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Hydrodynamic characteristics of UASB granular sludge produced from combined anaerobic/aerobic treatment systems

A.M. Dohdoh, A.M. Aboulfotoh*

Environmental Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Sharkia 44519, Egypt, Tel. +0020552304987, Fax +0020552304987, email: aydohdoh@gmail.com, aymandohdoh@zu.edu.eg (A.M. Dohdoh), aseaf_1@yahoo.com, asalem@zu.edu.eg (A.M. Aboulfotoh)

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ABSTRACT

The hydrodynamic characteristics of granular sludge is the key factor for efficient operation of up flow anaerobic sludge blanket (UASB) reactor, This research aims to evaluate the hydrodynamic characteristics of anaerobic sludge produced from five different pilot scale configurations, based on its settle ability, expansion characteristics and particle size distribution. An experimental set-up was established to determine the parameters required for settle ability and expandability equations. For particle size distribution, the proposed technique involves the determination of the settling velocities of a sludge sample then calculating the corresponding diameters using a mathematical approach. Results show that the hydrodynamic characteristics of different types of granular sludge have been determined using simple, flexible and low cost techniques. Results also indicated that sludge settling characteristics were not affected by adding supporting plastic media to the UASB reactor. On the contrary, the excess activated sludge returned to UASB reactor enhanced the sludge settling properties. The particle size distribution ranged from 0.06 to 1.1 mm and the corresponding Reynolds number (R_e) for most sludge granules are from 0.1 to 50 which demonstrates that the settling process of the granules is in intermediate flow regime.

Keywords: Anaerobic/aerobic treatment; Granular sludge; Expansibility; Settle ability; Particle size distribution; UASB; Activated sludge

1. Introduction

Aerobic treatment processes have been widely applied for the treatment of domestic wastewater. Despite having some advantages, it has some drawbacks and technical limitations. To overcome these limitations, the high-rate anaerobic treatment processes have been introduced as a viable solution due to its inherent advantage of zero energy consumption and low excess sludge generation. However, similar to the aerobic processes, the anaerobic processes itself also have their own disadvantages. Accordingly, some researchers [1] demonstrated the benefits of combining the two processes together in order to have a trade off between the advantages and disadvantages of each system. The high-rate anaerobic treatment processes have undergone several developments and the up flow anaerobic sludge blanket (UASB) reactor was considered as the most significant developments [2]. On the contrary, various aerobic treatment processes have been proposed by many researchers for the post-treatment process. These includes activated sludge system [3], sequencing batch reactor (SBR) system [4], moving-bed biofilm reactor [5] and down flow hanging sponge (DHS) [6]. The excess sludge produced in the aerobic stage may be recycled to the anaerobic unit for stabilization in order to eliminate the need for an independent sludge digester [7].

The performance of the UASB reactor depends mainly on the development of a dense sludge bed at the bottom of the reactor, where biological digestion takes place. The dense granules in this bed have good settling properties and therefore are not susceptible to washout from the system under operating conditions. It is worth mentioning that,

*Corresponding author.

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the quality and stability of the sludge can directly affect the behavior of the entire treatment system [8]. For the proper design of UASB reactors, it is important to identify the hydrodynamic characteristics of the granular sludge such as the settling velocity, the settle ability, the expansibility, and the particle size distribution [9]. The more accurate procedure for the evaluation of the settle ability seems to be the one developed by Vesilind, which is based on the relationship between the zone settling velocity and the sludge concentration [10]. The expansibility of the sludge bed was investigated by some researchers such as [10,11]. The most challenging parameter is the particle size distribution. Although many techniques were used to determine the particle size distribution, none of them can be easily set up in the treatment plants. This was due to their complexity and high cost. A simple up flow velocity test, to characterize the settling properties of granular sludge, which was proposed by Andras et al. [12] and utilized by Vlyssides et al. [13]

It is worth mentioning that the type of sludge can have a significant effect on the relationship between solid concentration, up flow velocity, bed expansion and sludge age. Thus, these relationships need to be determined on site, i.e. at the wastewater treatment plant. Additionally, it is important to develop simple and flexible techniques to determine sludge hydrodynamic characteristics in-situ at the wastewater treatment plants [11].

Although many researchers evaluated the performance of UASB/AS combination systems, little is known about the hydrodynamic characteristics of the granular sludge produced in the UASB unit. The aim of the present work is to evaluate the hydrodynamic properties of the granular sludge produced in the UASB reactor combined with the AS system using simple, flexible and low cost techniques. The investigated parameters include it's the settle ability, the expansibility and the particle size distribution

2. Materials and methods

The experimental program was carried out at the Laboratory of Environmental Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt.

