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Investigation of biokinetics constants for dairy effluent in hot climate countries

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ABSTRACT

In this paper biokinetics parameters for dairy wastes in Iraq's hot climate have been determined for the first time and investigated with the typical wastewater biokinetics of different eluents. The huge number of spreaded dairy industries over the country creates the need to know more about the biokineticks which were essential in the design of dairy effluent treatment plants. A laboratory model of an activated sludge process is included in this study to obtain reliable results on biokineticks parameters. The model is carried out at Abu Ghraib Dairy Industries site for four months in order to determine the biokinetic constants of the dairy effluent wastes. The average value of the kinetic constant *Y*, (decimal fraction of food mass converted to biomass) is revealed as lower than the expected having the higher ambient air temperature which was rather over 32 ^{o}C. High ambient air temperatures found to be the main factor affecting the biokinetics which are obtained for the dairy effluents for first time in hot climate countries.

***Keywords*: Dairy Effluents Biokineticks, BOD removal efficiency, Sludge Yield Coefficient (Y) in Hot Climate**

1. Introduction

The importance of the Dairy Industry in many countries may be judged from the fact that dairy products provide some 24% of the protein content of the national diet at a cost of approximately 18% of the total food cost (Herzka & Booth, 1981). Huge amounts of dairy products were appeared, recently in Iraqi markets which lead to a large number of small and medium dairy factories are spread here and there which, most of them, are out of control. The "Public Company of dairy Products", the field of this research work, is one of the largest governmental enterprises, producing dairy products in, many districts, e.g. Abu- Graib, Ninawa and AL- Kadisya. Each of these sites includes a number of milk reception centers and a number of factories producing different products.

Abu-Graib, the central location of the company, includes the largest collection of milk reception centers and production lines in the country. During the three years (1996-1998), for instance, some of raw milk (6.0366×10^4 m^3) was processed in Abu- Graib factories collection. Treatment of dairy effluents becomes very important in Iraq because of their heavy pollution loads which mostly disposed to the surface waters. This research work have been performed in Abu-Ghraib Dairy Industries to calculate the dairy biokinetics which can be used in the design of the full prototype wastewater treatment plants not only for Abu-Ghraib, but for all dairy industries in Iraq and the hot climate countries.

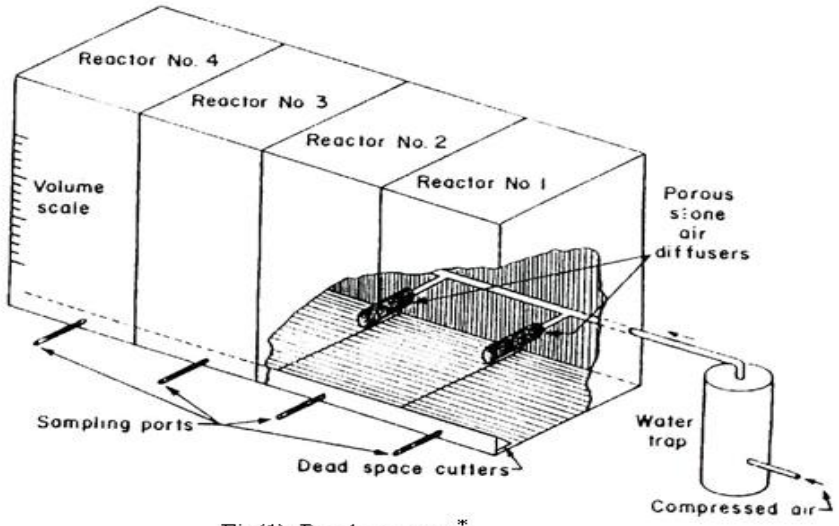
Knowledge of production of mixed liquor volatile suspended solids (MLVSS) and oxygen utilization is needed for design of aerobic biological reactors. Obtaining mathematical models yields these two values, several biokinetic parameters designated by the symbols $\overline{Y}$, Y, K_d, a and b are briefly defined in the following section.

