

# Modification of UASB reactor by using CFD simulations for enhanced treatment of municipal sewage

Suprotim Das, Supriya Sarkar and Sanjeev Chaudhari

## ABSTRACT

Up-flow anaerobic sludge blanket (UASB) has been in use since last few decades for the treatment of organic wastewaters. However, the performance of UASB reactor is quite low for treatment of low strength wastewaters (LSWs) due to less biogas production leading to poor mixing. In the present research work, a modification was done in the design of UASB to improve mixing of reactor liquid which is important to enhance the reactor performance. The modified UASB (MUASB) reactor was designed by providing a slanted baffle along the height of the reactor having an angle of  $5.7^\circ$  with the vertical wall. A two-dimensional computational fluid dynamics (CFD) simulation of three phase gas-liquid-solid flow in MUASB reactor was performed and compared with conventional UASB reactor. The CFD study indicated better mixing in terms of vorticity magnitude in MUASB reactor as compared to conventional UASB, which was reflected in the reactor performance. The performance of MUASB was compared with conventional UASB reactor for the onsite treatment of domestic sewage as LSW. Around 16% higher total chemical oxygen demand removal efficiency was observed in MUASB reactor as compared to conventional UASB during this study. Therefore, this MUASB model demonstrates a qualitative relationship between mixing and performance during the treatment of LSW. From the study, it seems that MUASB holds promise for field applications.

**Key words** | anaerobic reactor, CFD study, low strength wastewaters, mixing, UASB

**Suprotim Das** (corresponding author)

**Supriya Sarkar**

Research & Development, Tata Steel Limited,  
Jamshedpur 831001,  
India

E-mail: [suprotimdas@gmail.com](mailto:suprotimdas@gmail.com)

**Sanjeev Chaudhari**

Centre for Environmental Science and Engineering  
(CESE),

Indian Institute of Technology Bombay,  
Powai, Mumbai 400076,  
India

## INTRODUCTION

Anaerobic treatment of wastewater is a cost-effective technology compared to aerobic treatment process. This process has significant advantages like low energy consumption, low sludge production, biogas production in form of methane ( $\text{CH}_4$ ) and formation of stabilized sludge (Cherni-charo & Nascimento 2001; Nykova *et al.* 2002). In an anaerobic process, complex organic matter is converted into a mixture of biogas ( $\text{CH}_4$  and  $\text{CO}_2$ ) in number of steps. All reactions of anaerobic process take place in a single reactor in anaerobic digester where sludge retention time (SRT) is almost same as hydraulic retention time (HRT). In the last decades, various high-rate anaerobic systems were developed which allows maintaining higher SRT during the operation with lower HRT. Among various high-rate reactors, up-flow anaerobic sludge blanket (UASB) reactor is the most commonly used. The ability to retain high concentration of biomass by achieving granulation is the major advantage of UASB reactor over other high-rate anaerobic reactors (Lettinga *et al.* 1993). It has

been reported that UASB reactor has high efficiency for the treatment of high strength wastewaters (HSWs) but UASB reactor has limitations for the treatment of low strength wastewaters (LSWs) like municipal sewage (Sato *et al.* 2006; Tare & Nema 2007). Researchers have described LSWs as those which contain chemical oxygen demand (COD) concentration below 500 mg/L. Wastewaters produced domestically (domestic sewage) are also usually of low strength (Ganesh *et al.* 2007). Several studies were conducted for the treatment of industrial LSW as well as domestic sewage by using UASB reactor. It was observed that the efficiency of the UASB reactor was in the range of 55–86% during the treatment of industrial low and medium strength wastewaters when the influent concentration was in the range of 300 mg/L to 1,850 mg/L (Sayed *et al.* 1987; Kato & Field 1994; Monroy *et al.* 2000; Ahn *et al.* 2001; Buzzini *et al.* 2005). Wide variation in the efficiency of UASB reactor (COD removal 26–85%) was reported during the treatment of municipal sewage (Sanz

and Fdz-Polanco 1990; Bodik *et al.* 2000; Uemura & Harada 2000; Mahmoud *et al.* 2004; Tandukar *et al.* 2005; Ruiz *et al.* 2008; Das and Chaudhari 2009; Aiyuk *et al.* 2010).

The possible reasons for low efficiency of UASB reactor treating LSWs may be due to low mixing inside the reactor. Higher mixing due to high biogas production during the treatment of HSWs increases the contact of the sludge biomass with incoming wastewater which is necessary to overcome mass transfer limitations. However, dilute wastewater produces low biogas due to low substrate concentration and causes poor mixing of the sludge biomass with wastewater. To improve the performance, researchers have focused on design modification in the UASB reactor (Chong *et al.* 2012) for the treatment of LSWs. Better performance of modified UASB (MUASB) reactor was achieved by enhancing retention of particulate matter (hybrid UASB) or by combining with other reactor (UASB-anaerobic filter). However, the performance of bio-reactor is also influenced by several other factors, among which mixing of liquid with reactor biomass is very important and it is governed by hydrodynamics of the bioreactor (Kundu *et al.* 2013). According to Jin & Lant (2004), reactor configuration and hydrodynamics has significant impact on sludge biomass characteristics such as size distribution, compressibility and the settling rate in suspended aerobic growth bioreactor system. The complex hydrodynamics of three phase bioreactors are not well understood due to complicated phenomena such as solid-solid, solid-liquid and solid-gas interactions. Placing probes within the fluid domain in reactor for direct measurement of parameters such as pressure, velocity and volume fraction can be difficult. Advancement in computational fluid dynamics (CFD) have provided an efficient, economical and time-saving tool for understanding hydrodynamics of multiphase reactor (Wang *et al.* 2010) and it is becoming increasingly popular in environmental technology (Terashima *et al.* 2009; Ding *et al.* 2010). Therefore, an attempt was made to use CFD simulation for analysing hydrodynamics in anaerobic reactors. The objective of the study was to analyse the flow field of the reactors i.e. velocity distribution, pressure distribution, vorticity magnitude and volume fraction of different phase and to compare these parameters between MUASB and UASB reactors. Hydraulic modelling was done by using ANSYS Fluent 6.3 CFD flow modelling software package to evaluate mixing and flow pattern in the reactors. Based on the CFD study, pilot-scale MUASB and UASB reactors were constructed and their performance was compared for the treatment of low strength municipal sewage.