2.1. Granular sludge

The hydrodynamic characteristics of anaerobic granular sludge from different UASB reactors have been evaluated experimentally. The examined samples of the granular sludge were obtained from five different pilot scale systems with the following configurations:

1. *The first system (Sys1):* It consists of conventional UASB reactor combined with conventional activated sludge reactor. In this configuration, the excess activated sludge is not returned back to the UASB reactor.
2. *The second system (Sys2):* It consists of a hybrid UASB-filter reactor combined with a hybrid activated sludge/biofilm process without returning the excess activated sludge back to the UASB. In the hybrid UASB-filter reactor, the top one-third of the reactor was filled with 0.025 m diameter plastic rings as a filter media instead of the standard UASB gas/solid separator to prevent the biomass washout. The hybrid activated sludge/biofilm process is usually referred as the integrated fixed-film activated sludge (IFAS) process. This process is created by introducing plastic elements as biofilm carrier media into a conventional activated sludge reactor.
3. *The third system (Sys3):* It consists of a conventional UASB reactor combined with a conventional AS reactor and the excess activated sludge was returned back to the UASB reactor.
4. *The forth system (Sys4)*: It consists of a hybrid UASB-filter reactor combined with IFAS process with the return of the excess activated sludge back to the UASB reactor.
5. *The fifth system (Sys5):* It consists of two stages UASB reactors in which two conventional UASB reactors operated in series without post treatment.

For all configurations mentioned above, the UASB reactor was 450 L in volume and 1.4 m in height and was fed with domestic sewage. Table 1 shows the wastewater characteristics and operating conditions for the five tested systems. The shown data are the average values collected after the system attains steady state conditions. When steady state was established, the composite sludge samples used in the current research were collected from taps located at 3 heights of the reactors (0.10, 0.35 and 0.60 m from the bottom). The UASB reactors were operated at up flow velocity of 1 m/h, the recommended velocity is usually up to 2 m/h [14].

Two laboratory experimental sets covered in the present study are: (i) *the settle ability and expandability test* to deter-

Table 1
Operational parameters of the examined systems

System	Sys1	Sys2	Sys3	Sys4	Sys5
HRT of system (h)	3	3	3	3	3
HRT of UASB (h)	1.4	1.4	1.4	1.4	1.4
SRT of UASB (d)	30	30	30	30	30
SRT on AS (d)	10	10	10	10	–
Upflow velocity (m/h)	1	1	1	1	1
COD_{inf} (mg/L)	500–800	500–800	400–800	400–800	450–900
T.S.S (mg/L)	220–300	220–300	265–415	265–415	260–325
T (OC)	26.2–28.8	26.2–28.8	24.2–26.4	24.2–26.4	17.5–20

mine the settle ability and expandability parameters of the granular sludge, and (ii) *the Up flow velocity test* to determine the particle size distribution.

2.2. Settle ability and expandability test

The settle ability and expandability of granular sludge were determined using two lab-scale plexiglas tubes with volume of 26.5 L, height of 1.5 m and internal diameter of 0.15 m. The system was equipped with recirculation pump and storage tank. The schematic diagram of the test rig is shown in Fig. 1. The composite samples of the granular sludge were analyzed for total and volatile solids prior to the test. 10 L sample of sludge was placed in each of the two lab-scale reactors (the experiments were done in duplicate). The reactors were then filled up with tap water and recirculation was started. The sludge height at different up flow velocity [How did you measure the velocity?] was determined. All physical-chemical analyses were performed as recommended by [15].

2.3. Up flow velocity test

The settling properties of granules were evaluated by the fractions of granules exited under certain up flow velocities in a fractionating device [12]. About 100 ml sludge sample, from a sludge bed reactor, was placed in a 0.35 m long and 0.025 m diameter glass column and subjected to gradually increasing the up flow velocity. The up flow velocity was achieved by a head tank. The test column was moved up along graduated scale such that the water head can be changed and consequently the up flow velocity as shown in Fig. 2. Eight different flow velocities, in ascending order, were investigated with each velocity was kept fixed for 5 min. The granules exit the glass column via an overflow port and the fraction of sludge exiting at each particular velocity is collected. TSS and VSS of each fraction were determined.

