**Hydrodynamics Investigation of Laboratory-Scale Internal Gas-Lift Loop
Anaerobic Digester using Non-Invasive CAPRT Technique**

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Abstract

Internal gas-lift loop reactor (IGLR) was used as an anaerobic digester and its hydrodynamics were studied using Computer Automated Radioactive Particle Tracking (CARPT) Technique. This paper deals with the experimental study on a laboratory-scale digester. An anaerobic digester is a three-phase system consisting of gas, liquid, and solids; however solid-liquid slurry was treated as a single phase due to smaller size and lower density of solids. The effect of various geometric and operating variables on the hydrodynamics was studied. The superficial gas velocity was maintained at very low values and IGLR was operated in bubbly flow regime, which is suitable for operation of anaerobic digesters. The flow pattern and liquid velocity profile was obtained and effect of gas superficial velocity, draft tube diameter, type of sparger on liquid velocity and dead volume was studied in detail. Mean circulation times were calculated and compared for different digester configurations. Results showed that the increasing gas velocity increases the liquid velocity, decreases circulation time but does not offer any significant advantages in reducing the dead volumes. The configuration with draft tube diameter to tank diameter ratio of 0.5 showed good liquid circulation throughout the digester volume and low mean circulation time implying better mixing.

Keywords: Flow pattern; draft tube; sparger; mean circulation time; dead volume; mixing

1. Introduction

Due to the importance of mixing in digesters to provide uniform mixing or agitation environment [1], in majority of digesters some kind of external mixing is provided [2,3]. From a detailed review of digestion process [4–6] and commercially used digesters [7,8], it is evident that digesters can be mechanically mixed with impellers (stirred tanks), mixed by gas recirculation (gas-lift reactors), mixed by liquid recirculation (slurry reactors) or not mixed at all (plug flow reactors and anaerobic lagoons).

Internal Gas-lift Loop Reactors (IGLR) are extensively used in many multiphase chemical and biochemical operations because of the advantages they offer over the other conventional types of reactors. IGLRs are equipped with a draft tube and gas is sparged inside a draft tube to create a defined liquid circulation pattern [9–11] and uniform suspension of solids. IGLRs are simple in construction, without moving internal parts and have good mass transfer and heat transfer characteristics. Low intensity of uniformly distributed shear stress produced by IGLRs, as compared to stirred tanks and bubble columns, make them suitable for biochemical applications where microorganisms and cells may be disrupted by high shear stress values [12,13]. IGLRs provide good mixing at low energy consumption; this is one of the main reasons for their choice as anaerobic digester [9,14–16]. Another important factor is that the mixing effects produced by the evolved biogas and the imposed mixing are complementary. In a gas-lift digester the pumped biogas rises vertically upwards, carrying slurry upwards with it, thus facilitating evolution of biogas bubbles.

Common approach in designing IGLRs is using experiments to validate phenomenological hydrodynamic models or to formulate correlations to evaluate desired quantities like liquid velocity, gas holdup and mass transfer coefficients [9,13,17–25]. Local values of these parameters were evaluated by many researchers. However averaged values

obtained from the profiles of liquid velocity and gas holdup are more useful and informative as compared to the local values. Obtaining profiles of velocity and holdup is a difficult task due to the limitations of conventional experimental techniques and procedure. CFD models can be used to predict the velocity and holdup profiles [23,26–35], but multiphase flow CFD models still require validation against experimental data.

A hydrodynamic model formulated from first principle can offer many advantages such as, ease and reliability of reactor design and scale-up and ability to predict effect of operating conditions. However, such formulations are made difficult by inherent geometric complexity of system and the turbulent flow [36]. As a result, these models rely on one or more input parameters that are fitted from the experimental data or obtained from empirical correlations. Therefore, phenomenological models, just like empirical correlations, cannot be used or extrapolated for different geometries, scales, and operating conditions [29,37].

Considering the shortcomings of conventional experimental techniques, phenomenological models, and empirical correlations, advanced non-invasive experimental techniques like Computer Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT) are required to understand the hydrodynamics of IGLRs in detail. CARPT provides the knowledge of flow pattern, velocity profiles and turbulence parameters, while CT is used for obtaining local or averaged phase holdup [38–40]. CARPT and CT were applied by Karim *et al.* [41] for visualizing flow pattern and phase holdup profiles in an IGLR type anaerobic digester.

This paper deals with the use of CARPT for discerning hydrodynamics of lab-scale IGLRs. The focus of this study is on the application of IGLR as anaerobic digester. The effects of geometry (draft tube diameter, type of sparger) and operating conditions (air flow rate) on the

hydrodynamics of IGLR which affects its performance [11,13,42–45] are studied in this work using CARPT.