## MATERIALS AND METHODS

### CFD of UASB and MUASB reactors

#### Description of reactors

The simulated reaction zone of UASB and MUASB reactors used for simulation in CFD was 70 cm tall with a square shaped structure (7 cm × 7 cm). In MUASB, a slanted plate was kept in the reactor which is termed a baffle. The baffle was placed from height (from bottom) 15 cm to 45 cm having openings (two openings) of 2 cm × 7 cm along the vertical surface of the reactor wall to promote vertical mixing of reactor content. The mesh was created in the ANSYS Fluent GAMBIT pre-processor program and exported into the ANSYS Fluent 6.3 CFD flow modelling software package to solve the continuity and momentum equations. Structured grid is used to discretize the domain into small elements. A two-dimensional computational domain for the reaction zone was devised with 47,080 cells, 95,052 faces and 47,973 nodes for UASB, and 49,100 cells, 99,002 faces and 49,903 nodes for MUASB reactor. The properties of the materials used in this study are shown in Table 1.

#### CFD model

Multiphase flow in CFD is used to refer to any fluid flow consisting of one or more than one phase or component. A multiphase system is defined as a mixture of the phase of solid, liquid and gas. A group of models has been developed to describe multiphase system. Modelling of multiphase flow is very complicated and requires a large computing power (Manninen & Taivassalo 1996). In this study, mixture model has been used which is a simplification of multiphase model. This approach is a considerable alternative in simulating dilute suspensions of solid particles or small bubbles in liquid. A two-dimensional mixture three-phase fluid model was used to describe the flow behaviour of each phase. The biogas, wastewater and sludge granules

**Table 1** | Properties of wastewater, sludge granule and gas used in CFD simulation

Phase	Density (kg/m <sup>3</sup> )	Viscosity (kg/m-s)	Size (mm)
Water	998.2	0.001	–
Granule	1,250	0.005	1
Gas	0.6679	$1.087 \times 10^{-5}$	0.1

are treated as different continua, with wastewater as the primary phase, sludge granules and biogas (CH<sub>4</sub>) as the secondary phases. The mixture model solves for the mixture momentum equation and prescribes relative velocities to describe the dispersed phases. The density of the wastewater was assumed to be 998.2 kg/m<sup>3</sup>, the biogas was assumed as pure CH<sub>4</sub> and the gas phase volume fraction is related to the gas production. The chemical characteristics and the average concentration of the different pollutants of the wastewater are as mentioned in Table 2.

### Governing equations

The mass and momentum conservation equations are solved in a computational two-dimensional mesh. The reaction zone was assumed to be shared by the three phases, in proportion to their respective volume fractions. The motion of each phase is governed by respective mass and momentum conservation equations.

The continuity equation for the  $\frac{\partial}{\partial t}$  mixture is

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = 0 \quad (1)$$

where  $\vec{v}_m$  is the mass-averaged velocity

$$\vec{v}_m = \frac{\sum_{k=1}^n \alpha_k \rho_k \vec{v}_k}{\rho_m} \quad (2)$$

and  $\rho_m$  is the mixture density

$$\rho_m = \sum_{k=1}^n \alpha_k \rho_k \quad (3)$$

$\alpha_k$  is the volume fraction of phase  $k$ .

$m$  represents mass transfer due to cavitation mass sources.

The momentum equation for the mixture can be obtained by summing the individual momentum equations for all phases. It can be expressed as

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) \\ = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^T + \rho_m \vec{g}) + \vec{F} + \nabla \cdot \\ (\sum_{k=1}^n \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k})] \end{aligned} \quad (4)$$

where  $n$  is the number of phases,  $\vec{F}$  is a body force, and  $\mu_m$  is the viscosity of the mixture:

$$\mu_m = \sum_{k=1}^n \alpha_k \mu_k \quad (5)$$

$\vec{v}_{dr,k}$  is the drift velocity for secondary phase  $k$ :

$$\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m \quad (6)$$

### Relative (slip) velocity and drift velocity

The relative velocity (also referred to as the slip velocity) is defined as the velocity of a secondary phase ( $p$ ) relative to the velocity of the primary phase ( $q$ ):

$$\vec{v}_{qp} = \vec{v}_p - \vec{v}_q \quad (7)$$

The drift velocity and the relative velocity ( $\vec{v}_{qp}$ ) are connected by the following expression:

$$\vec{v}_{dr,p} = \vec{v}_{qp} - \sum_{k=1}^n \frac{\alpha_k \rho_k}{\rho_m} \vec{v}_{qk} \quad (8)$$

The mixture model makes use of an algebraic slip formulation. The basic assumption of the algebraic slip mixture model prescribes an algebraic relation for the relative velocity, a local equilibrium between the phases should be reached over short spatial length scales. The form of the relative velocity is given by

$$\vec{v}_{qp} = \vec{\tau}_{qp} \vec{a} \quad (9)$$

where  $\vec{a}$  is the secondary-phase particle's acceleration and  $\vec{\tau}_{qp}$  is the particulate relaxation time:

$$\vec{\tau}_{qp} = \frac{(\rho_m - \rho_p) d_p^2}{18 \mu_m f_{drag}} \quad (10)$$

where  $d_p$  is the diameter of the particles (or droplets or bubbles) of secondary phase  $p$

$$f_{drag} = \begin{cases} 1 + 0.15 Re^{0.687} & Re \leq 1000 \\ 0.0183 Re & Re > 1000 \end{cases}$$

**Table 2** | Chemical characteristics of LSW used in CFD simulation and pilot-scale study

Parameter	Average	Max. value	Min. value
Total COD (mg/L)	196	240	97
Soluble COD (mg/L)	106	128	42
Ammonia (mg/L)	13.8	15.4	6
Total alkalinity (mg/L)	270	324	142
Total volatile fatty acids (mg/L)	25	37	18
pH	6.9	7.2	6.8
Total suspended solids (mg/L)	142	175	130

The acceleration  $\vec{a}$  is of the form

$$\vec{a} = \vec{g} - (\vec{v}_m \cdot \nabla) \vec{v}_m - \frac{\partial \vec{v}_m}{\partial t}$$

The simplest algebraic slip formulation is the so-called drift flux model, in which the acceleration of the particle is given by gravity and/or a centrifugal force and the particulate relaxation time is modified to take into account the presence of other particles. Note that, if the slip velocity is not solved, the mixture model is reduced to a homogeneous multiphase model. In addition, the mixture model can be customized (using user-defined functions) to use a formulation other than the algebraic slip method for the slip velocity.