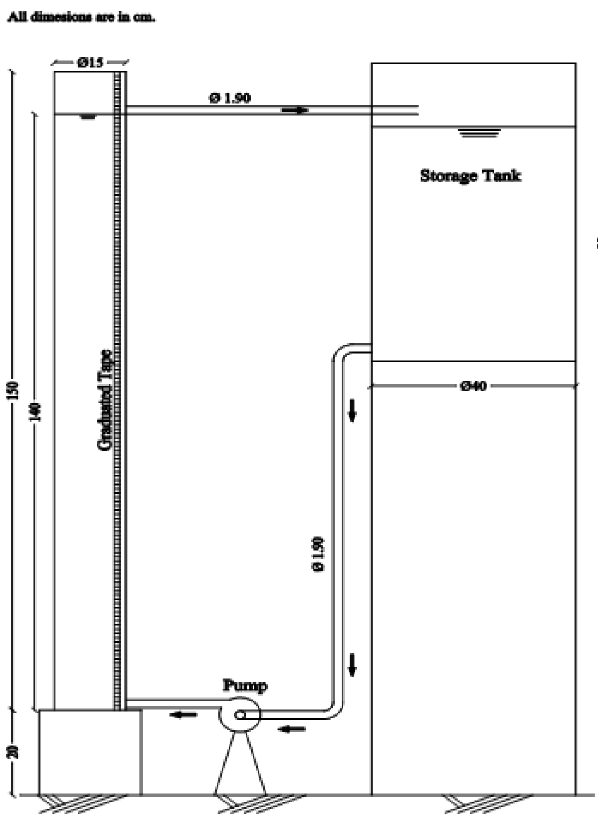

Fig. 1. Lab. scale reactor for settle ability and expandability test.

3. Results and discussion

3.1. Settle ability and expandability

3.1.1. Sludge settle ability

The sludge samples withdrawn from the pilot-scale reactor were tested for different up flow velocities in the lab-scale reactors. During the tests, the up flow velocity (U) in the reactor was first adjusted to the maximum value then was decreased gradually to zero. The maximum up flow velocity which does not cause granular sludge washout is defined as the zero washout up flow velocity (U_0) [16]. The results of the sludge bed height after stabilization for each up flow velocity was recorded and is presented in Fig. 3. As shown in the figure, the zero washout up flow velocity (U_0) was around 5 m/h for Sys1 and Sys2 while this value increased to around 8 for Sys3 and Sys4 and reached 10 for Sys5. This indicates that the plastic supporting media has minor effects on the granular sludge settle ability while the excess activated sludge returned to the UASB reactor has enhanced the sludge settle ability. Finally, the figure demonstrated that the granular sludge from the two stage UASB reactors has the best settle ability.

Leitao et al. [10] proposed a methodology for the evaluation of sludge settle ability which was based on determining the empirical constants of Vesilind equation;

$$U = U_{S,0} \times e^{-(kX)} \quad (1)$$

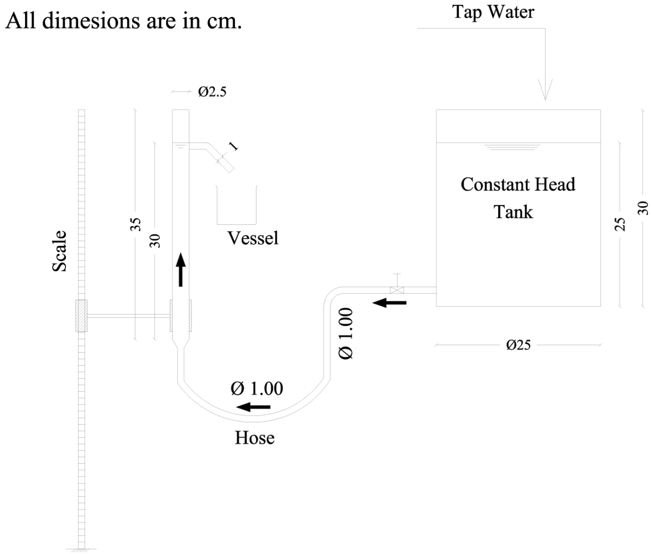

Fig. 2. Fractionating device for Up flow velocity test.

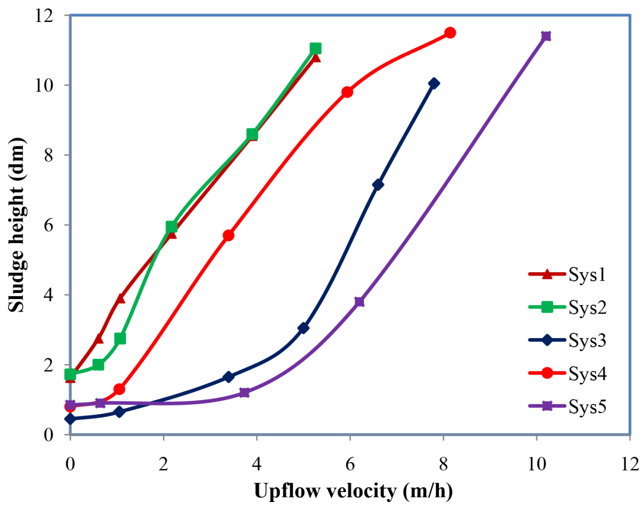

Fig. 3. Relations between up flow velocity and sludge height.

