HYDRAULIC MODELING OF THE LIQUID FLOW PATTERN IN A BENCH-SCALE UASB REACTOR

S. Bayoumi

Associate Professor, Environmental Engineering Department,
Faculty of Engineering, Zagazig University, Egypt
E-mail: drsbayoumi@yahoo.com

ABSTRACT

All bioreactor configurations are affected by mixing and transport phenomena and consequently the bioreactor's hydraulics governs the reactor's configurations as well as performance. For instance, to provide good conditions for substrate transport to, and from, the microbial aggregates, an even mixing pattern at the macro-level is desirable. However, the available data that either describe UASB flow regime or relate process performance to mixing characteristics are not that much.

The global objective of this paper is to determine the liquid flow model of UASB via a tracer study to characterize the overall flow behavior in this reactor. In particular, a tracer study has been utilized in this study to figure out the flow pattern in the UASB reactor and to determine the difference between theoretical and actual hydraulic retention time. The specific objectives of the present work have been reached through four steps; namely: (1) UASB bench-scale model setup, (2) tracer experimental study, (3) results statistical analysis to determine the reactor dispersion and actual retention time, and (4) selection of the model that can be used to describe the investigated reactor.

Among the main findings of the present study is that the CSTR model with some degree of short-circuiting, dead zones and bypassing flows seems to describe the overall hydrodynamics of UASBs. Also, the mean residence times were 87.68%, 80.35%, and 72.66% of the theoretical hydraulic retention times 6, 8, and 10 hours, respectively.

Keywords: UASB, Bench-scale Model, Flow Regime, Tracer Study

INTRODUCTION

Recent developments in the field of anaerobic treatment have proved that the anaerobic treatment processes are not restricted to the high strength wastewaters, but also they can successfully be applied to dilute low strength wastewaters. The success of anaerobic treatment in treating medium and high strength industrial wastewaters encouraged the researchers to study the anaerobic treatment of the domestic wastewaters. Interest in energy-saving waste treatment options has led to the development of high rate anaerobic digesters like up flow anaerobic sludge blanket (UASB), anaerobic fluidized bed (AFB), anaerobic filter (AF), expanded granular sludge bed reactor (EGSBR) and anaerobic sequencing batch reactor (ASBR) (Karim et al., 2004).

With respect to the concentration of the aggregates along the reactor height, three zones are usually distinguished inside a UASB reactor: (1) a dense sludge bed consisting of biomass aggregates in the bottom section, (2) a sludge blanket containing finely suspended flocs or aggregates, and (3) a zone of clarified water containing almost no solids in the internal settler. This heterogeneous sludge distribution along the height of the UASB reactor excludes the application of the majority of the numerous mathematical models developed for completely mixed anaerobic digestion systems as these models assume a homogeneous biomass distribution and hydrodynamic pattern within the reactor (Kalyuzhnyi et. al., 2006).

Nevertheless, the rate of conversion or removal of organic matter in any bioreactor is governed by two main interrelated factors: the performance of the microbiological processes and the hydrodynamics of the reactor. In other words, mixing and transport phenomena affect the efficiency of all bioreactor configurations. For instance, it is observed that mixing is one of the most important factors affecting the performance of the anaerobic digesters as it helps to homogenize the contents of the digesters (substrate and microorganisms), temperature and pH. As an even mixing pattern at the macro-level is desirable to provide good conditions for substrate transport to, and from, the microbial aggregates (Pena et. al., 2002), it is important to evaluate the amount of mixing required for uniform distribution of digester contents and to achieve the other needed conditions to improve the digester's performance. Consequently, better understanding of the mixing and hydrodynamics of the digester will result in appropriate design and configuration which will ultimately help to avoid digester failure (Karim et al., 2004).