2. Materials and Methods

2.1 Overview of CARPT Technique

Computer Automated Radioactive Particle Tracking (CARPT) is a method employed for measuring the flow field, instantaneous and time-averaged velocities, and turbulent parameters of the tracked phase. It is based on the principle of tracking the motion of a single radioactive particle as a marker of a typical element of the phase whose velocity field is to be mapped [46,47]. Such a "tracer particle" (representing a typical liquid element or a dispersed solid phase particle) is tracked by an array of NaI(Tl) scintillation detectors, placed at strategic positions around the reactor being studied. A typical CARPT experiment involves a sequence of steps, viz., tracer particle preparation, in situ calibration, experimental run, post-processing of the acquired data [47–50].

In the present set of experiments Scandium (Sc-46) was used the tracer. A 150 μm Sc-46 particle was first coated with 7 μm layer of Parylene and then sent for neutron activation to the University of Missouri Research Reactor to obtain the activity of 200 μCi . The activated scandium particle was then sealed inside a 1 mm hollow polypropylene sphere using epoxy resin. More details of tracer preparation are discussed elsewhere [46]. The density of the sphere was carefully adjusted by changing the air gap inside the polypropylene sphere to exactly match that of the liquid phase (water) density, through a series of single particle settling experiments. It is important to note that in case of the studied simulated digester a major portion of the dispersed phase was comprised of biomass (micro-organism) having a density very close to water. The tracer particle represented both the liquid (water) in the slurry and the microorganisms, which has density close to that of water.

The CARPT calibration was done in situ (i.e., the digester was in operation under the studied conditions). The prepared tracer particle (Sc-46) was positioned at about 400 known locations inside the digester using a glass rod. The photon counts were acquired at 16 numbers of NaI scintillating detectors arranged around the digester (Fig. 1a). Later on, spline fit calibration curves were developed between counts received by the detectors and the distance of the tracer particle from the detectors. The data acquisition frequency was set to 50 Hz.

Finally, the tracer particle was released in the flow field of digester and was allowed to move freely in the system. The digester was operated at desired conditions for 24 hours to collect sufficient statistics at each location in the digester. That means, allowing the tracer particle to visit each location sufficient number of times so that at the end, time-averaged mean velocity remains unchanged. The distance-count map generated during the calibration phase is used to reconstruct the instantaneous position of the tracer particle as a function of time (i.e., particle lagrangian trajectory). It involves application of a weighted least-squares algorithm, and wavelet based position filtering, followed by a particle position reconstruction algorithm implemented to reconstruct the best estimate of the particle position [46,48].

Time-differencing between two particle positions yields instantaneous velocities, which is averaged at each spatial location over the whole time span of the experiment to yield the ensemble averaged velocity flow map. To get Eulerian information, the digester was divided into 63,360 fictitious compartments (72 division in theta direction, 44 division axially, and 20 divisions radially). Then, the estimated instantaneous velocity is assigned to the compartment falling at the mid-point of the two particle locations.

The number of calibration points, number of detectors used, acquisition frequency, time of data acquisition, the reconstruction and filtering algorithms, all these factors decide the accuracy of CARPT results. An error of $\pm 10\%$ is inherent and acceptable in CARPT [48].

2.2 *Experimental set-up*

Experiments were performed in a six inch (15.24 cm) diameter digester equipped with a draft tube and a conical bottom with a slope of 25° (Fig. 1a). The liquid level was 22 cm and working liquid volume was 3.78 liters. Gas was recirculated from the bottom of the tank using a sparger. Two different types of spargers were used; viz., a single point sparger and a cross sparger. Single point sparger was a pipe with a single opening of 5 mm diameter, while the cross sparger (Fig. 1b) had 4 holes of 2.2 mm each. Draft tube diameter was changed from 3.8 cm to 7.6 cm and 11.4 cm, such that draft tube diameter to tank diameter ratio (D/T) is 0.25, 0.5 and 0.75 respectively. The dimensions of cross sparger were also changed with respect to the draft tube diameter.

Fig. 1 here

The experiments were conducted with slurry obtained from dairy waste. The slurry was screened to eliminate larger solids and then diluted to adjust the total solids concentration to 100 g L⁻¹ (or 10% by weight). To account for mixing created by the gas sparging only, anaerobic biogas production was hindered using sodium azide (2 g L⁻¹).