2. Kinetics Relationships and Methodology

Study of kinetics of aerobic biological treatment yields the rate at which microorganisms degrade a specific waste, and therefore provides the basic information required for sizing biological aerobic reactors. This study is conveniently performed in a laboratory – scale batch reactor. Fig. (1) shows a diagram of four units operating in parallel, each with a capacity of approximately 2.0 liters. Reactors are built of Plexiglas. Wastewater containing a seed of microorganisms is introduced into the reactors, and compressed air is blown in the system (Ramalho, 1983).

The biological sludge MLVSS is kept in a state of complete mixing due to agitation provided by air blown into the system. Substrate concentration, S of the waste water (measured as soluble BOD or COD, THOD, TOC) is determined at selected time intervals withdrawing samples for analysis. The mass of accumulated biological sludge (MLVSS) is also determined at the same time intervals by measuring the concentration of (MLVSS) in withdrawn samples and reading the volume of liquor in the reactor as indicated by the volume scale.

Typical curves for decrease of soluble substrate concentration, S and variation of the amount of MLVSS with time are presented in Fig. (2).



Fig(1) Batch reactor*

* Seed can be a mass of biological sludge taken from an operating activated sludge plant or from settled sewage (After Ramalho, 1983).

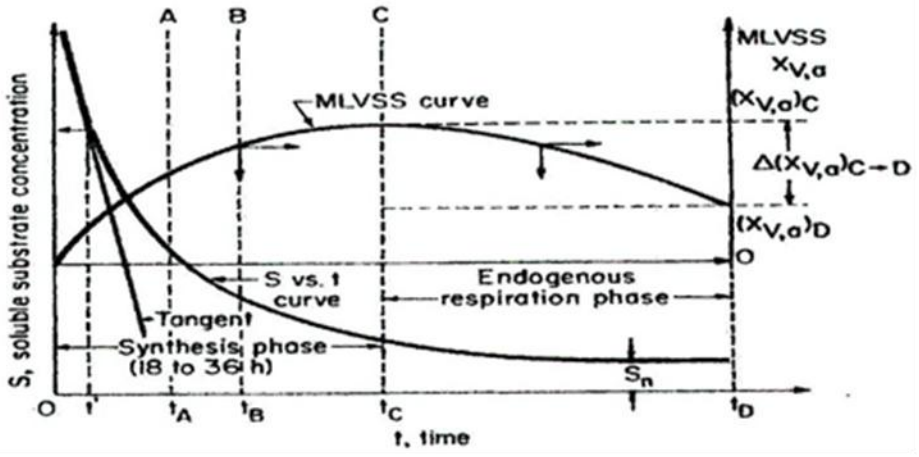


Fig.2. Typical Soluble Substrate Concentration and MLVSS Curves

(After Ramalho, 1983)

Soluble substrate concentration S of the wastewater, which is a measure of organic matter concentration, decreases with time as the organic matter is oxidized. A plateau is eventually reached corresponding to the amount of non-biodegradable matter (Sn).

If BOD is utilized to measure substrate concentration, Sn=0 at infinite time all biodegradable substrate has been oxidized. On the other hand, if; for example COD is utilized, it is possible to have Sn>0, corresponding to substrate that is not biologically degradable but is chemically oxidized by $K_2Cr_2O_7$.

Concentration of MLVSS increases at first (from time to time t_c) during the period when a substantial concentration of substrate is present to provide abundant food to sustain growth of microorganisms. This growth corresponds to the synthesis of new microorganism cells, indicated in Fig. (2) as "synthesis phase".

After time tc, when substrate concentration is considerably depleted, these is not enough food left to sustain growth of microorganisms. At this time, microorganisms start consuming their "follow microorganisms "as food. As this "cannibalistic feast "proceeds concentration of MLVSS drops when the rate of destruction of microorganism cells exceeds that of synthesis of new cells. This corresponds to the "endogenous respiration phase". The maximum on the MLVSS curve corresponds to time tc, when these two rates are exactly equal. Distance $\left(\Delta X_{v,a}\right)_{C\to D}$ corresponds to the net reduction of MLVSS concentration from t_c to t_d.