Previous studies on the hydrodynamics of three-phase reactors such as UASBs have shown that they are best described by the CSTR model with some short circuiting, dead-zones and bypass flows (Ottino, 1990, Heertjes and Kuijvenhoven, 1982). In some other models, the heterogeneous hydrodynamic pattern of a UASB reactor has been described by dividing its total volume into two or more compartments. Each of these compartments is assumed to have ideal attributes (such as ideal mixing or plug flow), and they are linked with each other by bypassing and back mixing flows (Bolle, et., al., 1986, Heertjes and Meer, 1978, Heertjes and Kuijvenhoven, 1982, and Wu, and Hickey, 1997). These multi-compartment models are generally capable of fitting experimental data quite satisfactorily for UASB reactors operating under steady-state conditions.

Another approach to model UASB reactor, referred to as a one-dimensional dispersed plug flow model, was developed by Kalyuzhnyi et al., (2006). This model focuses on the granular sludge dynamics along the reactor height, based on the balance between dispersion, sedimentation and convection using one-dimensional (with regard to reactor height) equations. A universal description of both the fluid hydrodynamics and sludge granular dynamics was elaborated by applying known physical laws and empirical relations derived from experimental observations. In addition, the developed model included: (i) multiple-reaction stoichiometry, (ii) microbial growth kinetics, (iii) equilibrium chemistry in the liquid phase, (iv) major solid-liquid-gas interactions, and (v) material balances for dissolved and solid components along the reactor height.

However, the calibration of these models relies on detailed experimental tracer studies to determine the volume fraction of each compartment and the degree of bypass flow for each regime modeled. Moreover many of these tracer studies deal only with short-term impulse loadings of a soluble tracer under steady-state conditions and thus neglecting the dynamics of solid components (Kalyuzhnyi S. V., et. al., 2006).

The global objective of this paper is to determine the liquid flow model of UASB via a tracer study to characterize the overall flow behavior in this reactor. In particular, a tracer study has been utilized in this study to figure out the flow pattern in the UASB reactor and to determine the difference between theoretical and actual hydraulic retention time.

The specific objectives of the present work have been reached through four steps; namely: (1) UASB bench-scale model setup, (2) tracer experimental study, (3) results statistical analysis to determine the reactor dispersion and actual retention time, and (4) selection of the model that can be used to describe the investigated reactor.

As the effluent stream from a continuous flow process is a mixture of fluid elements which have resided in the process for different lengths of time, the distribution of these residence times is an indicator of flow patterns within a process. In other words, the **R**esidence **T**ime **D**istribution **(RTD)** has been developed to characterize the overall flow behavior in a process. However, RTD is determined experimentally by injecting an inert chemical, called a tracer, into the reactor at some time $t = 0$ and then measuring the tracer concentration, C, in the effluent stream as a function of time. Analysis of these data allows calculation of the actual hydraulic retention time in the UASB, a parameter which is controlled by the extent of mixing.

The two most used methods of tracer injection are pulse input and step input. In the present study, the pulse input in which an amount of tracer is suddenly injected into the feed stream in as short a time as possible is employed. Then, a material balance for a pulse addition of tracer compares the actual amount of tracer added to the amount that leaves the process (Sacks, 1997).

MATERIALS AND METHODS

The UASB bench-scale model employed in the present study is the one designed, constructed and fully described by Bayoumi (2007). Utilizing that model, a tracer study using bromophenol blue sodium salt ($C_{19}H_9Br_4NaO_5S$), as a dye, has been executed at three hydraulic retention times; namely: 6, 8 and 10 hours. The color densities of the dye were measured using spectrophotometer at wave length 591nm and plotted versus time passed after injection. Different dye concentrations ranging from 0 to 6 mg/l were calibrated at that wave length. Figure (2) shows the calibration curve of this dye.

The feeding pump was used to feed the bench scale model of UASB with different discharges. The pump was Digital Waston Marlow model 505 S, furnished with tygon tubes or norperene tubes with 24 inch in diameter. The dye solution was added once at the model inlet, then continuing feeding the reactor with tab water and detecting the dye at the model outlet. Three experimental runs at three different Hydraulic Retention Times (HRT); namely: 6, 8, and 10 hrs have been executed in the present study. In each run, the tracer test ran for a period of no less than 24 hours (from 2 to 4 times HRT) when the entire tracer was recovered.