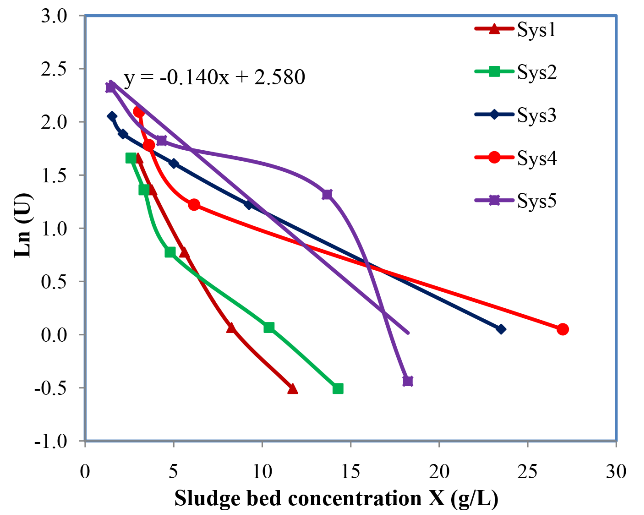

Fig. 4. Relation between Ln (U) and calculated sludge concentration.

where U is the upflow velocity (m/h), X is the sludge concentration (g/L), and $U_{S,0}$ (m/h) and k (L/g) are the Vesilind empirical constants.

Sludge concentration was calculated by:

$$X = \frac{X_0 \times V_0}{A \times h} \tag{2}$$

where X_0 is the initial sludge concentration of the composite sample (g/L), V_0 is the volume of composite sample (dm^3), A is the cross-sectional area of the reactor (dm^2), and h is the height of the sludge (dm).

The initial solid concentration of the sludge sample was determined. Since the volume of the sludge bed is proportional to the bed height, there was a different volume for each U and accordingly a different sludge bed concentration (X). To determine the Vesilind constants, equation 1 has been rearranged as follows:

$$Ln(U) = -k \cdot X + Ln(U_{S,0}) \tag{3}$$

Fig. 4 shows the relation between Ln(U) and sludge concentration (X). For each curve, a straight line was obtained using the least squares method as shown in Fig. 4 for Sys5 as an example. From the linear equation, the empirical constants (k) and ($U_{S,0}$) were determined and are presented in Table 2. Then the empirical constants for each system were substituted in the Vesilind equation. Fig. 5 shows the relation between the up-flow velocity and sludge bed concentration. In that figure at different up-flow velocities, the experimental results of sludge bed concentration were compared with calculated values using the Vesilind equation. The figure indicates that the predicted values are in good agreement with the measured values.

The empirical constants for the Vesilind model have been determined and can be used to determine the sludge concentration at the operated up-flow velocity. This procedure can be used for the optimization of UASB reactors and the determination of the different design parameters associated with the settling characteristics of sludge such as the optimum height of the UASB reactor and the frequency of anaerobic sludge wastage.

Table 2
Vesilind empirical constants for tested systems

System	Sys1	Sys2	Sys3	Sys4	Sys5
X_0 (g/L)	5.70	5.05	2.70	6.20	2.90
V_0 (L)	10	10	10	10	10
k (L/g)	0.25	0.17	0.09	0.07	0.14
$U_{S,0}$ (m/h)	9.77	6.68	8.12	7.49	12.88

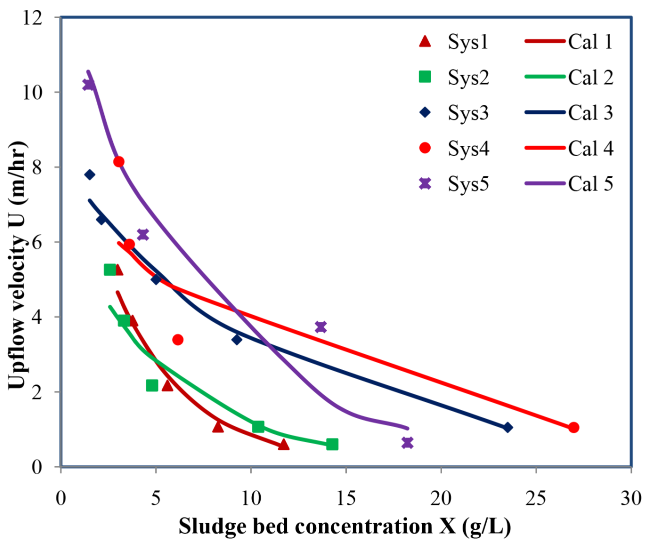

Fig. 5. Up flow velocities versus measured and calculated concentrations.