There are two fundamental differences between operations of continuous and batch reactors:

I. Contrary to what happens in the batch reactor, BOD of the wastewater in the continuous reactor operating at steady state conditions remains constant (S_e). This corresponds generally to a low substrate concentration since the biological reactor is usually designed for removing most of the influent BOD.

II. Contrary to what happens in the batch reactor, concentration of MLVSS in the continuous reactor operating at steady state is kept constant ($X_{v,a}$) at a selected value.

Maintenance of this constant $X_{v,a}$ is obtained by providing the calculated amount of concentrated return sludge.

Line B corresponds to the conventional activated sludge process. In this case, these are a net production of MLVSS (positive slope for the MLVSS curve at the point of its intersection with line B). The steady- state values S_e and $X_{v,a}$, for the case of the continuous reactor operating with a residence time t_B, correspond to the intersection of line B with the BOD and MLVSS curves, respectively, and are typically within the following ranges:

S_e: corresponding to BOD reduction of 85-95%

$X_{v,a}$: 2000-3000 mg/ liter

Line C corresponds to the extended aeration process. In this case, the net production of MLVSS is theoretically nil (tangent to MLVSS curve is parallel to the abscissa).

Steady – state values for $X_{v,a}$ for the case of the continuous reactor operating with residence time t_C, correspond to the intersection of line C with the MLVSS curve, and are within the range of 300-6000 mg/ liter.

Line A corresponds to the high –rate activated sludge process. In this case, the rate of substrate removal d_s/d_t (slope of tangent to S versus t curve) is appreciably higher than that for the conventional activated sludge process. Typical range of steady – state $X_{v,a}$ values is lower (600-1000 mg/ liter) and BOD reductions are of the order of 60-75% for the case of the continuous reactor with a residence time t_A. These values correspond to the intersection of line A with the MLVSS and S versus t curves, respectively.

Kinetic data obtained from the batch reactor portrayed by the Michaelis- Menten relationship. Two important corollaries of this relationship are postulated next, the second one being commonly utilized for design of the continuous biological reactor:

Corollary 1: At high substrate concentrations, substrate removal follows zero- order kinetics. This means that the rate of removal is essentially constant, independent of substrate concentration. This situation is found in early stages of the batch reactor operation, when

substrate concentration is still very high (high BOD). This corresponds to the section of the S versus t curve Fig (2) from time zero to time t^{-1}. In this region, the tangent to the S versus t curve, which equals the rate of substrate removal d_s/d_t, coincides essentially with the curve itself (constant slope).

Corollary 2: Substrate removal at low substrate concentrations (corresponding to BOD values below 500 mg/ liter) follow first- order kinetics. This means that rate of removal is proportional to remaining substrate concentration. This corresponds approximately to the section of the S versus t curve between times t_A and t_C. Slope of the S versus t curve (which equals rate of substrate removal (d_s/d_t) decreases with time as substrate concentration is lowered. A plot of these slopes versus corresponding S values yields a straight – line relationship. Thus in is this region, the rate of substrate removal is directly proportional to its concentration (first- order kinetics).

2.1 Continuous Biological Reactor Material Balance

Consider a continuous biological reactor under steady- state and complete mix condition (CFSTR) as illustrated by Fig. (3).

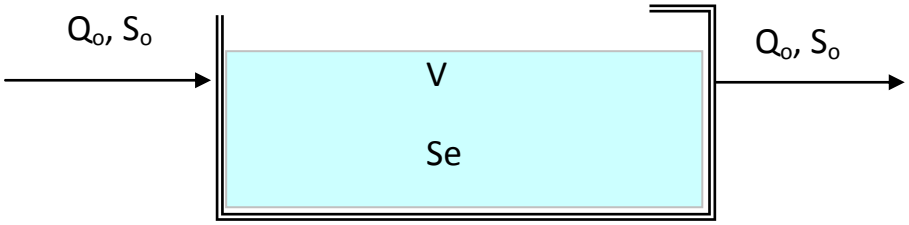


Fig. 3. Simplified Diagram for Continuous Reactor

A material balance for substrate entering and leaving the reactor can be written as follows:

$$\begin{bmatrix} \textit{Net} \text{ of change of substrate in reactor} \end{bmatrix} = \begin{bmatrix} \textit{Rate} \text{ at which Substrate enters reactor (in influent)} \end{bmatrix} - \begin{bmatrix} \textit{Rate} \text{ at which Substrate leaves reactor (in effluent)} \end{bmatrix} - \begin{bmatrix} \text{Rate at which Substrate is oxidized in reactor} \end{bmatrix} \quad (1)$$

