HYDRODYNAMIC BEHAVIOR OF A LAB-SCALE UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR (UASB) OPERATED WITH AN ADOPTED HYDRAULIC RETENTION TIME (HRT) OF 12 HOURS

Comportamento hidrodinâmico de um reator anaeróbio de manta de lodo (UASB) em escala de bancada operando com tempo de detenção hidráulica (TDH) de 12 horas

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ABSTRACT

The present research was carried out in the Laboratory of Water Analysis at the Engineering Department at Federal University of Lavras (LWAED-UFLA), in order to evaluate the hydrodynamic behavior of a lab-scale upflow anaerobic sludge blanket reactor (UASB) that was continuously fed with liquid effluent from swine manure with solid separation over 2mm. The hydrodynamic parameters were determined by a tracer study, under hydraulic retention time (HRT) of 12 hours, using Lithium Chloride (LiCl) as a tracer. The system was monitored periodically through physical analysis of samples collected at UASB, during the steady-state operational conditions. The physical-chemical analyses were accomplished using a flame photometry. The operational average temperature in the UASB reactor was 23.9°C .The UASB hydrodynamic parameters determined were: average residence time ($\bar{t}$) of 38.3 h, number of dispersion d= 0.27, and the flow type was characterized as dispersed flow of great intensity. This research is of great importance due to the fact that the scaling-up of biological reactors is based on the hydrodynamic behavior, through which the bacterial kinetic is directly influenced, as reported by Saleh (2004).

Index terms: Hydrodynamic, hydraulic retention time, tracer studies, UASB reactor.

RESUMO

A presente pesquisa foi realizada no Laboratório de Análise de Água do Departamento de Engenharia na Universidade Federal de Lavras (LAADEG-UFLA), para avaliar o comportamento hidrodinâmico de um reator anaeróbio de manta de lodo (UASB), em escala laboratorial, alimentado continuamente com água residuária do confinamento de suínos isenta de sólidos com diâmetro acima de 2 mm. Na avaliação dos parâmetros hidrodinâmicos foi utilizado o cloreto de lítio (LiCl) como traçador, sob tempo de detenção hidráulica (TDH) de 12 horas. O monitoramento foi realizado, quando o reator UASB apresentava condições permanentes “steady-state”. As análises físico-químicas foram realizadas em fotômetro de chama, de amostras retiradas na saída da unidade de tratamento, em intervalos constantes de tempo. A temperatura média operacional do reator UASB foi de 23,9ºC. Os parâmetros hidrodinâmicos do reator UASB, determinados por meio da avaliação foram: tempo médio de residência = 38,3 h, número de dispersão **d**= 0,27 e tipo de fluxo, o qual foi caracterizado como disperso de grande intensidade. A pesquisa se reveste de importância, uma vez que o escalonamento “scale-up” de reatores biológicos, se baseia diretamente nos comportamentos hidrodinâmicos do mesmo, em função da elevada influência que os referidos comportamentos possuem sobre a cinética bacteriana, conforme relatado por Saleh (2004).

Termos para indexação: Hidrodinâmica, tempo de detenção hidráulica, traçador, reator UASB.

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INTRODUCTION

The use of UASB reactors treating swine wastewater has been reported in many scientific articles developed mainly in several international researches dedicated to this subject. These works reveal encouraging results related to this technology, and therefore demonstrate a real applicability concerning to the Brazilian swine production. This happens not only due its stability and efficiency, which makes easy the operational management, but also because of the subproducts generated by the anaerobic process, such as biogas and biofertilizers, normally able to be utilized in the country areas. (Ferreira et al., 2003; Campos et al., 2005a,b, 2006; Ramires, 2005; Lourenço, 2006).