Air was used as the gas phase; air flow rate was varied from 16.66 cm³ s⁻¹ to 50 cm³ s⁻¹ (1 L min⁻¹ to 3 L min⁻¹). These flow rates resulted in superficial gas velocity (based on tank diameter) of 0.91 mm s⁻¹ and 2.74 mm s⁻¹, respectively. The gas flow rate of 16.66 cm³ s⁻¹ corresponds to energy input density of 8 W m⁻³ (minimum suggested by US, EPA 1979 for proper digester mixing). At this low gas superficial velocity the IGLR operates in regime one called as bubbly flow regime or no gas entrainment regime [51–54]. Both non-uniform single-point sparger and a uniform multi-point cross sparger were used in this study. Total five CARPT runs were performed; the operational details are given in Table 1.

Table 1 here

3 Results and Discussion

3.1 Experiment L1: Flow pattern and liquid velocity profile

The overall flow pattern for experiment L1 (Fig. 2) consists of two circulation loops; the bigger circulation loop extends from the top of the digester to the bottom of the draft tube, and it is directed upwards inside the draft tube (riser section). Another smaller circulation loop exists at the top of the draft tube close to the slurry surface. The liquid moves upward in the center and downwards towards the wall. There are big dead zones outside the draft tube (downcomer section) and close to the digester wall having very low or about zero velocities (represented with smaller arrows or dots in Fig. 2). This flow pattern has been reported and discussed in detail by [33,41,55,56]. Similar flow patterns were observed for experiments L2 to L5, and are discussed in the following sections 3.2-3.4.

Fig. 2 here

The time averaged and circumferentially averaged axial liquid velocities (Fig. 3) are positive inside the draft tube and negative outside the draft tube; indicating the upward and downward motion of the liquid, respectively. The velocities are zero near the wall region and near the bottom of the digester which shows the location of the dead zones. Higher velocities inside the draft tube are due the turbulence created by the air bubbles rising inside with high velocities and the maximum axial velocities existed near the sparger hole openings. Similar liquid velocity profiles were obtained for other studies [41,57,58] for 8 inch (20.32 cm) diameter IGLR.

Fig. 3 here

3.2 Effect of gas flow rate

The flow pattern at gas flow rate of $50 \text{ cm}^3 \text{ s}^{-1}$ (experiment L2) resembles to the flow pattern showed in Fig. 2 for $16.66 \text{ cm}^3 \text{ s}^{-1}$, except that the liquid velocities are higher inside the draft tube. The liquid velocity profile for experiment L2 is also similar to that of Fig. 3 for 16.66

cm³ s⁻¹. The effect of gas flow rate on the liquid velocity is shown in Fig. 4. It is clear from Fig. 4 that the increase in the time averaged axial liquid velocity at higher gas flow rate was significant in the riser but negligible in the downcomer. In bubbly flow regime, at very low superficial gas velocities, as the superficial gas velocity is increased, increasing gas hold up in the riser increases the driving force for the liquid flow, and thus increasing the liquid velocity [3,23,51,57–59]. At higher gas flow rates corresponding to the turbulent regime, the gas bubbles coalesce and also occupy some part of downcomer, without any substantial increase in the liquid velocity. The liquid velocity in downcomer should also increase with increasing gas flow rate in bubbly flow regime, but the magnitude of the increase depends on the flow area in the downcomer. With D/T ratio of 0.25, because of large cross sectional flow area of downcomer, the increase in liquid velocity with increase in gas flow rate is not appreciable. This effect of superficial gas velocity on average liquid circulation velocity was observed by many researchers [17–19,25,35,42,60,61].

Fig. 4 here

3.3 Effect of draft tube diameter

The draft tube size determines the superficial velocity of gas in the riser and considerably influences the hydrodynamics of IGLR. It also plays an important role in determining the minimum velocity necessary to fluidize the solid particles. A large draft tube diameter with D/T ratio greater than 0.75 is required to achieve optimum gas hold up [62], favorable for aerobic fermenters. D/T ratio of less than 0.6 should be used if high liquid velocities in the riser are required in order to avoid sedimentation of heavy solid particles or large microbial aggregates. Thus, the effect of D/T ratio on liquid velocity is investigated here.