Under steady- state conditions, the substrate concentration in the reactor remains constant and therefore the left- hand member of Eq. (1) vanishes, i.e.

$$0 = \begin{bmatrix} \text{Rate at which} \\ \text{substrate} \\ \text{enters reactor} \\ (\text{in influent}) \end{bmatrix} - \begin{bmatrix} \text{Rate at which} \\ \text{substrate} \\ \text{leaves reactor} \\ (\text{in effluent}) \end{bmatrix} - \begin{bmatrix} \text{Rate at which} \\ \text{substrate} \\ \text{is oxidized} \\ \text{in reactor} \end{bmatrix} \quad (2)$$

The two first terms in the right – hand member of Eq. (2) refer to net removal of substrate due to hydraulic action only, and they are:

$$\begin{bmatrix} \text{Rate at which} \\ \text{Substrate} \\ \text{enters reactor} \\ (\text{in influent}) \end{bmatrix} = Q_o S_o \quad (3)$$

$$\begin{bmatrix} \text{Rate a which} \\ \text{Substrate} \\ \text{enters reactor} \\ (\text{in effluent}) \end{bmatrix} = Q_o S_e \quad (4)$$

The rate of substrate removal due to microbial utilization (aerobic degradation) is given by the slope ds/dt of the BOD curve in Fig. (2). Since the derivative ds/dt is intrinsically negative, its absolute value, denoted as $(d_s/d_t)_a$, will be utilized hence, i.e.,

$$(d_s/d_t)_a = -(d_s/d_t) \quad (5)$$

Since the substrate S is expressed in terms of unit volume (e.g., mg BOD_5 / liter) the value $(d_s/d_t)_a$ must be multiplied by the reactor volume V before substitution into Eq. (6)

Therefore:

$$\begin{bmatrix} \text{Rate at which} \\ \text{Substrate} \\ \text{is oxidized} \\ \textit{inreactor} \end{bmatrix} = \left(\frac{ds}{dt}\right)_a V \tag{6}$$

Substitution of Eqs, (3), (4) and (6) into Eq. (2) Yields:

$$0 = Q_o S_o - Q_o S_e - (ds/dt)_a V \tag{7}$$

From which

$$(ds/dt)_a = Q_o (S_o - S_e)/V \tag{8}$$

Usually, the substrate removal rate is expressed per unit mass of MLVSS present in the reactor. This quantity, denoted as q, is designated as specific substrate removal rate, and is defined as:

$$q = -\frac{1}{X_{v,a}}\left(\frac{ds}{dt}\right) = \frac{1}{X_{v,a}}\left(\frac{ds}{dt}\right)_a \tag{9}$$

Combining Eqs, (8) and (9):

$$q = \frac{1}{X_{v,a}}\left(\frac{ds}{dt}\right)_a = \frac{Q_o(S_o - S_e)}{V\ \mathrm{X_{v,a}}} \tag{10}$$

However:

$$t_h = \frac{V}{Q_o} = \frac{\textit{cubic}\ \text{meter}}{\text{cubic metre /day}} = \textit{day} \tag{11}$$

t_h = hydraulic residence time (t_h) in reactor

Consequently, from Eqs, (10) and (11):

$$q = \frac{1}{X_{v,a}}\left(\frac{ds}{dt}\right)_a = \frac{S_o - S_e}{X_{v,a}.t_h} \tag{12}$$

The specific substrate removal rate $(S_o\text{-}S_e)/ X_{v,a}t_h$ corresponds to the rate of removal of substrate in the continuous reactor per unit mass of MLVSS present in the reactor. Units are:

$$(S_o - S_e)/ X_{v,a}t_h = \frac{mg/liter \text{ of BOD removal}}{(mg/liter \text{ of MLVSS})(day)}$$