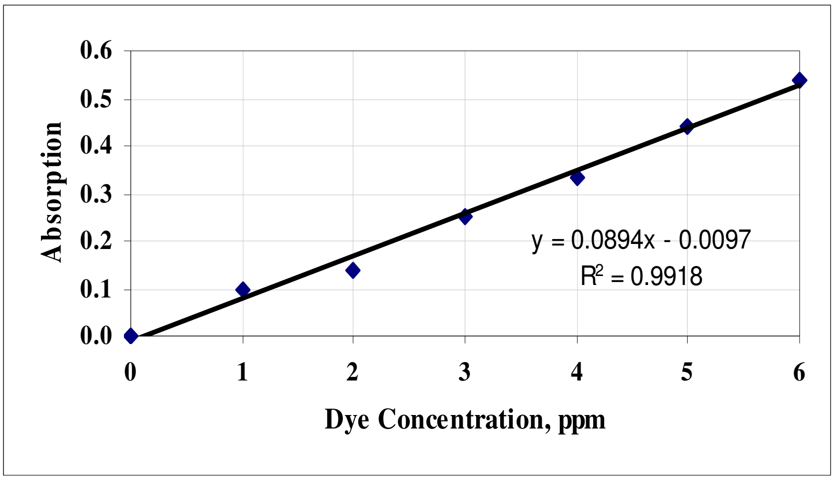

Figure (2): Tracer Calibration Curve

RESULTS, STATISTICAL ANALYSIS, MODELING, AND DISCUSSION

At the start of the experiment, the injected tracer had concentrations of 2.5, 6 and 5.5 ppm at 6, 8 and 10 hr HRT, respectively. The output tracer concentrations have been monitored and measured at the outlet of the reactor. Figures (3 through 5) show the output tracer concentrations versus time after injection at 6, 8, and 10 hours-HRT.