### Volume fraction equation for the secondary phases

From the continuity equation for secondary phase (granule)  $p$ , the volume fraction equation can be obtained:

$$\frac{\partial}{\partial t} (\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{v}_m) = -\nabla \cdot (\alpha_p \rho_p \vec{v}_{dr,p}) \quad (11)$$

The turbulence viscosity of the continuous phase is obtained by the  $k_{-e}$  turbulence model:

$$\mu_{t,L} = C_{\mu} \rho_L \left( \frac{k_L}{\varepsilon_L} \right) \quad (12)$$

The equations of change for the turbulent kinetic energy ( $k$ ) and the energy dissipation rate for the primary phase are given by

$$\frac{D\lambda_L \rho_L k_L}{Dt} = \nabla \cdot \left( \lambda_L \left( \mu + \frac{\mu_{t,L}}{\sigma_{kL}} \right) \nabla k_L \right) + \lambda_L \rho_L (p_{kL} - \varepsilon_L) + \lambda_L \rho_L \Pi_{kl} \quad (13)$$

$$\frac{D\lambda_L \rho_L \varepsilon_L}{Dt} = \nabla \cdot \left( \lambda_L \left( \mu + \frac{\mu_{t,L}}{\sigma_{\varepsilon L}} \right) \nabla \varepsilon_L \right) + \lambda_L \rho_L (C_{\varepsilon 1} p_{kL} - C_{\varepsilon 2} \varepsilon_L) + \lambda_L \rho_L \Pi_{kl} \quad (14)$$

### Numerical solution

The initial sludge bed was packed with granular solids with a volume fraction of 0.3. To simplify the reactor condition, it was assumed that gas enters from inlet and passes through the sludge bed. The liquid inlet of the reactor was modelled with a velocity-inlet boundary condition. The outlet was set as a pressure-outlet boundary condition. All other solid surfaces were defined by wall boundary conditions with free slip for the biogas and no slip for the sludge or wastewater.

In this study, the simulation was operated in steady-state conditions. All simulations were carried out on a computer with a 32 bit processor (Intel Core 2 Duo CPU T9300) with 2 GB of random access memory, run at a clock speed of 2.50 GHz. The simulation procedure includes the following steps:

1. Define the solver as two-dimensional, steady-state, implicit, and pressure based
2. Activate the realizable  $k_{-e}$  turbulence model
3. Define the material properties (granule, wastewater and  $\text{CH}_4$ ) and operating conditions (Table 1)
4. Activate the gravity force
5. Initialize the simulation
6. Patch the region with the defined volume of fraction value of water, sludge and gas phase
7. Run the simulation to obtain steady-state results.

Vorticity (similar to hydraulic gradient) is considered as parameter for the comparison of the hydrodynamics for the three reactors used in this study. In general, vorticity is a vector quantity that defines sense of circulation while mixing is a scalar quantity which gives strength of circulation. In other words circulation or mixing is integration of vorticity along the prescribed path as shown in Equation 15. Mixing can be more precisely defined by vorticity. Conceptually, vorticity could be determined by marking the particles of the fluid in a small neighbourhood of the point in question, and watching their relative displacements as they move along the flow. More precisely, the vorticity of a flow is a pseudo vector field  $\vec{\omega}$  equal to the curl (rotation) of its velocity field  $\vec{v}$ . It can be expressed by the vector analysis formula:

$$\vec{\omega} = \vec{\nabla} \times \vec{v} \quad (15)$$

where  $\vec{\nabla}$  is the del operator.

The vorticity is related to the flow's circulation (line integral of the velocity) along a closed path by the Stoke's equation. Namely, for any infinitesimal surface element  $C$  with normal direction  $\vec{n}$  and area  $dA$ , the circulation  $d\Gamma$  along the perimeter of  $C$  is the dot product  $\vec{\omega} \cdot (dA \vec{n})$  where  $\vec{\omega}$  is the vorticity at the centre of  $C$ .

### Onsite pilot-scale study

#### Description of the pilot-scale UASB and MUASB reactor

Based on the CFD study, pilot-scale UASB and MUASB reactors were constructed. The detailed specifications of the pilot-scale UASB and MUASB reactors are presented in Table 3. The pilot-scale study for the treatment of low strength



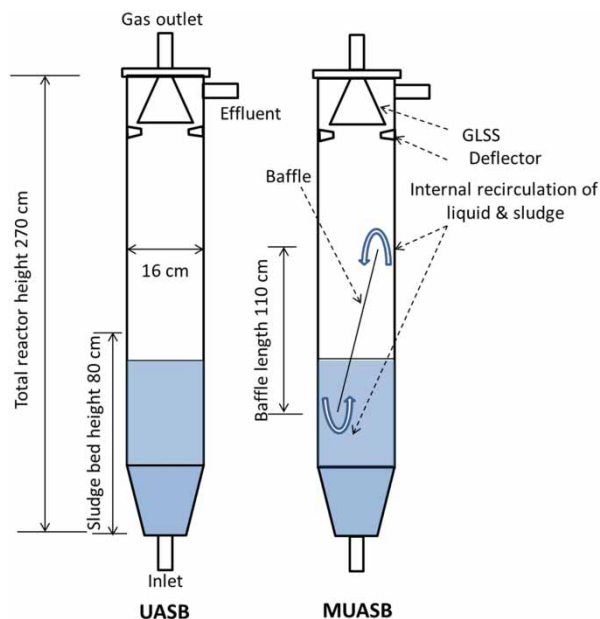
**Table 3** | Specifications of pilot-scale UASB and MUASB

Item	UASB	MUASB
Shape cross section	Square	Square
Total height (cm)	270	270
Gas space (cm)	20	20
Internal cross section (cm)	16 × 16	16 × 16
Hopper bottom height (cm)	15	15
Lower dimension (cm)	6	6
Empty bed liquid volume (L)	62	62

municipal sewage was conducted under ambient condition with reactor liquid temperature in the range of 24°C to 28°C. The detailed specifications of the reactors are as follows.

**UASB:** The UASB model was fabricated by using acrylic sheet in a square cross-sectional form. The total height of the reactor was 270 cm including the height of hopper bottom. A gas hood (slope 60) together with a deflector beam made of acrylic sheet called ‘gas-liquid-solid-separator’ (GLSS) was placed at the top of the reactor to separate the solid particles from the mixture (gas, liquid and solid) after treatment and hence allowing liquid and gas to leave the UASB reactor.

**MUASB:** A slanted baffle was placed along the length of the reactor. The lower end started from 60 cm from the bottom and extended up to 170 cm having an opening of 3 cm × 16 cm. The granule along with effluent came out from the narrow opening of the baffle with higher velocity and fell on the other side of the baffle and thus circulated