= mg BOD removal / (day) (mg MLVSS)

= kg BOD removal / (day) (kg MLVSS)

In order to apply Eq. (12), it is necessary to decide which kinetic is to be utilized for

$$\left(\frac{ds}{dt}\right)_a$$

It will be assumed here that the substrate removal follows a first order kinetics, i.e.

$$\left(\frac{ds}{dt}\right)_a = KS_e \tag{13}$$

Under the assumption of first – order kinetics, substitution of $(d_s/d_t)_a$ given by Eq. (13) into Eq.(12) yields:

$$q = (1/X_{v,a})KS_e = (S_o - S_e)/ X_{v,a}t_h \tag{14}$$

Since the steady state concentration of MLVSS ($X_{v,a}$) is fixed for a specific continuous reactor operation, the rates ($K /X_{v,a}$) is constant and will be designated as k

$$K = \frac{K}{X_{v,a}} \tag{15}$$

Consequently, Eq. (14) becomes:

$$q = (S_o - S_e)/ X_{v,a} t_h = KS_e \quad (16)$$

Eq.(13) shows that K has dimensions of time (e.g. day^{-1}, hr^{-1}). On the other hand, from Eq. (14) it follows that k should be expressed as day^{-1} × liter / mg or hr^{-1} × liter/ mg.

Eq. (16) indicates that the substrate removal rate is proportional to substrate concentration S_e (first- orders kinetics). Substrate removal rate constant K (day^{-1}) is determined according to Eq. (16) from a plot of $(S_o-S_e) /X_{v,a} t_h$ versus S_e.

2.2 Mechanism of Biokinetics

It can be represented, diagrammatically by Fig. (5), that substrate is removed during the biological process in two ways:

I. Cell metabolism: part of the substrate, after being consumed as food by microorganisms, is utilized to synthesize new microorganism cells, resulting in an increase of biomass.

II. Energy metabolism: The remainder of the substrate is oxidized, find products being mainly CO_2 and H_2O. This oxidation process is essential for production of energy of maintenance by the cells to maintain their life- supporting functions, such as synthesis of new cells and mobility.

Since the substrate (organic material) is removed continuously to provide for cell metabolism and energy metabolism, the concentration of organic material will be depleted. Once the source of organic material becomes exhausted, the microorganisms will enter into the endogenous respiration phase. Under these conditions, cellular of material is oxidized to satisfy the energy of maintenance requirements. Consequently, the quantity of biomes will be reduced.

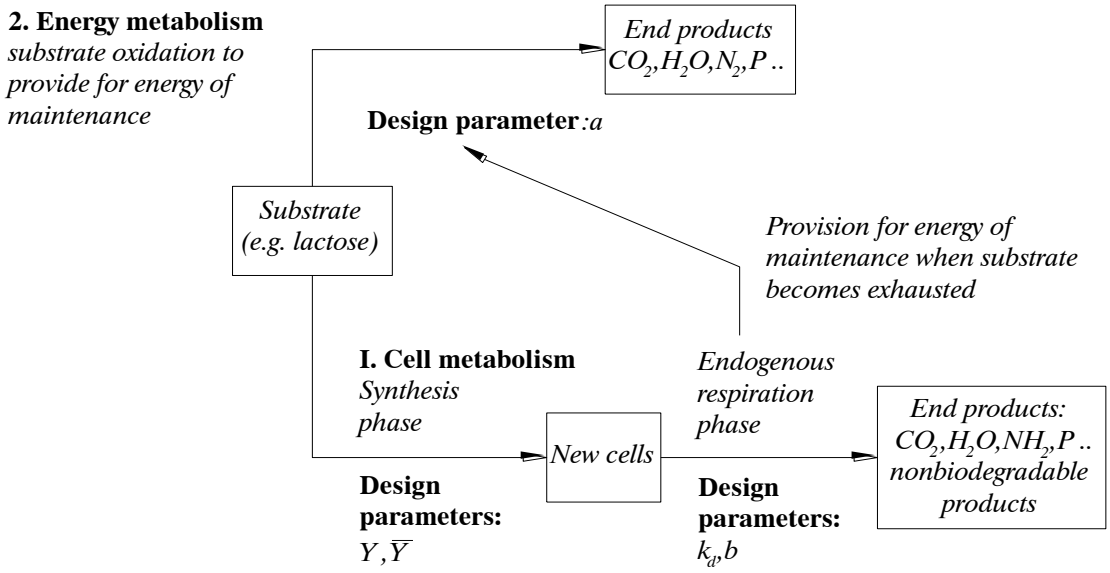


Fig. 4. Mechanism of aerobic biological degradation (After Ramalho, 1983)