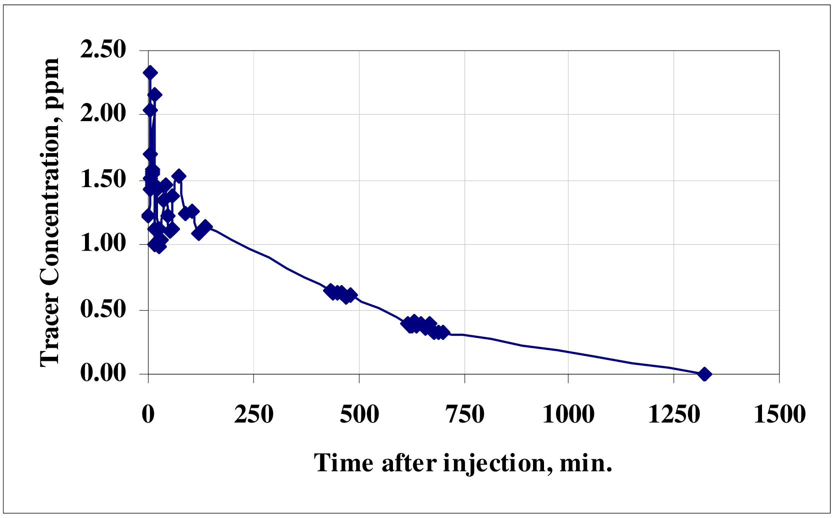

Figure (3): Tracer Concentration vs. Time at 6 hrs-HRT

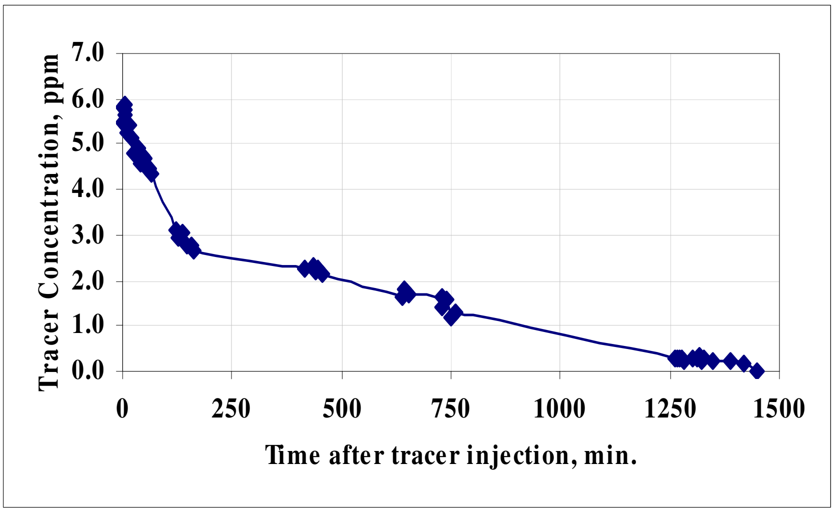

Figure (4): Tracer Concentration vs. Time at 8 hrs-HRT

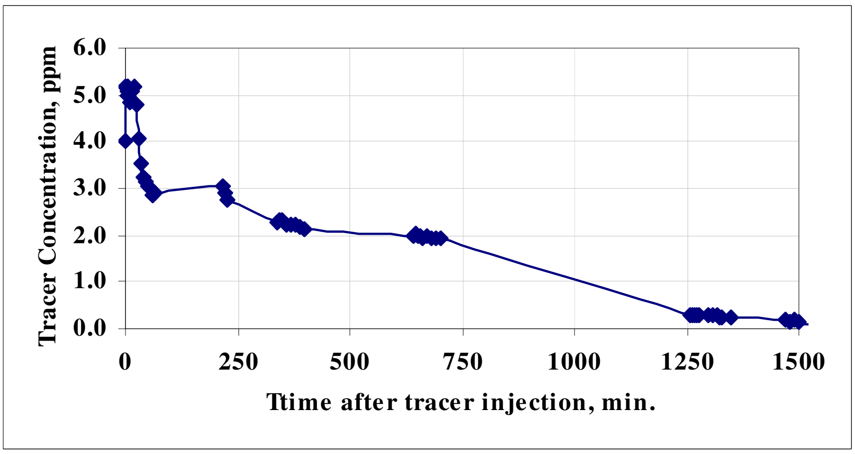

Figure (5): Tracer Concentration vs. Time at 10 hrs-HRT

Statistical Analysis

In order to determine the **M**ean **R**esidence **T**ime **(MRT)**, the dispersion number, as well as the pertinent statistical parameters (standard deviation), the presented above results that obtained from the experimental program has been statistically analyzed utilizing the following equations (**Levenspiel, 1999):**

$$\bar{t} = \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \tag{1}$$

$$\sigma^2 = \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - \bar{t}^2 \tag{2}$$

$$\sigma^2{}_\theta = \frac{\sigma^2}{\bar{t}^2} = 2\left(\frac{D}{uL}\right) - 2\left(\frac{D}{uL}\right)^2 \left(1 - e^{-uL/D}\right) \tag{3}$$

Where:

t	=	the time after dye injection, minutes,
c	=	the tracer output concentration, ppm,
$\bar{t}$	=	the Mean Residence Time, minutes,
σ^2	=	the standard deviation, minutes^2,
θ	=	$t/\bar{t}$,
d	=	the dispersion number
	=	*D/uL*,
D	=	dispersion coefficient, cm^2/min.,
u	=	the mean displacement velocity, cm/min., and
L	=	Length of the reactor, cm.

The determined values of the mentioned parameters are presented in Table (1). These values illustrate large amount of dispersion as the dispersion number is larger than 0.2. On the other hand, the mean residence times were 87.68%, 80.35%, and 72.66% of the theoretical hydraulic retention times 6, 8, and 10 hours, respectively.