**Figure 1** | Schematic diagram of UASB and MUASB reactors.

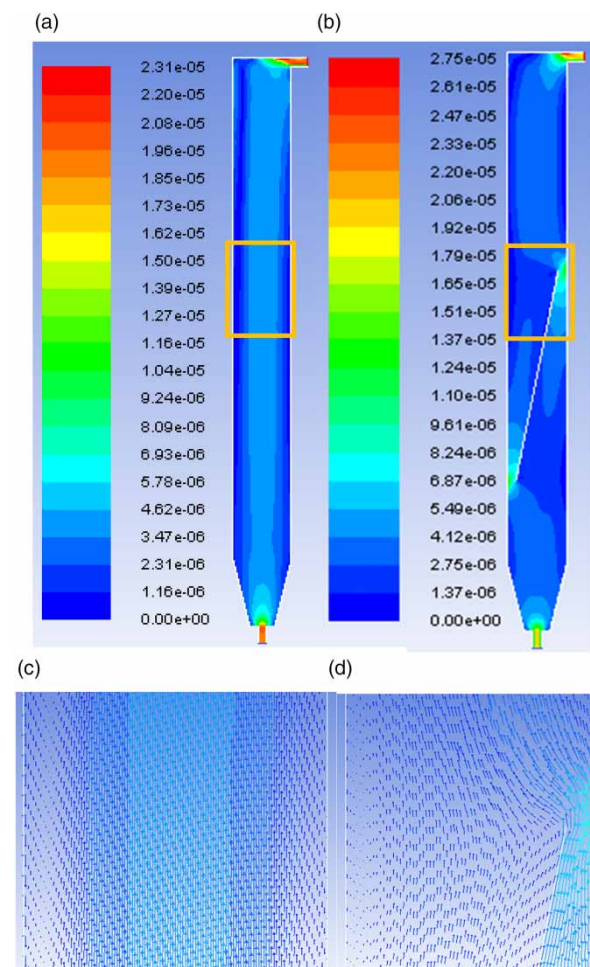
into the reactor. Baffle increases contact of sludge granules with wastewater by enhancing the internal recirculation of sludge biomass and thereby improves reactor performance due to better mixing (Figure 1). The source of sewage, the properties of seed sludge for reactors and analytical techniques used in this pilot-scale study were described elsewhere (Das & Chaudhari 2015).

## RESULTS AND DISCUSSION

### Computational fluid dynamics

#### Single phase simulation

In single phase simulation, only liquid was used, gas and sludge in reactor were not considered. The water velocity

**Figure 2** | Contour of water velocity (m/s) of (a) UASB and (b) MUASB reactor; magnified view (marked by rectangle) of velocity vector of (c) UASB and (d) MUASB reactor during single phase simulations.

and vorticity magnitude in the reactor were compared to evaluate mixing phenomena. Continuity equation (Equation 1) and momentum equation (Equation 4) were solved in this study for liquid phase only where  $m$  is liquid (water only). Figure 2 presents the water velocity inside the reactors. Water moves up through the inlet at a defined speed. Higher velocity gradient is observed at inlet as well as outlet of all three reactors due to its small cross section. The velocity is similar in the lower zone of UASB and MUASB reactor. However, there is a large velocity gradient distribution observed in the small opening of the baffle region of MUASB reactor which is far away from the water inlet (Figure 2(b) and 2(d)). High velocity gradient in this region in MUASB reactor may be beneficial to achieve liquid mixing. Therefore, from the Figure 2, it is quite clear that there is a difference in reactor hydrodynamics in MUASB as compared to UASB reactor due to the presence of baffle (position 0.15 m to 0.45 m). Higher vorticity is observed in the inlet and the outlet position of all three reactors due to smaller cross-section area (Figure 3).

The relation between vorticity and mixing has been discussed earlier. Higher vorticity indicates better mixing in the reactor. Considerably higher vorticity is observed in MUASB reactor from 0.15 m to 0.45 m along the reactor height due to the presence of baffle (Figure 3(b)). Better mixing due to higher vorticity in MUASB reactor will provide a good sludge wastewater contact in the reactor which overcomes mass transfer limitation and plays an important role to achieve better reactor performance as observed during the experiment with LSWs.

### Effect of biogas on reactor mixing

The effect of biogas on reactor hydrodynamics was investigated in three phase simulation where water was considered as the primary phase, sludge granule and biogas were considered as secondary phases. The simulation was conducted for organic loading rate  $0.64 \text{ kg COD/m}^3/\text{day}$ . The properties of biogas are mentioned in Table 1. It was assumed that the biogas bubble in the sludge bed will

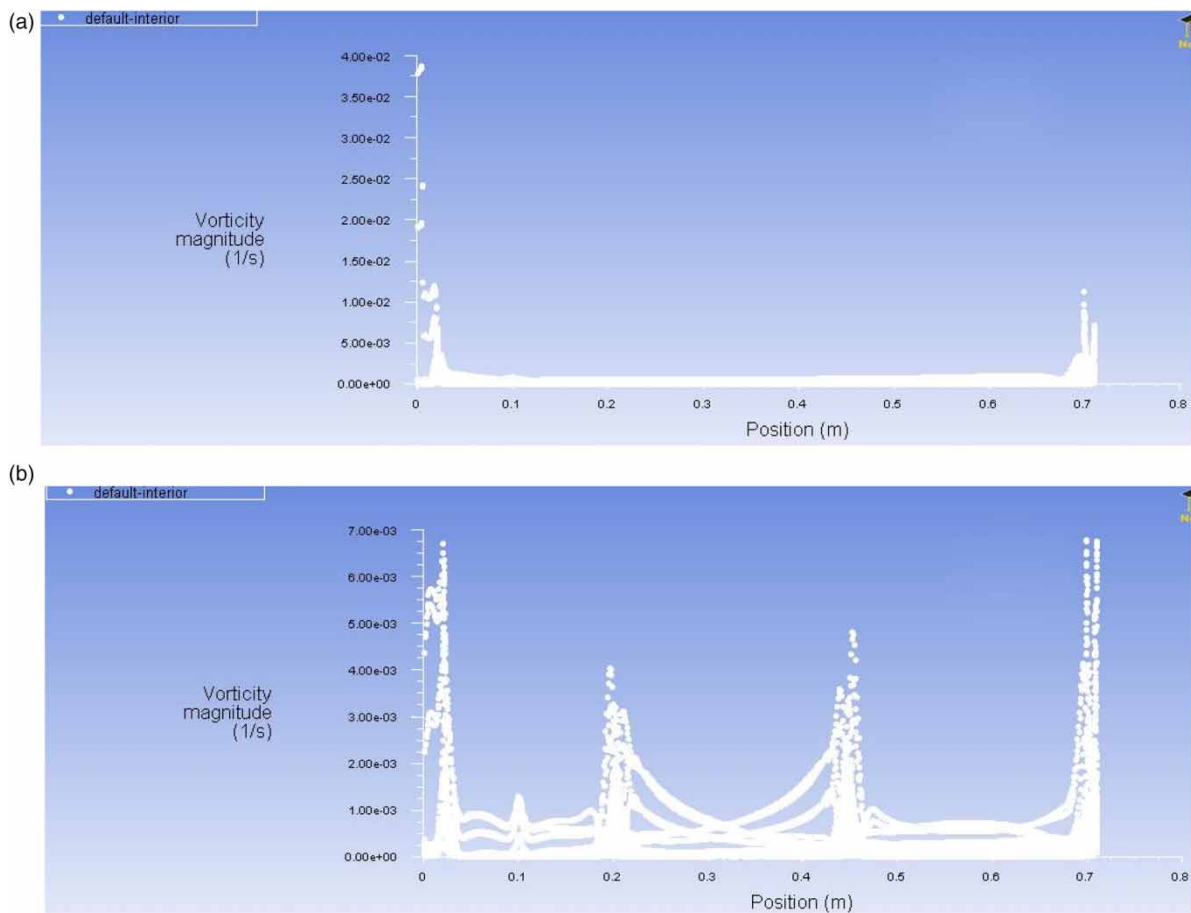


Figure 3 | Vorticity magnitude in different heights of (a) UASB and (b) MUASB reactor during single phase simulations.