However, problems related to full scale reactors may occur leading to irreversible performance of those units, as reported by Levenspiel (1988). Consequently, this work aim at demonstrating basically the viability of the methodology proposed by Campos (1990) for characterizing the hydrodynamic model of a reactor, giving a reliable base for projects related with lab-scale, as well as, full scale reactors, mainly for those that operate at

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continuous flow rate. Such technology named as stimulus technique was reported also by Levenspiel (1988) and can be applied to any type of reactor, either chemical, physical-chemical, or biological ones, since the tracer to be used ought to be compatible to the medium under research, avoiding sorption (absorption and adsorption). The results are crucial for scaling up systems, from lab-scale to pilot and full scale dimensions. The use of tracer substances is fundamental, in order to have a trustful hydraulic retention time (HRT), specially in wastewater treatment systems; instead of the estimated one, which implies to divide the volume of the liquid container per the flow rate. Through the applying of tracer studies one can determine the true HRT, dead zones, and also hydraulic short-circuits.

Hydrodynamic of reactors

A hydrodynamic model of a reactor is a function related to the flow type and mixture pattern, the last one depending on basically of the geometric shape, the quantity of energy introduced per unit volume and also on the reactor scale. The pattern of flow in the reactor may assume the following two conditions: intermittent (batch) or continuous flow rate. The mixture pattern consequently is characterized traditionally through two ideal hydraulic models, plug-flow and complete mixture. However, these two ideal models only allow characterizing a large range of dispersive flow; common to all types of reactors (Levenspiel, 1988; Campos, 1990; Sperling, 1996).

In the plug-flow regime the flow occurs in steps which flow sequentially. For this type of mixture the substrate concentration varies along the space and time, however in the complete mixture in the reactors, the changes are related only to the time and the substrate is immediately dispersed, as soon as it is introduced in the container. Therefore the concentration of the contents inside the reactor is homogeneous at each moment “t”.

Although not all reactors follow strictly these mixture patterns, the majority of them behave quite close to these, and the error bare minimum. Some other cases, characterized as dispersive flow, the deviation related to the ideal flow may be quite considerable, and may be possibly caused by the formation of small channels of preferential flow (short-circuit), quite normal in the sludge bed of the reactors, mainly to those that do not use agitation systems, forming dead zone regions inside the reactors, quite common to the prismatic shape of reactors due to the corners and other intrinsic conditions.

Due to the problems in modeling actual reactors, which will guide to projects with better operational performance, normally approximation is made for one of the two ideal hydraulic models. However, reactor modeling for dispersive flow regime is quite possible since one can determine the specific hydrodynamic parameters for each reactor model, and for each operational condition, emphasizing the hydraulic loading rate applied, or in other words, the influent volume introduced per unit volume of reactor under a determined interval time. The main hydrodynamic parameters to be determined are: the number of dispersion (**d**) and the fluid average residence time ($\bar{t}$). The reactors normally have “**d**” values ranging from **0** to ∞ , these extreme values characterize the ideal flows such as plug-flow and complete mixture flow, respectively. (Campos, 1990; Sperling, 1996).

The knowledge of the residence time distribution of the flow in the interior of a reactor is the only condition needed to establish its hydrodynamic behavior. This information can be determined through a methodology named stimulus and response. The stimulus is performed using a tracer injection inert to the medium of the container, and in the effluent the response is a concentration of tracer which comes out of the reactor in constant intervals (***C(t)***).

As a result, having the influent flow rate, the tracer pulse signal, the normalized response is called $\boldsymbol{C_N}$, which is needed in order to determine precisely the flow rate of non ideal condition. The curve may be obtained using Equation 1 according to Levenspiel (1988) and Campos (1990).

$$\int_0^\infty C_N\,dt = \int_0^\infty \frac{C(t)}{Q}\,dt = 1 \qquad (1)$$

where, $Q = \int_0^\infty C(t)\,dt$

for,

$\boldsymbol{C_N}$ - normalized concentration for one tracer signal – pulse entrance;

C(t) - equation which describes the behavior of the tracer concentration as a function of time in the outlet of the reactor(mg L^{-1});

Q - area under the curve which is described through the equation ***C(t)*** (mg L^{-1}.h).

