be taken into consideration. When a separate bench-scale respirometer was used, the activity of the activated sludge in a treatment plant cannot reflect the real system thoroughly. In this study, however, the jet loop reactor itself was used as a respirometer. Thus, the kinetic parameters found reflecting the characteristics of microorganisms used for biodegradation would be more realistic. Another important point is, especially for long-term studies, since the characteristics of leachate change, the activated sludge would adapt itself, and therefore the characteristics of activated sludge would also change. Therefore, if the main reactor, here the jet loop reactor, would be used as the respirometer, the kinetic parameter changes can easily be monitored in the long run.

The current approach involved two phases: diagnosis and analysis. In the diagnosis stage, process parameters were identified via Monod's cell growth rate based state equations with existing knowledge of organic matter breakdown, while in the analysis stage; the oxygen uptake rate (OUR) was computed against time and substrate concentration.

Furthermore, such an approach would potentially form the concept for economical analysis of oxygenation problems before a more in-depth and comparatively cumbersome analytical approach involving costly laboratory procedures was adopted.

DTM method presents a convenient way in the solutions of the state equations in particular from the point view of software implementation. As a sequential work, therefore, maintaining the process parameters, within their corresponding specified ranges, will be possible by means of a control strategy, which will depend on the mathematical solution proposed in this study. The solution also makes the automatic adjustment of the aeration on–off time possible, leading to further process efficiency and energy save.

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Appendix A

Theorem 1. If $f(x) = g(x) \pm h(x)$, then $F(k) = G(k) \pm H(k)$

Theorem 2. If $f(x) = cg(x)$, then $F(k) = cG(k)$

Theorem 3. If $f(x) = \frac{\mathrm{d}^n g(x)}{\mathrm{d}x^n}$, then $F(k) = \frac{(k+n)!}{k!} G(k+n)$

Theorem 4. If $f(x) = g(x)h(x)$, then $F(k) = \sum_{k_1=0}^{k} G(k_1)H(k - k_1)$

Theorem 5. If $f(x) = x^n$, then $F(k) = \delta(k-n)$, where $\delta(k-n) = \begin{cases} 1, & k = n \\ 0, & k \neq n \end{cases}$

Theorem 6. If $f(x) = g(x)h'(x)$ then $F(k) = \sum_{k_1=0}^{k} G(k_1)(k+1-k_1)H(k+1-k_1)$

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