3.1.2. Sludge bed expandability

The expansion ratio (ER) is defined as the bed height at certain up-flow velocity over the bed height when the velocity is zero [11]. The higher the feed flow rate, the greater the sludge expansion ratio.

$$ER = \frac{Bed\ hieght\ at\ velocity\,(U)}{Bed\ hieght\ at\ velocity\,(0)} \quad (4)$$

Table 3 lists the ER results at corresponding up-flow velocities for the different tested systems. The concentrations presented in Table 3 are the expanded bed TSS concentrations. If this concentration is multiplied by the up-flow velocity, the flux in kg TSS/(m²·h) of the solids in the column is obtained, which are also listed in Table 3.

As shown in the table, the solid flux ranged from 7 to 15.7 kg/(m² h) for Sys1, 8.6–13.6 for Sys2, 12–31.5 for Sys3, 19.3–28.4 for Sys4 and 11.75–51 for Sys5. This supports the aforementioned conclusion that the biomass washed out from the attached dia has minor effects on the sludge settle ability. On the contrary, the excess activated sludge returned back to the UASB reactor enhanced the sludge settling properties. The solid flux values obtained in the present study are comparable to the values obtained by Poinapen et al. [11], which ranged from 1 to 31 kg/(m² h).

Table 3
Expansion ratio and solid flux

	U (m/h)	Height (dm)	ER	X (kg/m³)	Flux (kg/m²·h)
Sys1	0.00	1.63		19.84	
	0.60	2.75	1.69	11.72	7.06
	1.07	3.90	2.40	8.27	8.84
	2.17	5.75	3.54	5.61	12.18
	3.90	8.55	5.26	3.77	14.72
	5.26	10.80	6.65	2.99	15.71
Sys2	0.00	1.73		16.56	
	0.60	2.00	1.16	14.28	8.60
	1.07	2.75	1.59	10.39	11.11
	2.17	5.95	3.45	4.80	10.43
	3.90	8.60	4.99	3.32	12.96
	5.26	11.05	6.41	2.59	13.60
Sys3	0.00	0.45		33.94	
	1.05	0.65	1.44	23.50	24.72
	3.39	1.65	3.67	9.26	31.41
	5.00	3.05	6.78	5.01	25.04
	6.60	7.15	15.89	2.14	14.10
	7.80	10.05	22.33	1.52	11.85
Sys4	0.00	0.80		43.84	
	1.05	1.30	1.63	26.98	28.38
	3.39	5.70	7.13	6.15	20.88
	5.94	10.80	13.50	3.25	19.29
	8.15	11.5	14.38	3.05	24.84
Sys5	0.00	0.85		19.30	
	0.64	0.90	1.06	18.23	11.75
	3.73	1.20	1.41	13.67	51.03
	6.20	3.80	4.47	4.32	26.76
	10.20	11.40	13.41	1.44	14.69

3.1.3. Expandability constants

Richardson and Zaki [17] developed an empirical equation to relate upflow velocity of the liquid to sludge bed expansion [18].

$$U = U_{E,0} \times (\varepsilon)^m \quad (5)$$

where ε (%) is sludge bed expansion, $U_{E,0}$ (m/h) and m (L/g) are the expansibility constants, U (m/h) is the up-flow velocity.

The sludge bed expansion (ε) was calculated as follows:

$$\varepsilon = 100 \times \frac{h - h_0}{h_0} \quad (6)$$

where h is the height of the sludge bed (dm), h_0 is the height of the sludge at *U = 0 (dm)*.

Using the methodology developed by Leitao et al. [10] to determine the empirical constants, Eq. (6) was written in the form: (Log(U) = m × Log(ε) + Log($U_{E,0}$)) then Log(U) was plotted versus log(ε) as shown in Fig. 6. The parameters of the linear equation [Eq. (6)] can be calculated from the straight lines obtained using the least squares method. In this figure, the straight line for the sludge of system 5 was plotted as an example. The expandability constants for the tested systems are presented in Table 4.

The expansibility constants were substituted into Eq. (4) for each system. Fig. 7 shows the relation between sludge bed expansion and the up-flow velocity. At different velocities, the experimental results (shown as discrete points) have been compared with the calculated velocity by Eq. (4) (represented in the graph by the continuous line).

