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Hydraulic characteristics analysis of an up-flow anaerobic sludge blanket fixed film (UASB-FF) using tracer experiments

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ABSTRACT

The hydraulic characteristic of an up-flow anaerobic sludge blanket fixed film (UASB-FF) were studied by changing two important hydraulic factors that can impact significantly on the hydraulic regime of the UASB-FF bioreactor: the Up-flow velocity (V_{up}) and biogas production rate (Q_g). The analysis of the reactor hydraulic performance was performed by studying hydraulic residence time distributions (RTD) obtained from tracer (Rhodamine B) experiments. The region of exploration for the process was taken as the area enclosed by V_{up} (0.5 and 3.0 m/h) and Q_g (14.87 and 7.96 l/d). Three dependent parameters viz. deviation from ideal retention time ($\Delta\tau$), dead volume percentage and Morrill dispersion index (MDI) were computed as response. The maximum $\Delta\tau$ and dead volume percentage were 33.58 min and 26 % at V_{up} of 0.5 m/h and Q_g of 14.87 l/d, respectively. While, the minimum responses (4.15 min and 19.3 %) were obtained at V_{up} of 3.0 m/h and Q_g of 7.96 l/d, respectively. The values of MDI computed at the minimum and maximum V_{up} and Q_g are identified as 11.33 and 10, respectively, showing that the hydraulic regime in UASB-FF bioreactor is a semi-complete mixing.

1. Introduction

The hydraulic behavior in biological reactors is of fundamental importance for the efficiency of the wastewater treatment processes. Examples of hydraulic phenomena with adverse impacts on the bioreactors performance include short circuiting streams and dead volumes. The unfavorable hydraulic situations in the bioreactors may cause lower process performance and thus higher residual concentrations in the treated wastewater. This may be particularly significant in high loaded bioreactors (Levenspiel. 2000; Fogler Scott. 2001) Comparison of actual hydraulic characteristics of a reactor measured using tracers, to the expected theoretical response can be used to assess the degree to which the ideal design has been achieved (Fogler Scott. 2001; Metcalf & Eddy. 2003).

The up-flow anaerobic sludge blanket fixed film (UASB-FF) reactors offer an alternative treatment technology to the biohydrogen production systems. Because of the widespread use of UASBs in the recent years, and on the other hand the reactor hydraulic directly affects the treatment performance, determination of hydraulic characteristic is of great importance. Poor hydraulic conditions reduce the HRT and effective volume, resulting in lower hydrogen production efficiencies of the bioreactor. Presence of a good design model for UASB reactor is a useful tool describing and predicting the UASB hydraulic regime (Yamaguchi et al. 1999; Kargi et al. 2003; Najafpour et al. 2006).

Many studies have carried out by using the tracer tests to indicate the presence of short circuiting streams and dead volume in different reactors. Hydraulic characterization is performed by retention time distribution (RTD) curve (Mansouri et al. 2012; Newell et al. 1998; Williams et al. 1998; Chen et al. 2010; Martin. 2000). However, there is not any tracer study done on the hydraulic characteristics of the UASB-FF bioreactor.

Nevertheless, a few quantitative models have been proposed. In all these models, there is no common agreement on whether an UASB behaves as a plug-flow or a completely mixed reactor. Various indexes have been used to describe the mixing and hydraulic flow pattern in the different operational units.

In the present study, in order to explore the best operational conditions achieving a high hydraulic performance in an UASB-FF, the effect of two effective variables, the Up-flow velocity (V_{up}) and biogas production rate (Q_g), on the hydraulic regime of the UASB-FF were investigated. The deviation from ideal retention time ($\Delta\tau$), volume of dead space and dispersion indexes (MDI and d) as the responses were determined using the data obtained from the tracer experiments and the hydraulic characteristics.