Table (1) Tracer Statistical Parameters

Parameter	**Unit**	**Value**		
		6 hours *HRT*	***8 hours*** *HRT*	***10 hours*** *HRT*
$\bar{t}$	minutes	315.56	385.68	435.97
σ^2	Minutes^2	68345.56	93850.72	87301.36
d	-	0.77	0.63	0.34

Modeling

For more complex reaction kinetics, it is necessary to first set up a model for the flow patterns in the reactor before an estimate of conversion or removal of organic matter in any bioreactor can be made. The next step is, therefore, to fit simple non-ideal flow models to the RTD curves. Selection of a flow model is based on the physical configuration of the reactor, visual observation of the flow patterns where possible, and the shape of the RTD curve. The model is fitted to the RTD curve by comparing the theoretical model with the experimental RTD curve. The parameters of the theoretical flow model are varied until the closest fit between the theoretical and experimental curves is achieved (Sacks, 1997).

The output concentrations of the tracer were plotted versus time after injection for the both UASB reactor and CSTR and presented in Figures 6 through 8. On the other hand, **R**esidence **T**ime **D**istribution **(RTD)** or Dimensionless Exit age curves (**E-curves**) have been derived from the experimental tracer study that has been executed at three HRTs; namely: 6, 8, and 10 hours for UASB, CSTR, and two tanks in series and presented in Figures 9 through 11.

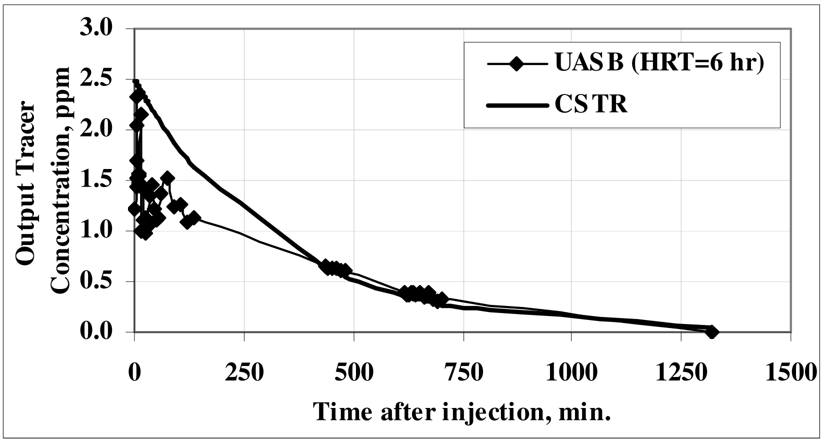

Figure (6): Output tracer concentration vs. time for the UASB reactor and CSTR (at 6 hr-HRT)

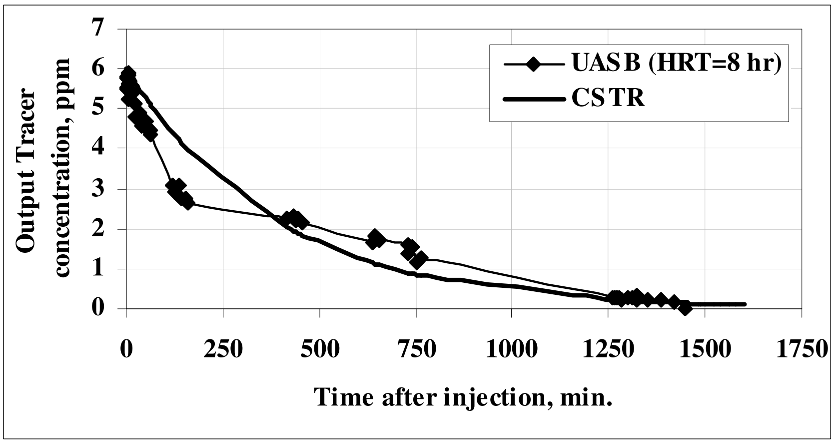

Figure (7): Output tracer concentration vs. time for the UASB reactor and CSTR (at 8 hr-HRT)