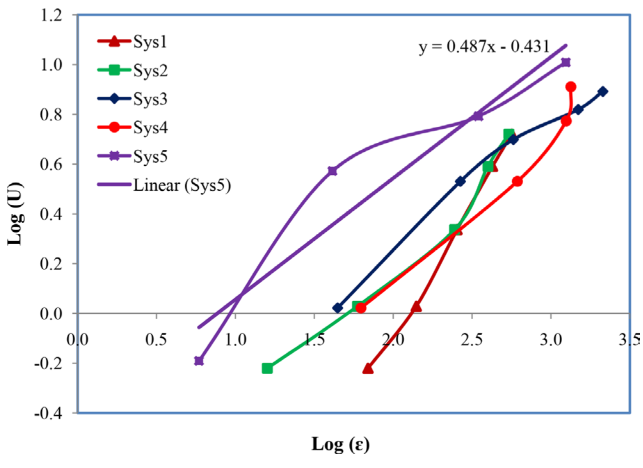

Fig. 6. Relation between bed expansion and up-flow velocity.

Table 4
Empirical constants for tested systems

System	Sys1	Sys2	Sys3	Sys4	Sys5
h_0 (dm)	1.63	1.73	0.45	0.80	0.85
m (L/g)	1.054	0.598	0.51	0.601	0.49
$U_{E,0}$ (m/h)	0.006	0.103	0.17	0.083	0.37

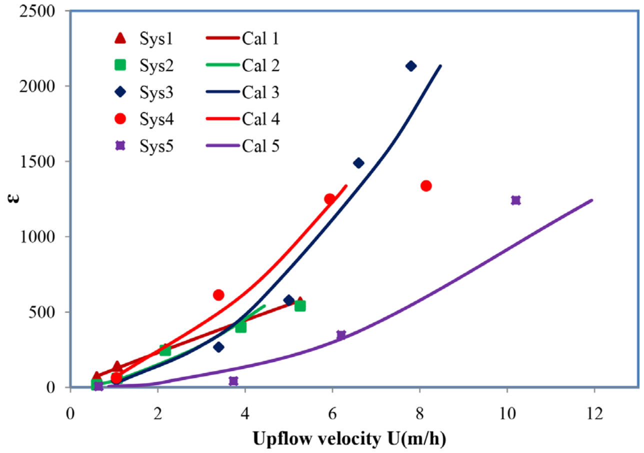

Fig. 7. Sludge bed expansion versus measured and calculated up-flow velocity.

The model used for the prediction of the sludge bed expansion, adapted from the equation by Richardson and Zaki [17], can be applied for the optimization of the sludge bed height in an UASB reactor if the reactor to be operated with sludge wastage. If the flow rate fluctuation regime is known, it is possible to predict the variation of the sludge bed height. So, in order to avoid any substantial sludge washout during hydraulic overload that can deteriorate the post treatment step. This procedure may improve the performance of the system as the system will operate with its maximum sludge accumulation capacity.

3.2. Up flow velocity and particle size distribution

3.2.1. Settling properties of granular sludge

The settling velocity of the granular sludge has been measured. For instance, the constant up-flow velocity applied to the bottom of the vertical tubes will separate the granular sludge of the lower settling velocity [16]. The mass percentage of the washed-out granular sludge from the vertical tube to the collection vessel could be recorded. The increments of the up-flow velocity gradually fraction-ates the entire sludge sample according to its settling velocity. The sludge mass percentages corresponding to the up-flow velocity are presented in Fig. 8 and summarized in Table 5. It can be seen from the results that at up-flow velocity of 5 m/h, more than 95% of the total sludge mass was retained in the UASB reactor for Sys2. This implies that almost all the solids in the sludge had a very good settle ability. Since the operating up-flow velocity for theses reactors was 1 m/h, therefore higher hydraulic loads can be applied in those reactors without any risk of considerable sludge washout.

The results also show that, for the five tested sludge types, the majority of sludge was lost at up-flow velocities between 10–50 m/h which is in good agreement with Andras et al. [12].

3.2.2. Particle size distribution

A mathematical approach was developed in order to estimate the size distribution of sludge particles using the measured up-flow velocity and (VSS/TSS) percent of each fraction. Assuming that the granules had a spherical shape with a free settling process. Taking into account the flow regime, the diameter of each fraction could be estimated.