flow upward with the stream swirl. This movement of biogas makes the bulk up-flow velocity of the mixture greater than the up-flow velocity of the water alone. As seen in single phase simulation, multiphase simulation also showed large velocity gradient distribution within the baffle region in MUASB reactor (Figure 4(b)). The velocities as well as the vorticity magnitude are increased significantly in the MUASB reactor as compared to single phase study (Figure 4(b) and 5(b)) due to the rising of gas bubbles which is beneficial for solid-liquid mixing. Enhanced velocity and vorticity magnitude improves the sludge recirculation in MUASB reactor (Figure 6(b)). Core-annulus structure is observed to be formed in the sludge blanket zone of MUASB reactor which enhances internal circulation of reactor contents.

When the influent moves upward at a fixed up-flow velocity through the bottom of the reactor, higher velocity is observed at the small opening of the baffle in MUASB reactor (Figure 2(b) and 4(b)). This change of fluid velocity enhances sludge recirculation. This phenomenon could be explained by Bernoulli's principle (Chanson 2004). In fluid dynamics, Bernoulli's principle states that an increase in the speed of the fluid occurs simultaneously with a decrease in pressure considering other losses as zero. When water and biogas flow through the small opening of baffle in

MUASB reactor it reduces the pressure on the top of the baffle (Figure 7(b)). Due to higher velocity at this point, higher bed expansion occurs and sludge granule along with water and gas bubble moves up through the opening of the baffle to the top of MUSAB reactor. The pressure difference in MUASB reactor is clearly visible in Figure 7(b) and 7(c). At higher pressure and lower velocity in the upper region above the baffle, sludge particles settle down on the other side of the baffle.

Volume fraction of the sludge biomass in the reactor is also influenced by hydrodynamics. Initially (without any liquid flow) the sludge bed was assumed to be packed with granular sludge with a volume fraction of 0.3, up to the reactor height of 30 cm. However, sludge bed expansion observed in both reactors during this operation (Figure 7). In this condition, maximum volume fraction of sludge biomass was observed in sludge bed. Higher volume fraction of sludge biomass was observed in sludge bed as well as in the baffle region of MUASB which indicates higher sludge bed expansion in MUASB reactor (Figure 6(b)). Higher sludge bed expansion enhances the chance of interaction of reactor biomass with the liquid and gas phases. This interaction may play a significant role to overcome mass transfer limitation during the treatment of LSWs. A good flow regime is required to achieve efficient contact between microbes and wastewater. As observed from this experiment, baffle in MUASB reactor improves flow regime which helps to achieve efficient contact of reactor biomass with wastewater and gave rise to better reactor performance as compared to other reactors during treatment of LSWs.

### Performance comparisons of pilot-scale MUASB and UASB reactors

Based on the CFD study, MUASB and UASB reactor were designed and constructed. Experiment was conducted to compare the performance of onsite pilot-scale MUASB with UASB reactor for the treatment of domestic sewage as LSW. The reactors were operated for 100 days. Wastewater was taken directly from pumping station and was stored in every 4 h in a storage tank regularly. Average composition of sewage during the study is presented in Table 2. The influent COD exhibited seasonal variations.

### COD removal efficiency

Significant variation of total COD removal efficiency in each reactor was observed during the pilot-scale

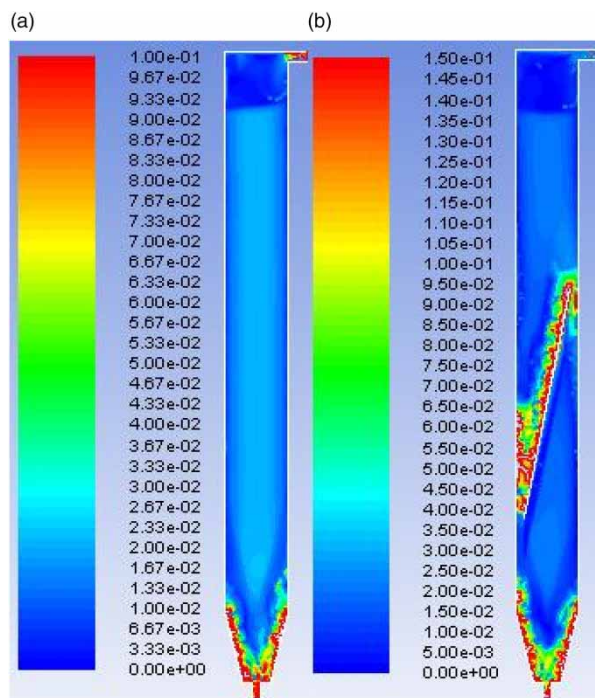
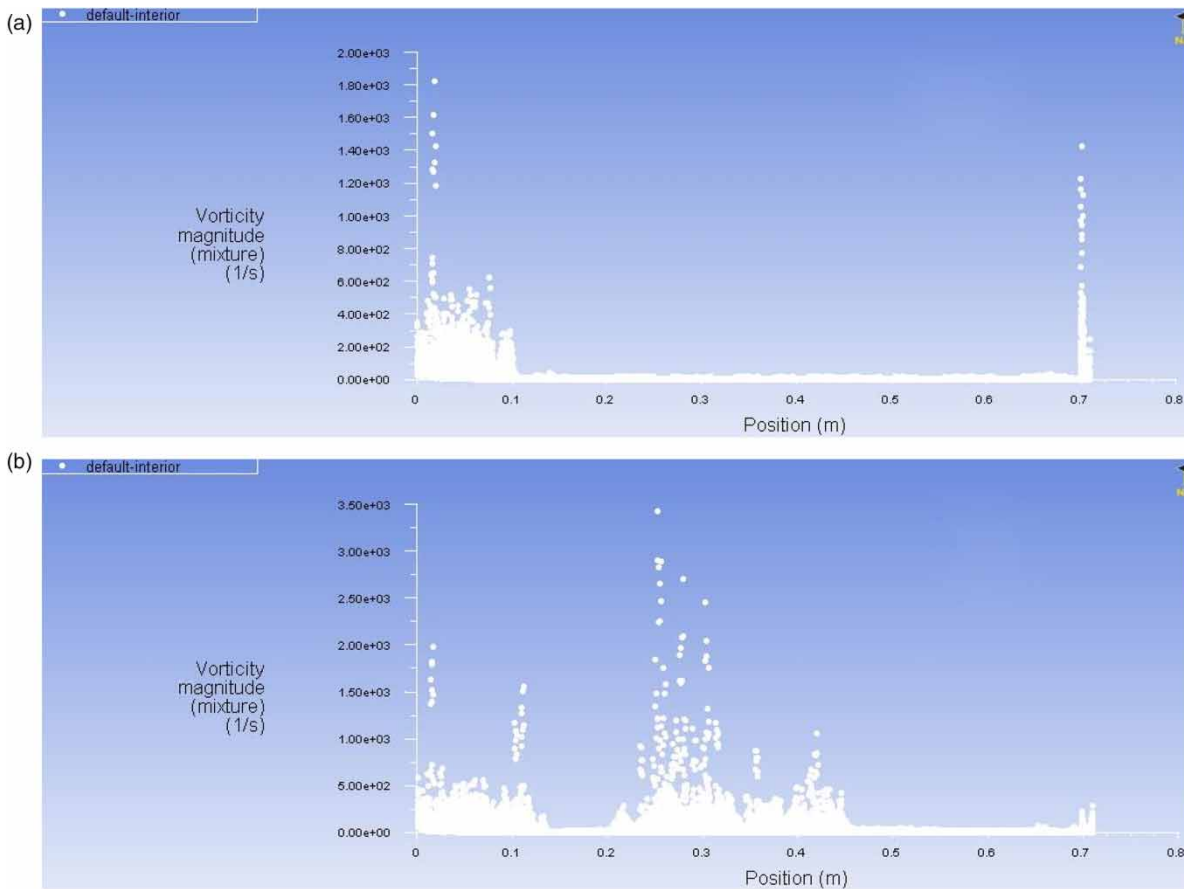