When one works with tracers, the results are obtained through mathematical concepts as the average value of the distribution and the distribution dispersion (variance), shown in the Equations 2 and 3, as follow.

$$\bar{t} = \frac{\int_0^\infty tC(t)\,dt}{\int_0^\infty C(t)\,dt} \tag{2}$$

$$\sigma^2 = \frac{\int_0^\infty t^2C(t)dt}{\int_0^\infty C(t)dt} \tag{3}$$

The variance represents the square of the amplitude of the distribution and it has units of time taken to the power of two. It is quite important when one intend to adjust the experimental curves and compare them with many theoretical families of curves. Several models can be used in order to characterize the non-ideal flow, among them, the ones denominated dispersion model, based in the analogy of one effective flow and a diffusion process. In this type of model, with high frequency, it is considered important to measure the time in order to obtain the average time residence (θ), giving a dimensionless measurement according to the Equation 4.

$$\theta = \frac{t}{\bar{t}} \text{ , and } \quad d\theta = \frac{dt}{\bar{t}} \tag{4}$$

The dispersion model is characterized by plug-flow regime which is overlapped by some mixture, independent on the portion inside the container. It shows a non-existence of dead zones or short-circuits. Nevertheless, with the intensity of the turbulent variation or mixture, this model may vary from tubular to a uniform continuous flow.

Since the mixture process produces a redistribution of the material, and as it repeats for a several number of times during to the flowing process throughout the vessel, these perturbations are considered static in nature, similar to the molecular diffusion governed by the Fick's Law, Equation 5, where ***D*** (diffusion coefficient) is a parameter which characterizes the process.

$$\frac{\partial \boldsymbol{C}}{\partial \theta} = D\frac{\partial^2 \boldsymbol{C}}{\partial x^2} \tag{5}$$

In a similar way, the parameter ***d*** (dispersion coefficient) characterizes the degree of mixture during the flow, as shown in the Equation 6.

$$\frac{\partial \boldsymbol{C}}{\partial t} = d\frac{\partial^2 \boldsymbol{C}}{\partial x^2} \tag{6}$$

The admensional form, where $z = x/L$ e $\theta = t/\bar{t} = tu/L$, represents the basic differential Equation 7, which is the dispersion model, as shown below,

$$\frac{\partial \boldsymbol{C}}{\partial \theta} = \left(\frac{d}{uL}\right)\frac{\partial^2 \boldsymbol{C}}{\partial z^2} - \frac{\partial \boldsymbol{C}}{\partial z} \tag{7}$$

where the admensional value (*d*/uL), called dispersion number, is the parameter that measures the extension of the axial dispersion. Therefore,

• *d*/uL $\rightarrow$ 0, the dispersion is despised, the flow may be tubular or plug-flow;

•*d*/uL $\rightarrow \infty$, enormous dispersion, the flow is completed mixed.

This model, in general, represents adequately the flowing which is not far from the plug-flow.

The curve which describes the behavior of the tracer modifies its form significantly, mainly when it passes from the bary center point, presenting a non-symmetrical shape and also presents a tail, the flowing conditions in the injection point and the measuring point, called bounder conditions, will interfere in the shape of the curve $\boldsymbol{C_N}$ obtained. In this way it is not possible to achieve, under the conditions of closed vessels, analytical expressions for the curves $\boldsymbol{C_N}$,. On the other hand, through numerical methods, the conditions are inverse. The average and the variance of these curve families are given in Equations 8 e 9, Levenspiel (1988):

$$\bar{\theta}_c = \frac{\bar{t}_c}{\bar{t}} = 1 \tag{8}$$

$$\sigma_\theta^2 = \frac{\sigma^2}{\bar{t}^2} = 2\frac{d}{uL} - 2\left(\frac{d}{uL}\right)^2\left(1 - e^{-uL/d}\right) \tag{9}$$

where,

u - average velocity of the flow in the reactor (m. h^{-1});

L - length of the way inside the reactor (m).