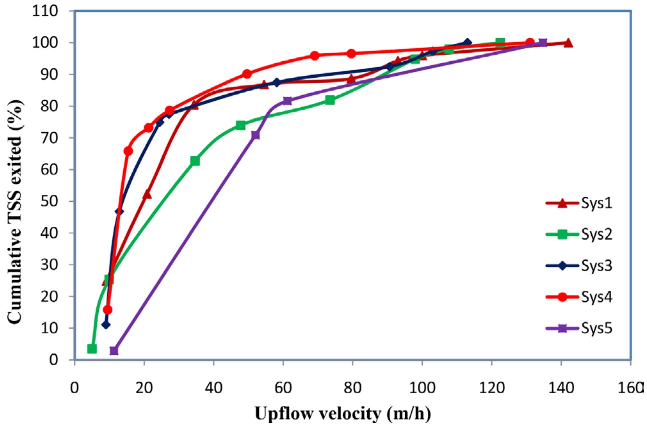

Fig. 8. Cumulative percent of TSS exited versus up-flow velocity.

Liu et al. [9] developed a mathematical model based on Allen' law, for calculating the settling velocity of the granules in the intermediate flow regime as follows:

$$u = 0.781\left[\frac{d_P^{\,1.6}\left(\rho_P - \rho\right)}{\rho^{0.4}\mu^{0.6}}\right]^{0.714} \tag{7}$$

where d_p is the particle diameter (mm), u the up-flow velocity of the liquid (m/h), ρ the liquid density (kg/m^3), ρ_P the particle density (kg/m^3), μ the dynamic viscosity of the flowing liquid (8.777 × 10^{-4} kg/m s).

The values of Reynolds number (R_e) should be verified to check the assumption of intermediate flow ($0.2 < R_e < 500$) [18]:

$$R_e = \frac{\rho d_P u}{\mu} \tag{8}$$

Rearranging Eq. (7) for particle size calculation:

$$d_P = \left[\frac{1.24\,u^{0.875}\rho^{0.25}\mu^{0.375}}{\left(\rho_P - \rho\right)^{0.625}}\right] \tag{9}$$

For the calculation of the particle size of the granular sludge, the equations above were used assuming that the liquid phase behaved as water. Thus, for the calculations ρ = 995 (kg/m^3), μ = 8.777 × 10^{-4} (kg/m s) [13].

3.2.3. Particle density

It was calculated using the equation developed by Vlyssides et al. [12] in which the granule density was correlated to the volatile suspended solid percent.

$$\rho_P = 1387 - 3.77\frac{VSS}{TSS} \tag{10}$$

where VSS/TSS = the percentage of volatile suspended solid (%).

The results for different sludge types have been tested and presented in Table 5. These results include: volatile sus-

Table 5
Settling properties and particle size distribution

	U (m/h)	TSS% exited	VSS/ TSS%	ρ_P	dp (mm)	R_e
Sys1	9	25	66	1139	0.15	0.4
	21	27	57	1172	0.28	1.8
	34	28	57	1174	0.43	4.6
	54	7	35	1253	0.51	8.8
	80	2	35	1255	0.71	17.8
	93	5	34	1260	0.80	23.5
	100	2	34	1257	0.86	27.1
	142	4	27	1285	1.10	49.1
Sys2	5	4	53	1186	0.08	0.1
	10	21	50	1200	0.13	0.4
	35	38	49	1204	0.39	4.3
	48	11	34	1259	0.45	6.7
	73	8	30	1273	0.63	14.7
	98	13	28	1281	0.80	24.7
	108	3	30	1274	0.88	30.0
	122	2	22	1304	0.93	35.7
Sys3	9	11	59	1163	0.10	0.3
	13	36	57	1171	0.18	0.7
	24	28	51	1194	0.30	2.3
	27	2	39	1239	0.29	2.5
	58	11	39	1241	0.56	10.2
	91	4	40	1238	0.83	23.6
	103	5	36	1252	0.89	29.0
	113	3	39	1241	1.00	35.5
Sys4	10	16	65	1144	0.10	0.3
	15	50	63	1149	0.23	1.1
	21	7	47	1211	0.25	1.7
	27	6	41	1233	0.29	2.5
	50	11	41	1234	0.49	7.7
	69	6	40	1237	0.66	14.3
	80	1	36	1251	0.72	17.9
	131	3	35	1256	1.09	45.1
Sys5	11	3	28	1280	0.12	0.4
	52	68	28	1281	0.46	7.6
	61	11	27	1287	0.52	10.1
	135	18	24	1298	1.02	43.3

pended solid percent, the particle density, Rynolds number as well as the calculated particle size from Eq. (9) at different up-flow liquid velocity. Fig. 9 shows the corresponding size distribution for the tested samples. It is clear that by using a simple settling test, which could be performed at site, the particle size distribution of a sludge sample could be obtained avoiding boring, imprecise and expensive tests such as microscope sizing, image and laser analysis.