2. Materials and methods

2.1. Bioreactor configuration

The schematic diagram of the laboratory-scale UASB-FF bioreactor (total volume of 3.5 l, working volume of 2.55 l and liquid height of 80 cm) rig set-up used in this study is shown in Fig. 1. The glass bioreactor column was fabricated with an internal diameter of 55 mm at the bottom and middle parts and 75 mm at the top part. The bioreactor comprised of three sections. The lowest section of the UASB reactor's column accommodated 67.84 % of the total working volume. The middle section of the fixed film reactor accommodated 14.51 % of the working volume. The top section of the bioreactor accommodated 17.65 % of the working volume consisting of a gas-solid separator and outlet zone.

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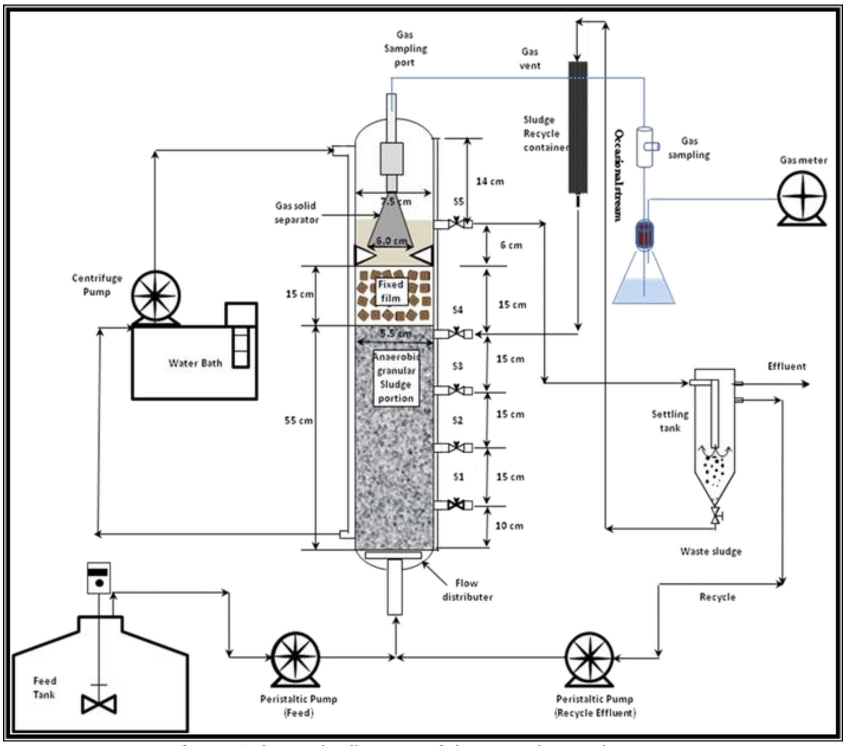

Fig. 1. Schematic diagram of the experimental set-up.

2.2. Tracer experiments procedure

In order to carry out the analysis of the hydrodynamic process within the UASB-FF, the reactor was filled with water till the top level of the outlet. Then, pulses of an inert substance was introduced into the reactor inflow and subsequently measured at the outflow. To study the flow pattern in the reactor, a technique involving analysis of tracer-response profiles was used. In this tracer study, Rhodamine B is introduced into the reactor at the influent end as a tracer and collected the tracer-output profile in the fluid leaving the reactor. Rhodamine B was used as a tracer because this substance will not be absorbed on or reacts with the exposed reactor surface, and can be detected at very low concentration using a spectrophotometric method. In each run, the influent of water into the reactor was adjusted and fed by a peristaltic pump. Subsequently, 2.5 ml of 0.01 M Rhodamine B was immediately fed into the inlet of the reactor. Effluent samples were collected immediately and then at every 5 minutes, or at even shorter time intervals if required. The collected samples were subjected to spectrophotometric reading at 554 nm. The operation was continued until no tracer was detected for at least two or three consecutive samples.

2.3. Experimental design

Up-flow velocity (V_{up}) and biogas production rate (Q_g) are two important hydraulic factors and can impact significantly on the hydraulic regime of the UASB-FF bioreactor. In this study, V_{up} and Q_g were chosen as the most critical operating factors for the hydraulic regime of the UASB-FF bioreactor. The region of exploration for the hydraulic regime was decided as the area enclosed by V_{up} (0.5 and 3.0 m/h) and Q_g (14.87 and 7.96 l/d). Selection of the values of the Qg was based on the results obtained from the earlier studies. In order to carry out a comprehensive analysis on the hydraulic regime, three dependent parameters were calculated as response. These parameters were deviated from ideal retention time (Δτ), volume of dead space, and Morrill dispersion index (MDI).