2.3 Dairy Effluent Biokineticks

The activated sludge process is used successfully to a great extent in the dairy industry for the disposal of material impurities in effluents from milk processing and dairy products manufacturing plants (Carta-Escobar, et al., 2005).The excess sludge formed during the purification plants causes a series of difficulties involving storage, processing and transportation. The main cause of these difficulties is insufficient knowledge of sludge production and its kinetics (Janczukowicz, et al., 2007).

Comprehensive Experimental work under full- plant and model conditions has been carried out by "Joromir Salplachta" in the Dairy Research Institute; water Management Department, Brno, Czechoslovakia (1978). In this work a suitable arrangement of activated sludge tank, oxidation ditch and semi- continuous activated sludge process models have been aerated by mechanical aeration, by means of aeration cylinders mounted on one common shaft.

Under summer conditions the sludge production was studied in the activated sludge system, in the oxidation ditch and in the semi- continuous activated sludge. Under winter conditions only the activated sludge system and oxidation ditch has been studied. Under summer conditions, at sludge suspension temperature from 21 to 25 ºC, both continuous mixing activated sludge systems were simultaneously in operation at the proposed sludge age values of 3, 5, 10, 20, 30 days. While under winter conditions, at sludge suspension temperatures between 5.7 and 9.3 ºC, the activated sludge and oxidation ditch models were operated with sludge age values of 5,15 and 30 days.

The continuous model systems were loaded by artificially prepared dairy effluents with about 1000 mg/l BOD_5. This concentration was achieved by mixing 1.6 liter of fresh whey, 0.85 liter of whole milk, 0.09 liters of detergent solution (75gm NaOH + 200 gm Alkon in a

liter of water) added to 175 liter of tap water. Alkon has the following composition: 40% Na_2CO_3, 30% Na_2PO_4 .$12H_2O$, 20% NaOH, and 10 % Na_2SO_4. The amount of effluents processed in the individual systems and the concentration of material impurities were derived from the results of the plant-scale experiments (Salplachta, 1978). The oxygenation capacity ratio to BOD_5 was around 6.5:1 for the activated sludge model and 4:1 for the oxidation ditch. The physio-chemical analysis was performed according to the "Unified methods for chemical analysis of waters". Temperature, pH, BOD_5, COD (Using Dichromate) and suspended solids were investigated daily using well shaken samples of crude and purified effluents.

2.4 Lab-scale Continuous Flow Reactor

This unit was, originally, designed and built by Bio- Development Associates, Austin, Texas (Ramalho, 1983; Eckenfilder, 1980). Although many difficulties was faced due to financing aspects, a four parallel bench-scale were constructed using normal glass sheets and equipped, as shown in Fig. (5), with the proper fittings to keep the reactors running properly for a long time (four months including seeding and stability periods to attain steady- state (conditions of biological growth).