Figure 4 | Contour of water velocity (m/s) of (a) UASB and (b) MUASB reactor during three phase simulations.



**Figure 5** | Vorticity magnitude of mixture (a) UASB reactor and (b) MUASB reactor during three phase simulations.

investigation (Figure 8(a)). The influent total COD varied from 196 mg/L to 240 mg/L. Both the reactors achieved quasi-steady state after 35–40 days. In this study, HRT was kept 8 h. At this HRT, the average total COD removal efficiencies were 63.9% and 79.3% and the average effluent total COD concentrations were 73.5 mg/L and 42.6 mg/L for UASB and MUASB reactors, respectively.

A compilation of quasi-steady-state reactor performance with standard deviation is given in Table 4. It was observed that the effluent soluble COD was similar in both the reactors. However, the average effluent total COD was significantly lower in MUASB (42 mg/L) as compared to UASB (71 mg/L) reactor which indicated effective removal/degradation of particulate matter. The pilot-scale investigation with domestic sewage showed higher total COD removal and lower total suspended solids (TSS) concentration (Figure 8(b)) in MUASB as compared to UASB reactor. Improved performance obtained during this study was perhaps due to higher

mixing that promoted better sludge wastewater contact. Analysis of variance (ANOVA) test confirmed that the differences in total COD removal efficiencies are significant ( $p < 0.05$ ). It implied that there is significant difference in the performance of each reactor compared to MUASB in terms of COD removal efficiency during the treatment of LSW.

The flow and movement of the reactor content in the baffle region in MUASB was observed visually. It may be mentioned that as observed during CFD study (Figure 7) mixing of MUASB reactor content (visual observation) was much better than that observed in UASB reactor. In MUASB, sludge gets fluidized, and moves through top end region of baffle and then moves on the other side of the baffle and gets deposited on the lower side of the baffle from where it gradually gets recirculated. There was some accumulation of sludge biomass observed between lower end of the baffle and reactor wall which clearly indicated sludge recirculation (Das & Chaudhari 2015). Improved mixing in MUASB reactor enhances the



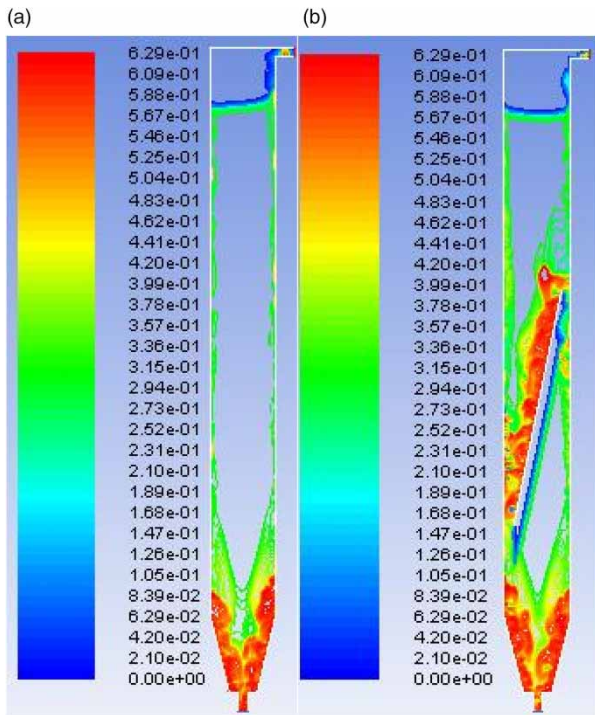


Figure 6 | Volume fraction (%) of sludge granules of (a) UASB and (b) MUASB reactor during three phase simulations.

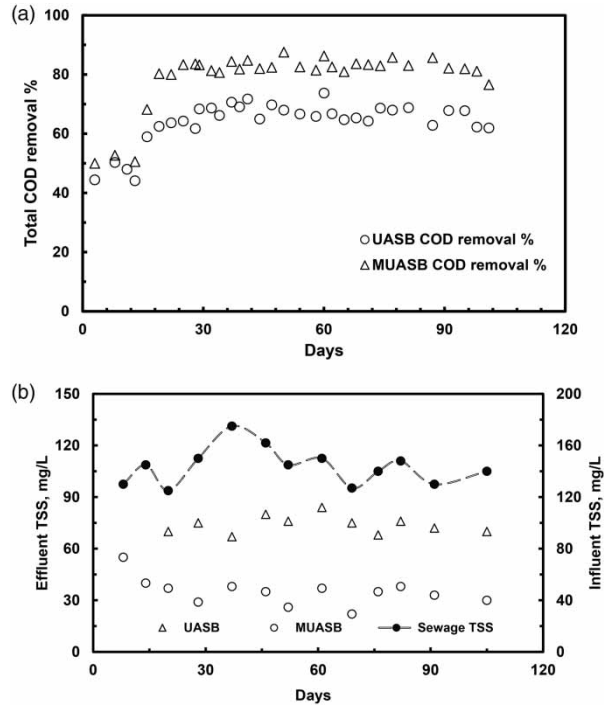


Figure 8 | (a) Total COD removal efficiency and (b) influent and effluent TSS in UASB and MUASB reactor during the pilot-scale study.