3. Results and discussion

3.1. Hydraulic performance analysis

The hydraulic performance of the UASB-FF bioreactor is analyzed by studying water flow patterns or hydraulic residence time distributions (RTD) obtained from the tracer experiments. Fig. (2a-b) represents the modeled and experimental data curves of tracer concentration time distribution at different V_{up} (0.5 and 3.0 m/h) and Q_g (14.87 and 7.96 l/d). The ideal flow concentrations were calculated based on the equation (1):

$$\mathrm{C, Ideal, (mmol)} = \mathrm{C_0} \times \mathrm{Exp}(-\frac{\mathrm{t}}{\tau}) \quad (1)$$

Where, C is the ideal flow concentration (mM), C_0 is the initial flow concentration of the tracer (mM), t is sampling time (min), and τ is theoretical retention time (min).

The figure makes it clear that the increase in V_{up} resulted in pronounced deviation from ideal flow pattern. It can be seen that the deviation obtained at V_{up} of 0.5 m/h and Q_g of 14.87 l/d was less than the deviation obtained at V_{up} of 3.0 m/h and Q_g of 7.96 l/d. As depicted in Fig. 2b, high volume of the tracer arrives at the outlet before complete mixing with the bulk of the liquid in the reactor. It could be due to the short cut phenomenon occurred originated from the reactor geometry, inlet and outlet design and inadequate mixing (see next section). If the concentration versus time tracer response curve is defined by a series of discrete time step measurements, the theoretical mean residence time is typically approximated as:

$$\bar{t}_{\Delta c} \approx \frac{\sum \mathrm{t_i C_i \Delta t_i}}{\sum \mathrm{C_i \Delta t_i}} \quad (2)$$

Where, $\bar{t}_{\Delta c}$ is the mean detention time based on discrete time step measurements, (min), t_i is the time at ith measurement, (min), C_i is the concentration at ith measurement, (mmol/l), and Δt_i is the time increment about C_i, (min).

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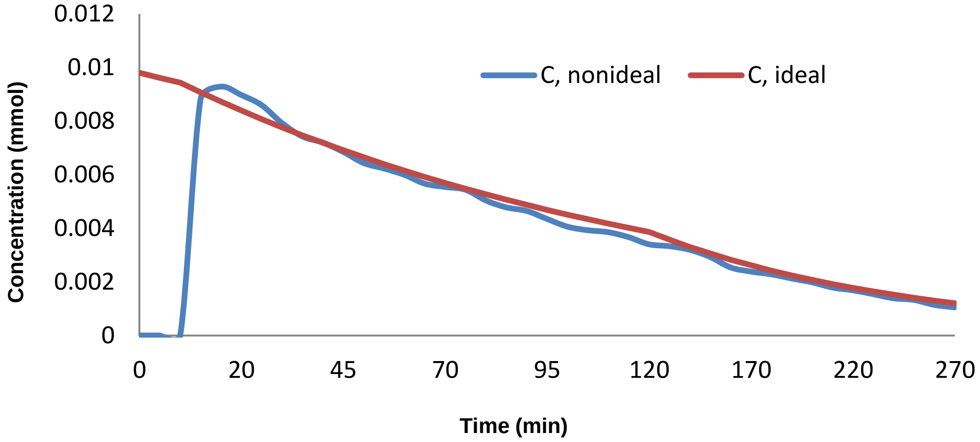
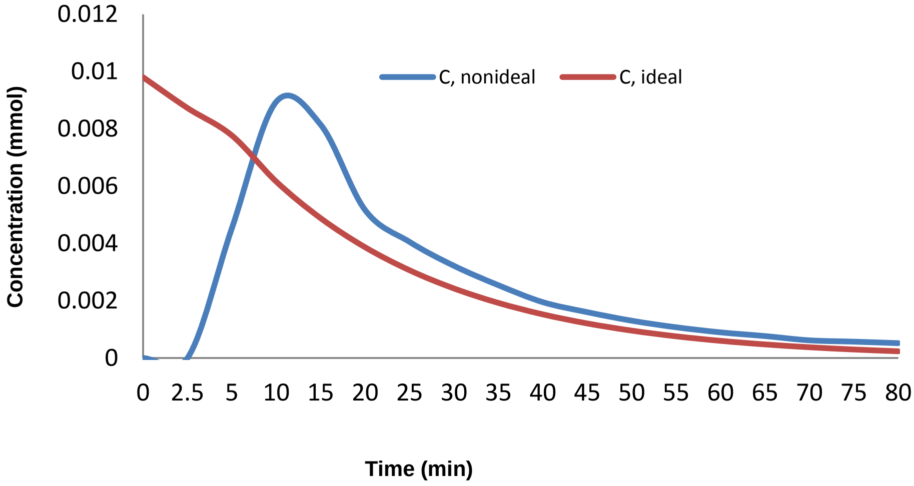