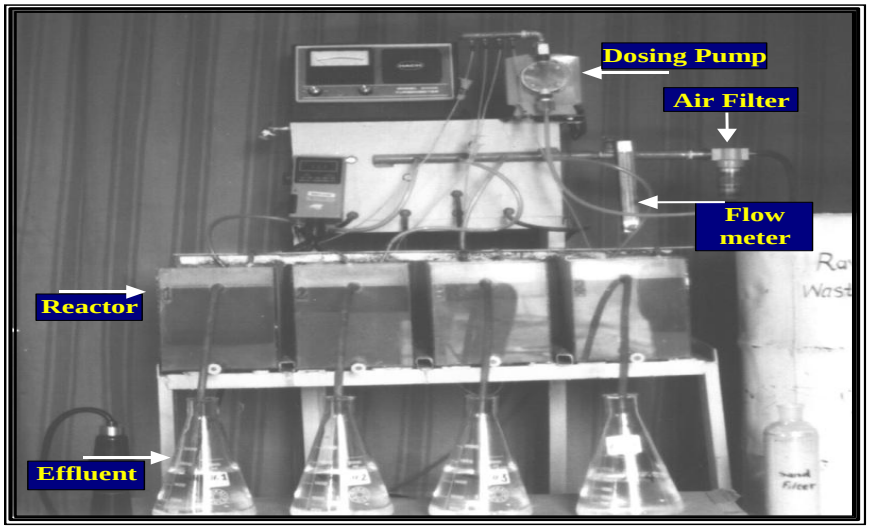


Fig.5. Model of Four Continuous Flow Reactors as they equipped in Parallel on Site

A set of test was performed daily, weekly and periodically according to schedules and availability of properly working instruments. The main difficulty was the continuity of running the four reactors with steady conditions of temperature, flow rate and concentration of representative influent along the period of the test.

The data from the model operation is obtained and analyzed considering several parameters. The measured BOD_5 of the influent is shown as S_o (mg/L). In this research, BOD_5 of the effluent is measured with the parameter of S_e (mg/L). The average Mixed Liquor Volatile Suspended Solids (MLVSS) is also considered in this study. $X_{v,a}$ (mg/L) is the

average of MLVSS. Moreover, the measured influent flow rate is as Q_o (L/hr). Sludge yield is measured as ΔX_v (gram /day). The resident time is calculated as:

$$T_h = V/Q_o \, (hr) \tag{17}$$

The ratio of BOD_5 of effluent to BOD_5 of influent is measured which is represented as S_e / S_o. The sludge yield ΔX_v (mg MLVSS / hr. L) is obtained as $\Delta X_v / V$.

Colum 13 shows the calculated BOD removed $S_r = S_o - S_e$ (mg/L).
Colum 14 shows the calculated MLVSS = $X_{v,a} * T_h$ (mg/L.) hr.

The calculated Specific Substrate Removal Rate is shown

$$q = (S_o - S_e)/ (X_{v,a} * T_h) \, (hr^{-1}) \tag{18}$$

Where, $S_r = S_o - S_e$ (mg/L) is the calculated BOD removed and $X_{v,a} * T_h$ (mg/L.) hr is calculated MLVSS. BOD Removal Efficiency is $\xi = (S_o - S_e)/S_o$ (%).

In addition, the calculated Food to Microorganism ratio is shown as:

$$F/M = S_o \, (mg.\ BOD_5) / X_{v,a} * T_h * 24 \, (mg.\ MLVSS * day) \tag{19}$$

The Specific Growth Rate of the Biomass is calculated as:

$$\mu = (\Delta X_v / V) / (V) \, (hr^{-1}) \tag{20}$$

The Sludge Age is calculated with the Eq. (5) as:

$$\Theta_c = 1/\mu \, *(1/24) \, (day) \tag{21}$$

3. Results and Discussion

Table (1-a) and (1-b) shows a part of the obtained data from the model operation and the, related, calculated data.

Table (1-a) Laboratory Data for the Determination of Biokinetics Constants (30 ºC)

Laboratory Data								Calculated Data				
1		2	3	4	5	6	7	8	9	10	11	12
REACTOR		Influent BOD_5 S_o (mg/L)	Effluent BOD_5 S_e (mg/L) (Unfiltered)	Average MLVSS $X_{v,A}$ (mg/L)	Flow Rate Q_o(L/hr)	Sludge Yield ΔXv (gram./day)	Sludge Vol. Index SVI	Resident Time T_h (hr)	$\frac{BOD_{eff.}}{BOD_{inf.}}$ (Unfiltered)	Sludge Yield ΔX_v (mg/day)	Sludge Yield ΔX_v (mg/hr.)	Sludge Yield (mg MLVSS /hr.L)
NO.	VOL. (L)											
1	10.87	2940	60	2106	0.267	3.451	73.77	40.712	0.0204	3451	143.792	13.228
2	11.42	2940	63	1678	0.308	1.239	102.9	37.078	0.0214	1239	51.625	4.52
3	11.25	2940	58.5	1792	0.25	4.224	120.4	45	0.0199	4224	176	15.644
4	11.31	2940	72	1557	0.222	5.293	77.6	50.946	0.0245	5293	220.542	19.45