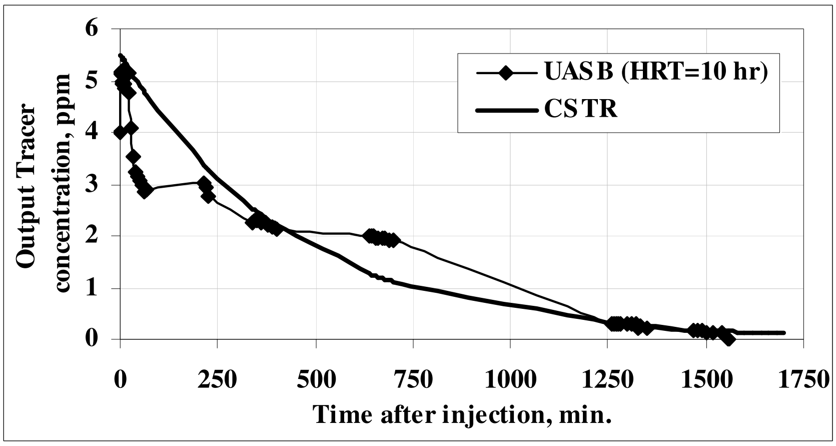

Figure (8): Output tracer concentration vs. time for the UASB reactor and CSTR (at 10 hr-HRT)

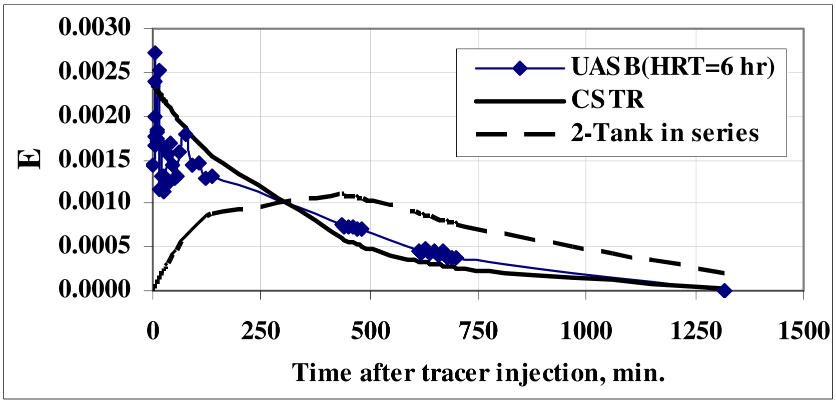

Figure (9) Dimensionless E curves for the UASB, CSTR, and 2-tanks in series (at 6 hr-HRT)

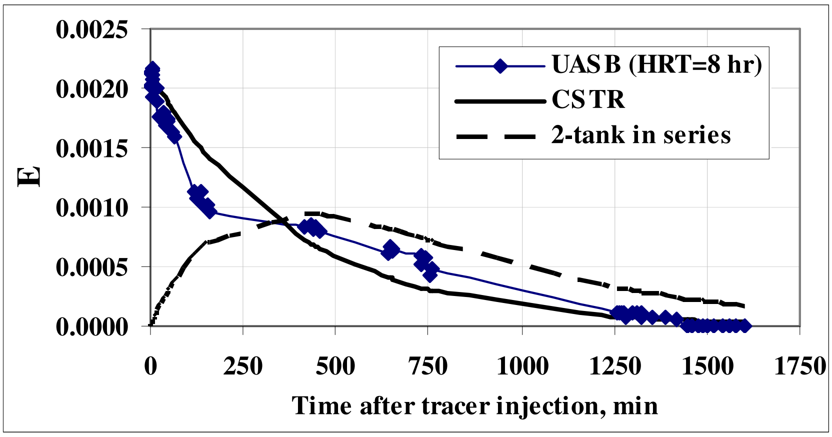

Figure (10) Dimensionless E curves for the UASB, CSTR, and 2-tanks in series (at 8 hr-HRT)