The results show that the granules with larger diameter have high average settling velocities. Additionally, for the examined settling velocities in the range of 5–140 m/h, the particle size distribution ranged from 0.06 to 1.1 mm.

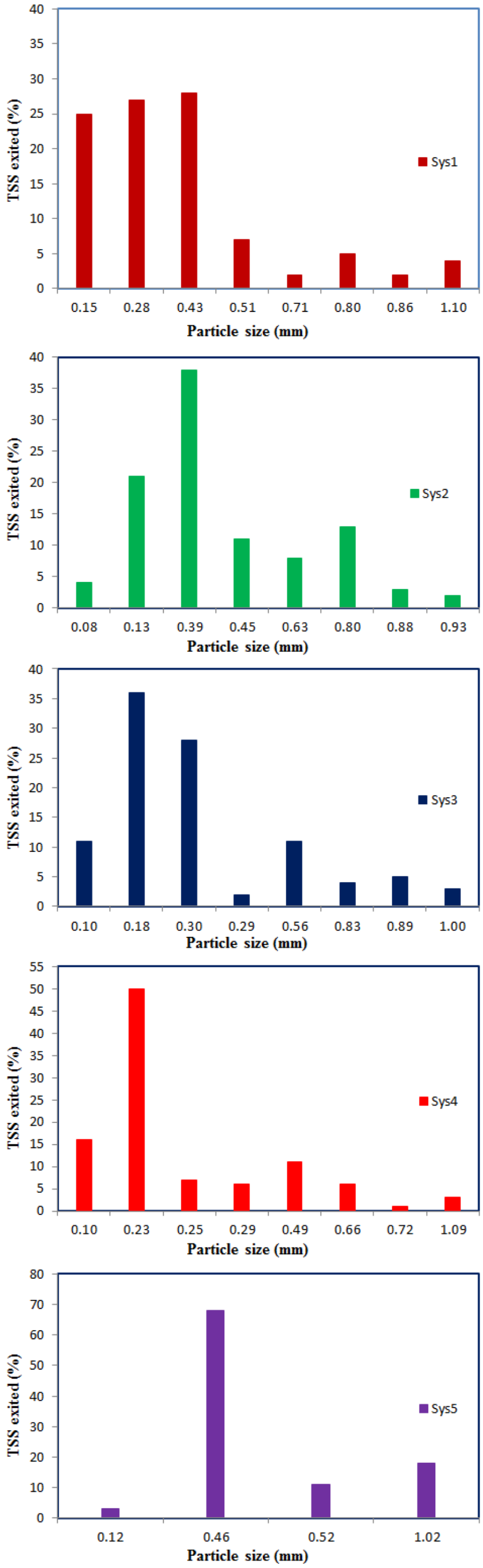

Fig. 9. Particle size distribution for the five systems.

These results are consistent with those obtained by Roghair et al. [19]. They concluded that most of the UASB granules had a diameter between 0.4 and 1.0 mm. On the other hand, Saravanan and Sreekrishnan, [18] examined the up-flow velocity in the range of 3.8–184 m/h and measured the corresponding particle size which ranged from 0.3 to 5.5 mm. Generally, the anaerobic granules have a spherical shape with a diameter ranging from 0.14 to 5 mm [9,20].

The corresponding R_e for most tested sludge granules ranged from 0.1 to 50, which increased with the size and density of the granules (see Table 5). The table demonstrates, theoretically, that the settling process of the granules was in the intermediate flow regime [9].

4. Conclusions

The experimental set-up and the procedures presented in this study are suitable for assessing the hydrodynamic characteristics of different granular sludge from combined anaerobic/aerobic configurations. The settle ability of anaerobic sludge in terms of the Vesilind equation, the expansion of a sludge bed by using the equation by Richardson and Zaki [17], as well as the particle size distribution by the test proposed by Andras have been evaluated. For particle size, the proposed technique consists of the determination of the settling velocities of a sludge sample, then calculating the corresponding diameters using mathematical equations. The important hydrodynamic characteristics of granular sludge have been determined by simple, flexible and low-cost techniques that could be performed at wastewater treatment plants. No sophisticated equipment is needed and results can be obtained within a couple of hours.

The parameters evaluated can provide data about settling properties of the granules, sludge bed level and the particle size. These data can help design the UASB reactor and determine the wastage frequency of anaerobic sludge. Also, it can improve the performance of the post treatment system. Finally the evolution of sludge characteristics is of vital importance for the monitoring of the UASB reactors

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