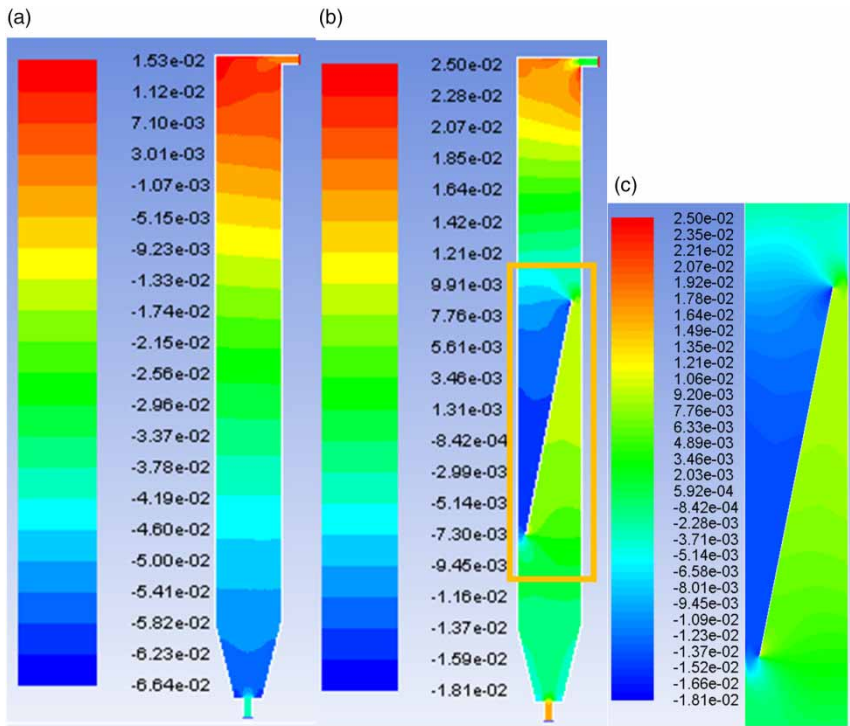


Figure 7 | Comparison of static pressure (Pa) of (a) UASB, (b) MUASB reactor and (c) magnified view (marked by rectangle) of baffle position in MUASB reactor.

**Table 4** | Quasi-steady-state pilot-scale reactor performance for the treatment of domestic sewage, with standard deviations

Organic loading rate (kg COD/m <sup>3</sup> /day)		0.64 ± 0.1
HRT (h)		8
Average influent COD concentration (mg/L)		206 ± 16.5
Average total effluent COD (mg/L)	UASB	73.5 ± 4.2
	MUASB	42.6 ± 3.8
Average % COD removal	UASB	63.9 ± 3.4
	MUASB	79.3 ± 2.9
pH	UASB	7.1 ± 0.2
	MUASB	7.3 ± 0.2
Average effluent volatile fatty acids, (mg/L)	UASB	26.2 ± 0.9
	MUASB	20.4 ± 1.1
Average gas production rate (L/d)	UASB	7.7 ± 0.5
	MUASB	9.3 ± 0.4
% methane content	UASB	68.8 ± 2.8
	MUASB	67.9 ± 3.2

possibility of contact of suspended particle in wastewater with sludge biomass, which possibly leads to better reactor performance. Hulshoff Pol & Lettinga (1986) stated that the biodegradable particulate matter present in the wastewater should be efficiently entrapped in sludge biomass in order to convert the particulate organics into CH<sub>4</sub>. This seems to be the possible reason for higher efficiency in MUASB reactor during the study with complex LSW. On the other hand, substrate transport limitation may occur in UASB reactor due to low mixing during the treatment of LSW. According to Hulshoff Pol & Lettinga (1986), in order to take maximum benefit of all retained sludge in UASB reactor, it is essential to avoid channelling due to low gas production during the treatment of dilute wastewaters. Better performance of MUASB reactor was observed possibly due to better mixing that reduces the channelling problem during the treatment of complex LSW. Lower performance of UASB due to poor removal of particulate matter during the treatment of LSW has been observed by many researchers (Ruiz *et al.* 2008; Aiyuk *et al.* 2010). Ramos *et al.* (2003) reported that there is a correlation between mixing in the reactor and mass transfer into the biofilm. A good mixing pattern is desirable for substrate transport to the microbial aggregates (Pena *et al.* 2006). Higher mixing in MUASB possibly promotes entrapment of particulate matter on sludge biomass surface. Subsequent liquefaction of particulate matter on the sludge surface occurs due to hydrolytic reaction. The hydrolysed molecules diffuse into the biomass and get degraded.

## CONCLUSIONS

A two-dimensional CFD simulation of gas-liquid-solid three phase flow in the reaction zone of a MUASB and a conventional UASB have been performed and compared the hydrodynamics for the treatment of low strength wastewater. The result showed that the gas-liquid-solid system in MUASB reactor displayed significant difference as compared to UASB reactor. Better mixing was observed in MUASB reactor as compared to UASB reactor. Experimental data from pilot-scale study for on-site treatment of dilute municipal sewage indicate a positive correlation between reactor hydrodynamics and reactor performance for the treatment of LSW.

The results of this research for the treatment of LSW by MUASB reactor have provided direction for future research needed in this area. One of these requirements would be to design the specific length and angle of the baffle along with openings between the reactor wall and baffle to achieve better mixing of reactor contents that plays a major role in effective performance of MUASB reactor. Proper design of openings between baffle and reactor wall in MUASB is important and would depend on strength and type of wastewater, as the characteristics of sludge biomass developed in reactor depend upon the characteristics of the wastewaters being treated. Recirculation of the reactor contents in MUASB enhances the retainment of particulate matter in reactor for longer time which may also help in the treatment of HSWs with higher fraction of suspended solids. CFD study does not provide the characteristics of the biomass developed in bioreactors and thus can only give an idea about mixing.

## ACKNOWLEDGEMENT

The authors thank IIT Bombay for support of this work. The authors also thank Tata Steel Jamshedpur for CFD study.

## REFERENCES

- Ahn, Y. H., Min, K. S. & Speece, R. E. 2001 *Pre-acidification in anaerobic sludge bed process treating brewery wastewater. Water Research* **35**, 4267–4276.
- Aiyuk, S., Odonkor, P., Theko, N., van Haandel, A. & Verstraete, W. 2010 *Technical problems ensuing from UASB reactor application in domestic wastewater treatment without pre-treatment. International Journal of Environmental Science and Development* **1**, 392–398.