MATERIALAND METHODS

The research was carried out in the Laboratory of Water Analysis, of the Engineering Department in the Federal University of Lavras – UFLA, situated in Lavras city, South of Minas Gerais State, with local geographic coordinates of 21°14’ e 45°00’, for latitude and longitude, respectively, and altitude of 920 meters. The climate, according to the Köppen classification is the type of Cwa (moderate with hot summers and cold and dry winters).

Treatment System

The effluent treatment system evaluated was composed with the following units: 1) acidification and equalization tank used also as settling tank, with liquid volume of 55 L (AET), batch fed with screened swine manure passed through a mach of nylon (2 x 2mm); 2) an upflow anaerobic sludge blanket reactor (UASB) assembled in glass, covered with polystyrene boards in order to maintain the vessel temperature. The liquid reactor volume was 12.1 L, a cross section of (15x15) cm, and a heating system container, with an automatic electrical thermostatic and a thermo-boiler. They were used in order to warm up the effluent using a coiled tube of cooper for heat exchanging, immersed in water, where the influent passed all the way through at constant temperature of 28ºC. In the upper part of the reactor a three-phase-separator was installed for biogas capture and solids sedimentation. The influent was introduced into the UASB reactor using a positive displacement membrane pump, PRO-MINENT, Model GALA 1602, able to operate at constant flow rate of 2.1 L h^{-1}.

Stimulus and response test

A concentrated salt solution of Lithium Chlorine (LiCl) with 100 mg L^{-1} (Li^+ ion) in distilled water was used for testing the stimulus and response. This high concentration solution was injected in order to apply a minimum volume and avoid perturbation in the influent flow. The amount of volume injected was only 7.4 mL. The tracer injection of Lithium Chlorine was carried out using a technique described by Campos (1990) and is denominated pulse injection, which according to the same author; makes simple the mathematical treatment.

An amount of 740 mg of Li^+ was injected at the inlet pipe of the UASB reactor, producing a maximum theoretical Li^+ (ion) concentration of 61 mg L^{-1}. The first collected sample of 3mL was at the same time of the injection, in order to detect short-circuits as emphasizes Campos (1990). The samples were collected at constant intervals of 12 minutes each, using a glass pipe with a volume of 5 mL. The samples were analyzed immediately after collection using a Flame Photometer (Micronal), Model 45, operated with photocell. Five standard concentrations were utilized during all the evaluation period, with Lithium concentration varying from 0, 15, 30, 45 and 60 mg L^{-1}, prepared as a function of molecular weight of Lithium Li^+ (ion) and Lithium Chlorine salt (LiCl).

The mathematical simulations using the collected data were made with MAT-LAB® and Maple® softwares.

RESULTSAND DISCUSSION

The amount of collected samples totalized 623 units during an interval period of 124 hours. The data was manipulated using the Excel® Software and ordained pairs (time x concentration) from which a curve was generated. This curve represents the behavior of the tracer along the reactor, and the respective equation (C(t)), obtained by statistic regression, showed a regression value of “R^2=0.971”, presented in Figure 1 and Equation 10, respectively.

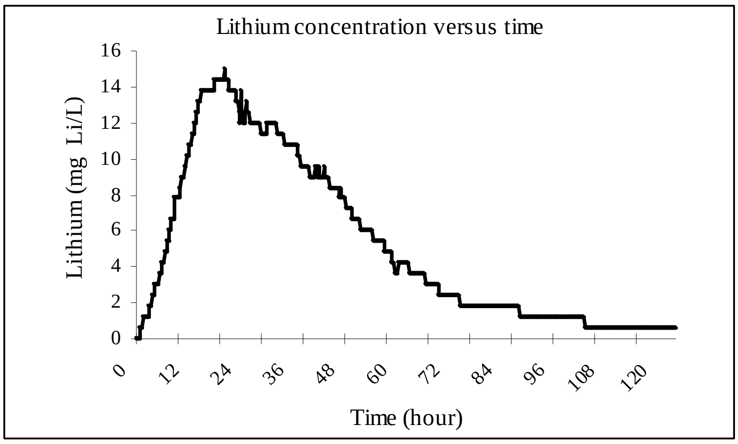

Figura1 – Distribution curve of Li^+ (ion) during the evaluation period.