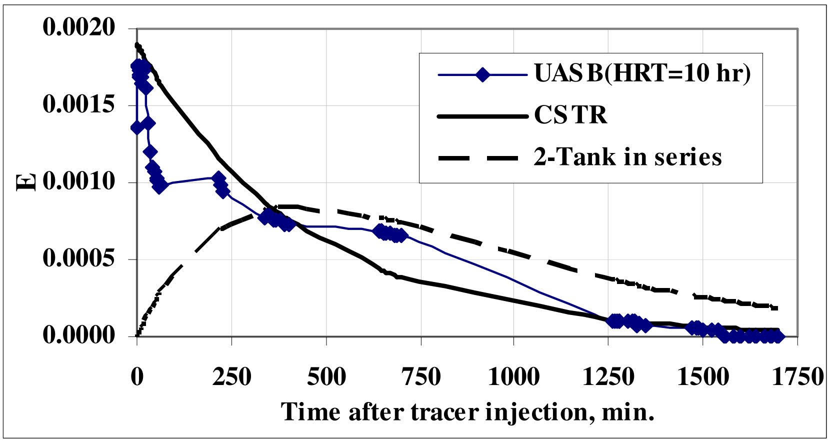

Figure (11) Dimensionless E curves for the UASB, CSTR, and 2-tanks in series (at 10 hr-HRT)

The above Figures illustrate the overall hydrodynamic behavior of the UASB reactor at the evaluated hydraulic loading rates. Significant statistical differences between the means of the parameters accompanied to the applied inflow rates are noticeable from those Figures. Thus the applied hydraulic loading rate does affect the mixing pattern and consequently the performance of the treatment process.

For instance, by decreasing HRT (i.e., increasing the hydraulic loading rate), the gross hydrodynamic pattern of the UASB approaches closely the CSTR model. In other words, the gross hydrodynamic behavior of the UASB reactor, when underloaded upon increasing the HRT, may be characterized by a dispersed flow pattern with coexisting mixed and dead volumes. However, as the inflow rate approaches its design value, the overall hydrodynamic pattern converged to CSTR model and flow distortion, such as stagnant volumes, short-circuiting and likely bypass flows, were minimized.

Also, the obtained RTD curves show the typical shape of a poorly mixed reactor with dead volumes in which most of the tracer mass left the reactor before one HRT. This feature, together with the steep and early descending branches of the RTD curves, confirms that the UASB reactor had part of its volume as dead space (Levenspiel, 1999).

These reached results are consistent with those previous studies on the hydrodynamics of three-phase reactors such as UASBs that have shown that they are best described by the CSTR model with some short-circuiting, dead zones and bypass flows (Ottino, 1990, Heertjes and Kuijvenhoven, 1982).

CONCLUSIONS AND RECOMMENDATIONS

Limited to the conditions under which the experimental runs had been run and based on the results obtained from the experimental program executed within the scope of this paper, it is found that the CSTR model with some degree of short-circuiting, dead zones and bypassing flows seems to describe the overall hydrodynamics of UASBs.

However, the following specific conclusions regarding the mixing characteristics of the UASB reactor may be drawn:

(1) The use of CSTR model is an adequate tool to describe the macro-mixing properties of UASB reactors.
(2) The mean residence times were 87.68%, 80.35%, and 72.66% of the theoretical hydraulic retention times 6, 8, and 10 hours, respectively.
(3) The gross hydrodynamic pattern of the UASB approaches closely the CSTR model upon decreasing the HRT (i.e., increasing the hydraulic loading rate).
(4) Both underloading and overloading events produce distortion of the gross mixing behavior with predominantly arbitrary flow patterns.

Finally, further research is recommended to provide additional information on the diverse interactions between the liquid, solid and gaseous phases, which are particularly important in multiphase bioreactor like UASBs treating complex substances. The proposed model(s) describing the macro-mixing properties of UASBs still needs fine-tuning as well.

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