(a)



(b)

Fig. 2. Mathematical and empirical curves of tracer concentration time distribution for (a) V_{up}=0.5 m/h and Q_g=14.87l/d, (b) V_{up}=3.0 m/h and Q_g=7.96 l/d.

3.2. Statistical analysis

3.2.1. Deviation from ideal retention time (Δτ)

Deviations from the ideal retention time (Δτ) can be caused by a number of factors viz. channeling and/or recycling of fluid, short-circuiting, creation of stagnant regions in the vessel, and etc. In the short-circuiting, a portion of the flow that enters the reactor during a given time period arrives at the outlet before the bulk of the flow that entered the reactor during the same time period arrives. This non-ideal flow may be caused by density currents due to the temperature difference, wind-driven circulation pattern, inadequate mixing and poor design (Metcalf & Eddy. 2003). Ultimately, the incomplete use of the reactor volume due to above reasons can result in the decreased Δτ and reduced treatment performance. In this study the values of Δτ were obtained at 33.58 and 4.15 min for V_{up} of 0.5 m/h and Q_g of 14.87 l/d and V_{up} of 3.0 m/h and Q_g of 7.96 l/d, respectively. From the results, increasing the V_{up} (τ from 21.5 to 128.8 min) resulted in the increase in Δτ (4.15 to 33.58 min). It was attributed to the relatively low up-flow velocity of the liquid within the reactor that may create dead space and inadequate mixing. Inadequate input energy for mixing, non-mixing of some portions of the reactor contents with the incoming water and poor design of the reactor at inlet zone cause dead zones to develop within the reactor or allow short circuiting to occur (Metcalf & Eddy. 2003). To elucidate the Δτ, the volume of dead zone was also obtained as a response (Eq. 3).

$$\Delta\tau = \left(\frac{\bar{t}_{\Delta c} - \theta}{\theta}\right) \times 1 \qquad (3)$$

In general, the long tail in the RTD curve shows a discrepancy between the mean residence time and the theoretical residence time. It is possible that stagnant hydraulic zones exist near the inlet and outlet parts of the reactor or in the fixed film zone, where tracer can be trapped and slowly released. It must be noted that, in this UASB-FF reactor, the liquid volume within the fixed film part was 17 % of the total liquid volume, likely to promote a relatively high dead volume. The values observed of the response (Δτ) were 26 % and 19.3 % of the total reactor volume at V_{up} of 0.5 m/h and Q_g of 14.87 l/d and V_{up} of 3.0 m/h and Q_g of 7.96 l/d, respectively.

3.2.2. Morrill dispersion index (MDI)

One important factor that indicates the type of the reactor (complete mix or plug-flow) is Morrill Dispersion Index (MDI). MDI can be used as an indicative tool for determining features of flow patterns in reactors. These consist of the regions of stagnant fluid (dead space) and/or the possibilities of bypassing. A ratio of 90 to 10 percent

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values from the cumulative tracer concentration curve could be used as a measure of the dispersion index. The value for an ideal plug-flow reactor is 1.0 and about 22 for a complete-mix reactor. MDI was computed for both operational conditions studied (Metcalf & Eddy. 2003).