$$C(t) = 90.97\exp^{(-0.0441t)} - 95.28\exp^{(-0.0676t)} \qquad (10)$$

Through Figure 1, it is possible to observe the behavior of the fluid trending to the flow pattern of dispersive mixture of great intensity, presenting particular characteristics, such as, asymmetric distribution curve and a great tail, showing the presence of dead zones inside the UASB reactor. It can also be observed the evidence of preferential channels of flow, known as short-circuits, once it was verified the presence of trace material in the effluent of the reactor, even before the first evaluation hour, one of the causes is due to the biogas production. It is important to observe that, the time expended in order to realize the test was 10 times superior to the HRT adopted of 12 hours. The amount of Li^+ recovered was nearly 90%.

The first step in the mathematic simulation was to integrate the Equation 10 along the interval from 0 to 124 h, in order to determine, using the relationship of instantaneous concentration, observed at each instant ***dt***, the general average of the flow of Lithium, based on its concentration during the time, finding then the result of 645 $mg.L^{-1}.h^{-1}$.

The next step was to determine the average flow of the experiment, using the mathematical ponder average of several determinations realized along the experiment period, finding the value of 1.03 $L.h^{-1}$. Relating the average flow of Lithium to the concentration of the average flow of the system, the total mass of Lithium recovered (664.32 mg) was determined during the experimental period, correspondent to 89.77%, nearly 90.0% of the total amount of Lithium injected (740 mg).

Through the normalization process, described in Equation 1, it was found the Equation $\boldsymbol{C_N}$, denominated normalized flow distribution of the residence time in the interior of the UASB reactor, which is presented in the Equation 11.

$$\int_0^{124} C_N = 0.1410462\exp^{(-0.0441t)} - 0.1477287\exp^{(-0.0676t)} = 1 \qquad (11)$$

Therefore, the average residence time of any particle in the interior of the UASB reactor can be estimated according to Equation 2, for a time interval within 0 to 124 h. Calculating the average of residence time of the flow in the reactor, the obtained value was 38.29 h, more than three times the adopted HRT of 12 hours. This calculated value was already expected, since the low mobility of the tracer inside the reactor, due to the presence of dead zones, was mainly caused by the prismatic shape of the reactor with many corners.

After the variance was determined for the normalized average value, and considering that the model was characterized as disperse of great intensity, the number of dispersion "**d"** was then determined according to Equation 9, which value was 0.2675.

Once the average residence time of the flow, in the interior of reactor ($\bar{t}$) was about 38.29 h, a value three times greater than the HRT imposed to the system, the presence of dead zones was confirmed in the interior of the reactor, which probably occurred due to the stagnation in several corners of the prismatic shape of the reactor.

CONCLUSION

The study of the hydrodynamic behavior of the Upflow Anaerobic Sludge Blanket (UASB) lab-scale reactor treating liquid effluent of swine manure, showed to be simple, practical and of great value, and can be applied to any scale. This evaluation must be understood as one of the most important tools for the management of chemical; physical-chemical and biological treatment units, since it contributes to understanding the hydraulic mechanisms and, therefore, to know exactly the actual HRT, and consequently the behavior of dissolved solids. From the results one can improve physically a treatment unit modifying its shape or adjusting bafflers, or even recycling the effluent in order to improve the efficiency of the whole system. Finally, the found results suggested that, even lab-scale units, normally well controlled, are under the phenomenon of non-ideal standard of mixture, demonstrating in this way that a simple adoption of theoretical parameters, such as HRT, flow rate and reactor volume, does not imply in a well designed unit, showing that many other factors may cause influence on the operational aspects inside a treatment unit.

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