Results indicated that, even with high food to microorganisms' ratios, high BOD removal efficiency was achieved. It can be observed from Table (1-b), that 97.96% BOD removal efficiency for F/M of 0.823, while 97.86% for F/M of 1.134. Very slight changes of efficiency removal were obtained compared with the changes of F/M.

The prevailing majority of the bench-scale experiments were affected mainly by failures in the stabilized situation. This instability was referred as fluctuation of the dosing pump, in addition to the clogging occurred, sometimes, in the influent piping. The sharp change of the climatic temperatures between the day and night times made it difficult to acclimate microorganisms on a certain conditions.

Table (1-b) Laboratory Data for the Determination of Biokinetics Constants (30 ºC)

Calculated Data										
1		13	14	15	16	17	18	19	20	21
Reactor		BOD Removed S_r (mg/L) (Unfiltered)	$X_{v,A}$*T_h (mg/L) hr	Specific Substrate Removal Rate q $(hr.)^{-1}$ (Unfiltered)	Food To Microorganism Ratio F/ M (mg. Bod_5/ mg. MLVSS *day)	Specific Growth Rate of The Biomass μ (hr^{-1})	Sludge Age cϴ (day)	$1/S_e$ (Unfiltered)	1/q (Unfiltered)	BOD Removal Efficiency ξ (%) (Unfiltered)
NO.	VOL. (L)									
1	10.87	2880	85739.5	0.0336	0.823	6.281*10	6.634	0.0167	29.762	97.96
2	11.42	2877	62216.9	0.0462	1.134	2.694*10	15.466	0.0159	21.645	97.86
3	11.25	2881.5	80640	0.0357	0.875	8.730*10	4.773	0.0171	28.011	98
4	11.31	2868	79322.9	0.0362	0.89	12.524*10	3.327	0.0139	27.624	97.55

The purification effects of, both low loaded and shock loaded with low sludge age range were around 96% while at sludge age of more than 9 days they were up to 99%. Under a stabilized situation, the calculated coefficient *Y* ranges from 0.0336 to 0.327 mg MLVSS /mg BOD_5, which is rather low, compared with that, determined by others (Benefield, 1980; Salplachta, 1978). Low values of *Y* may be related to: high temperature of reactor's wastewater, high BOD loads and removal efficiency. A fast increase of the depth of sludge blanket in the settling tank was obtained, and this caused the deeper penetration. Hence, there is no chance to get enough aeration. In the same time higher temperature caused septicity of the lower areas of the sludge, thus, lower sludge yield against BOD removed.

The average value of K_d = 0.0412 day^{-1} which is close to that determined by others at temperature different to those considered (Saplachta, 1978). Mandt & Bell, (1982); Metcalf & Eddy Inc. (2004), indicated that K_d for skimmed milk effluents around 0.045 day^{-1}.

4. Conclusions

i. High BOD removal efficiency where achieved with different food to microorganism ratios and sludge ages (for F/M = 0.6 –1.9, 95-98% BOD removal were achieved).

ii. The sludge yield coefficient Y is low compared with that in literature, which was due to high reactor temperatures and septicity in the lower layers of the sludge blanket in the settling tanks. Nevertheless, it is found that for an average Θ_c = 30 days.

iii. The decay constant K_d average about 0.421, which found to increase with rise in temperatures.

iv. Settling characteristics was found to be highly correlated with MLVSS concentration and *F/M* ratio. Minimum SVI was obtained at *F/M* =0.9 –1.1 with $\theta_c = 3-7$ days. These results were found to be more economical if compared with that obtained by others on the same conditions.

v. High ambient air temperatures were found to be the main factor affecting the biokinetics which were obtained for the dairy effluent.
vi. Biokinetic parameters determination showed that very low sludge growth with no significant excess sludge was produced in summer, and which increased in winter.

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