Morrill dispersion index,

$$\mathrm{MDI} = \frac{P_{90}}{P_{10}} \quad (4)$$

Where P90 is 90 percentile value and P10 is 10 percentile value from log-probability plot of the cumulative tracer concentration curve. The values of MDI computed at the minimum and maximum V_{up} and Q_g are identified as 11.33 and 10, respectively, showing that the hydraulic regime in UASB-FF bioreactor is a semi-complete mixing.

In order to further analyze the residence time distribution of the fluid in a reactor the E(t) and F(t) curves have been developed in the Fig. 3. Fluid elements may require differing lengths of time to travel through the reactor. The distribution of the exit times, defined as the E(t) curve, is the residence time distribution (RTD) of the fluid. The exit concentration of a tracer species C(t) can be used to define E(t). That is:

$$E(t) = \frac{\mathrm{C(t)}}{\int_0^\infty \mathrm{C(t)dt}} \quad (5)$$

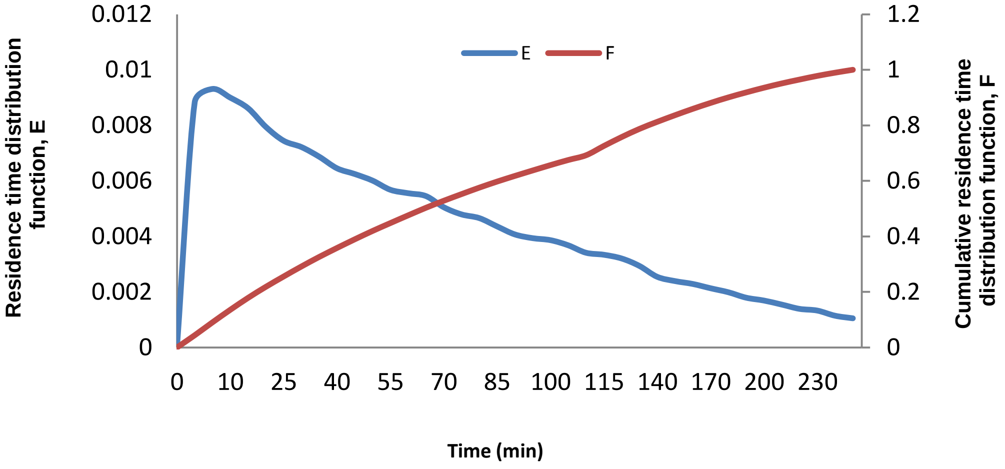
Such that:

$$\int_0^\infty \mathrm{E(t)dt} = 1 \quad (6)$$

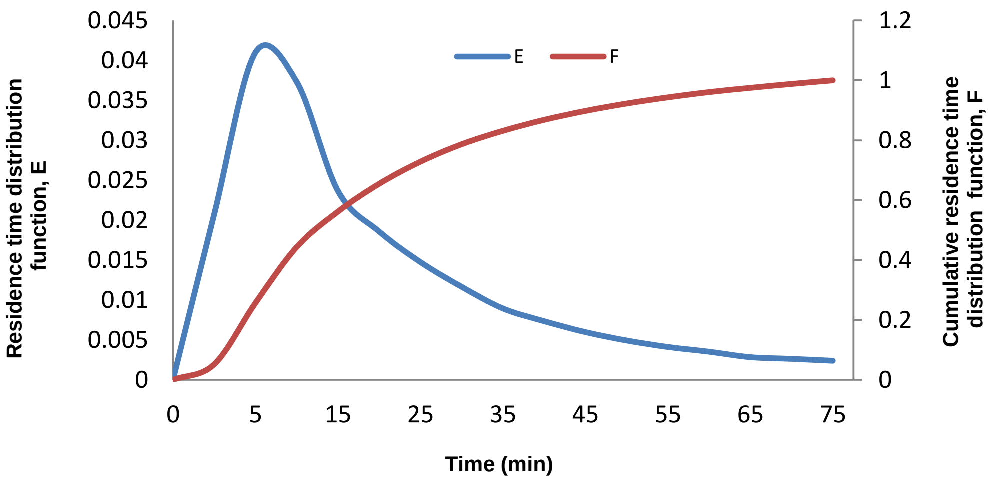
The F curve is defined as

$$\mathrm{F\ (t)} = \int_0^t \mathrm{E(t)dt} \quad (7)$$

where, F(t) is the cumulative residence time distribution function. As shown in the equation (7), the F(t) curve is the integral of the E(t) curve while the E(t) curve is the derivative of F(t) curve. In the fact, F(t) represents the amount of tracer that has been in the reactor for less than the time (t). As can be observed in the Fig. 3, retention time distribution (RTD) function, E(t) and F(t) showed a higher initial values at V_{up} of 3.0 m/h compared to the values at the V_{up} of 0.5 m/h. The interaction showed that up-flow velocity and gas flow rate played an important role in the MDI of the reactor.



(a)



(b)

Fig. 3. E(t) and F(t) plots with respect to
(a) V_{up}=0.5 m/h and Q_g=14.87l/d, (b) V_{up}=3.0 m/h and Q_g=7.96 l/d.

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4. Conclusion

The hydraulic characteristic of an up-flow anaerobic sludge blanket fixed film (UASB-FF) at various levels of the Up-flow velocity (V_{up}) and biogas production rate (Q_g) were investigated. The liquid volume within the fixed film part likely promotes a relatively high dead volume. V_{up} and Q_g were found to be influential on the deviation from ideal retention time ($\Delta\tau$). Increasing in the Q_g resulted an increase in $\Delta\tau$ while a reverse effect caused by increasing the up-flow velocity. The volume of dead space increased upon increasing the Q_g and decreasing the V_{up}. The values of MDI computed at various levels of the variables showed that the hydraulic regime in UASB-FF bioreactor is a semi-complete mixing.

References

Chen X., Zheng P., Guo Y., Mahmood Q., Tang C., Ding S., Flow patterns of super high-rate anaerobic bioreactor, Bioresource Technology 101 (2010) 7731–7735.

Fogler Scott H., Elements of chemical reaction engineering, Third Ed., Prentice Hall PTR, (2001).

Kargi F., Eker S., Performance of rotating perforated tubes biofilm reactor in biological wastewater treatment, Enzyme Microbial Technology 32 (2003) 464-471.

Levenspiel O., Chemical reactor engineering, Second Ed., Wiley, New York, (2000).

Mansouri Y., Zinatizadeh A.A., Mohammadi P., Irandoust M., Akhbari A., Davoodi R., Hydraulic characteristics analysis of an anaerobic rotatory biological contactor (AnRBC) using tracer experiments and response surface methodology (RSM), Korean Journal of Chemical Engineering 29 (2012) 891-902.

Martin A.D., Interpretation of residence time distribution data, Journal of Chemical Engineering Science 55 (2000) 5907-5911.

Metcalf & Eddy, Wastewater engineering, Fourth Ed., McGraw Hill, New York, (2003).

Najafpour G.D., Zinatizadeh A.A.L., Mohamed A.R., Isa M.H., Nasrollahzadeh H., High-rate anaerobic digestion of palm oil mill effluent in an upflow anaerobic sludge-fixed film bioreactor, Process Biochemistry 41 (2006) 370-379.

Newell B., Bailey J., Islam A., Hopkins L.P., Lant J., Characterizing bioreactor mixing with residence time distribution (RTD) tests, Water Science and Technology 37 (1998) 43-47.

Torkian A., Hashemian S.J., Alinejad K., Post treatment of Upflow Anaerobic Sludge Blanket-Treated Industrial Wastewater by a Rotating Biological Contactor, Water Environmental Research 75 (2003) 232-237.

Williams S.C., Beresford J., The effect of anaerobic zone mixing on the performance of a three-stage bardenpho plant, Water Science and Technology 38 (1998) 55-61.

Yamaguchi T., Ishida M., Suzuki T., Biodegradation of hydrocarbon by Prototheca zopfii in rotating biological contactors, Process Biochemistry 35 (1999) 403-409.

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