- Bodik, L., Herdova, B. & Kratochvil, K. 2000 The application of anaerobic filter for municipal wastewater treatment. In: *Proceedings 20th International Conference of Slovak Society of Chemical Engineering* 54, pp. 159–164.
- Buzzini, A. P., Gianotti, E. P. & Pires, E. C. 2005 UASB performance for bleached and unbleached kraft pulp synthetic wastewater treatment. *Chemosphere* 59, 55–61.
- Chanson, H. 2004 *Hydraulics of Open Channel Flow: An Introduction*. Butterworth-Heinemann, Oxford, p. 22.
- Chernicharo, C. A. L. & Nascimento, M. C. P. 2001 Feasibility of a pilot-scale UASB/trickling filter system for domestic sewage treatment. *Water Science and Technology* 44, 221–228.
- Chong, S., Sen, T. K., Kayaalp, A. & Ang, H. M. 2012 The performance enhancement of up-flow anaerobic sludge blanket reactors for domestic sludge treatment – A state-of-the-art review. *Water Research* 46, 3434–3470.
- Das, S. & Chaudhari, S. 2009 Improvement on biomass characteristics and degradation efficiency in modified UASB reactor treating municipal sewage: a comparative study with UASB reactor. *Asia-Pacific Journal of Chemical Engineering* 4, 596–601.
- Das, S. & Chaudhari, S. 2015 Effect of reactor configuration on performance during anaerobic treatment of low strength wastewater. *Environmental Technology* 38, 2312–2318.
- Ding, J., Wang, X., Zhou, X. F., Ren, N. Q. & Guo, W. Q. 2010 CFD optimization of continuous stirred-tank (CSTR) reactor for biohydrogen production. *Bioresource Technology* 101, 7005–7013.
- Ganesh, P. S., Ramasamy, E. V., Gajalakshmi, S., Sanjeevi, R. & Abbasi, A. 2007 Studies on treatment of low-strength effluents by UASB reactor and its application to dairy industry wash waters. *Indian Journal of Biotechnology* 6, 234–238.
- Hulshoff Pol, L. & Lettinga, G. 1986 New technologies for anaerobic wastewater treatment. *Water Science and Technology* 18, 41–53.
- Jin, B. & Lant, P. 2004 Flow regime, hydrodynamics, floc size distribution and sludge properties in activated sludge bubble column, air-lift and aerated stirred reactors. *Chemical Engineering Science* 59, 2379–2388.
- Kato, M. T. & Field, J. A. 1994 Treatment of low strength soluble wastewater in UASB reactors. *Journal of Fermentation & Bioengineering* 77, 679–686.
- Kundu, K., Bergmann, I., Klocke, M., Sharma, S. & Sreekrishnan, T. R. 2013 Influence of hydrodynamic shear on performance and microbial community structure of a hybrid anaerobic reactor. *Journal of Chemical Technology & Biotechnology* 89, 462–470.
- Lettinga, G., de Man, A., van der Last, A. R. M., Wiegant, W., van Knippenberg, K., Frijns, J. & van Buuren, J. C. L. 1993 Anaerobic treatment of domestic sewage and wastewater. *Water Science and Technology* 27, 67–73.
- Mahmoud, N., Zeeman, G., Gijzen, H. & Lettinga, G. 2004 Anaerobic sewage treatment in a one-stage UASB reactor and a combined UASB-Digester system. *Water Research* 38, 2348–2358.
- Manninen, M., Taivassalo, V. & Kallio, S. 1996 *On the Mixture Model for Multiphase Flow*. Technical Research Centre of Finland, VTT Publications 288, Espoo. 67 pp.
- Monroy, O., Fama, G., Meraz, M., Montoya, L. & Macariem, H. 2000 Anaerobic digestion for wastewater treatment in Mexico: state of the technology. *Water Research* 34, 1803–1816.
- Nykova, N., Muller, T. G., Gyllenberg, M. & Timmer, J. 2002 Quantitative analyses of anaerobic wastewater treatment processes: identifiability and parameter estimation. *Biotechnology & Bioengineering* 78, 89–103.
- Pena, M. R., Mara, D. D. & Avella, G. P. 2006 Dispersion and treatment performance analysis of an UASB reactor under different hydraulic loading rates. *Water Research* 40, 445–452.
- Ramos, A. C. T., Ratusznei, S. M., Rodrigues, J. A. D. & Zaiat, M. 2003 Mass transfer improvement of a fixed-bed anaerobic sequencing batch reactor with liquid-phase circulation. *Interciencia* 28 (4), 214–219.
- Ruiz, I., Alvarez, J. A., Diaz, M. A., Serrano, L. & Soto, M. 2008 Municipal wastewater treatment in an anaerobic digester-constructed wetland system. *Environmental Technology* 29, 1249–1256.
- Sanz, I. & Fdz-Polanco, F. 1990 Low temperature treatment of municipal sewage in anaerobic fluidized bed reactors. *Water Research* 24, 463–469.
- Sato, N., Okubu, T., Onodera, T., Ohashi, A. & Harada, H. 2006 Prospects for a self-sustainable sewage treatment system: a case study on full-scale UASB system in India's Yamuna River Basin. *Journal of Environmental Management* 80, 198–207.
- Sayed, S., van Campen, L. & Lettinga, G. 1987 Anaerobic treatment of slaughterhouse waste using a granular sludge UASB reactor. *Biological Wastes* 21, 1–28.
- Tandukar, M., Uemura, S., Machdar, I., Ohashi, A. & Harada, H. 2005 A low-cost municipal sewage treatment system with a combination of UASB and the 'fourth generation' down flow hanging sponge reactors. *Water Science and Technology* 52, 323–329.
- Tare, V. & Nema, A. 2007 UASB technology-expectations and reality. [https://www.sswm.info/sites/default/files/reference\\_attachments/TARE%20ny%20UASB%20Technology%20expectations%20and%20reality.pdf](https://www.sswm.info/sites/default/files/reference_attachments/TARE%20ny%20UASB%20Technology%20expectations%20and%20reality.pdf) (accessed 26 December 2017).
- Terashima, M., Goel, R., Komatsu, K., Yasui, H., Takahashi, H., Li, Y. Y. & Noike, T. 2009 CFD simulation of mixing in anaerobic digesters. *Bioresource Technology* 100, 2228–2233.
- Uemura, S. & Harada, H. 2000 Treatment of sewage by a UASB reactor under moderate to low temperature conditions. *Bioresource Technology* 72, 275–282.
- Wang, X., Ding, J., Guo, W. Q. & Ren, N. Q. 2010 A hydrodynamics–reaction kinetics coupled model for evaluating bioreactors derived from CFD simulation. *Bioresource Technology* 101, 9749–9757.

First received 24 June 2017; accepted in revised form 6 November 2017. Available online 21 November 2017