For D/T of 0.5, good overall mixing is achieved with three distinct circulation loops (Fig. 5a); one inside the draft tube as a result of sparger design, one at the top of the digester near the slurry surface and one outside the draft tube with relatively lower velocities. There is a significant

exchange of slurry between the riser and downcomer sections. Whereas for D/T of 0.75, a major recirculation loop is present inside the riser and one small circulation loop at the top of the downcomer section (Fig. 5b), but the exchange of slurry between the riser and downcomer section is relatively poor with very low liquid velocities. Comparison of flow patterns for varying draft tube diameters (Fig. 2, 5a and 5b) illustrates the significant effect of draft tube diameter on the hydrodynamic behavior of IGLR. The flow patterns are also affected by the sparger design as explained in section 3.4;

Fig. 5 here

Effect of D/T ratio on the time averaged liquid axial velocity radial profiles at the bottom of the draft tube and at the center of the digester is shown in Fig. 6a and 6b, respectively. The liquid axial velocities are higher at the center of digester ($z=11\text{cm}$). The velocities at the bottom of the tank ($z=4\text{cm}$) are low for D/T of 0.5 but for D/T of 0.75 these velocities are practically zero, indicating the dead zones. The negative velocities for D/T of 0.5 outside the draft tube region, indicates the downward velocities and existence of circulation loop.

Fig. 6a and 6b here

As the D/T ratio increases, the magnitude of axial velocity inside the draft tube decreases. As expected, with same gas flow rate, as the cross sectional flow area increases with the increasing draft tube diameter the velocity decreases, according to Bernoulli's principle [35,63,64].

One would expect that as the D/T increases, the liquid velocity in the downcomer should increase due to reduction in flow area. But higher D/T also means larger riser cross section, lower gas holdup and hence lower driving force for the liquid circulation. That is why, an optimum D/T exists for achieving the desired liquid velocities in the downcomer to minimize or reduce the existence of the dead zones. A study suggests that the riser and downcomer should have same

equivalent diameter to minimize the energy loss by friction [24] and higher energy dissipation [10,65].

3.4 Effect of sparger geometry

The overall flow pattern and hydrodynamics of IGLR depends on the gas hold up which affects the density difference between the riser and the downcomer and hence the recirculation intensity. However, gas hold up is partly decided by the design of sparger and hence, the effect of sparger design on hydrodynamics of IGLR is very important. A CFD study to investigate the effect of sparger geometry on the hydrodynamics of IGLR [66] found that a multipoint sparger creates higher gas holdup as compared to a single point sparger.

The flow pattern for digester with single point sparger and D/T of 0.25 (experiment L5) is similar to flow pattern obtained for experiment L1 (Fig. 2) and L2. No effect of sparger on the flow pattern was observed for D/T ratio of 0.25.

In experiment L1 and L5 the effect of sparger is not very important due to smaller draft tube diameter (D/T ratio of 0.25). For D/T of 0.25, since the draft tube diameter is small, the sparger holes are located close to each other and both types of spargers have similar effect of relatively uniform gas distribution inside the riser (Fig. 7). Therefore the internal circulation loop in the draft tube is absent in case of D/T of 0.25.

Fig. 7 here

As the draft tube diameter increases, the sparger hole locations extend away from the center and from each other thus creating more dispersed sparging (Fig. 7). This dispersed sparging gives rise to the internal circulation loop inside the draft tube, which becomes more prominent with increasing draft tube diameter (Fig. 5a and 5b).

The axial liquid velocities are higher for single point sparger as compared to that for the cross sparger inside the draft tube (Fig. 8), whereas the liquid velocities are the same for both the

spargers outside the draft tube. The higher velocities are the result of higher gas flow rate dispersed at one single location by the single point sparger as opposed to the cross sparger, where total gas flow is distributed and only one-fourth of given flow rate is dispersed at each of the four sparger holes.

Fig. 8 here

3.5 Volume of dead zones or stagnant regions

The dead zones or stagnant zones are the part of the reactor with no flow or very low velocities. Dead zones are undesirable as they reduce the effective reactor volume, enhance solids settling [24], cause buildup of pH and temperature and degrade the digester performance.

In the present study the dead zones volume was evaluated by locating the 3D mesh of CARPT measurement with very low velocities (an arbitrary low value of 1 cm s^{-1} was used here as limiting liquid velocity), and summing up the volumes of these 3D grids. The dead zone volumes (Table 1) can be used as mixing parameter [1] for comparison between different configurations, however the proper selection of limiting value of liquid velocity used for calculating dead zone volume is necessary.

Dead zone volume decreases by increasing the gas flow rate (Table 1, experiment L1 and L2), but it is clear from flow pattern in Fig. 2 and Fig. 5 that liquid movement is affected mainly in the riser section for D/T of 0.25 and not in the downcomer where dead zones are located, thus decrease in dead zone volume does not indicate more homogeneity in this case. The dead zone volume is statistically same for D/T of 0.5 and 0.75 (experiment L3 and L4) but it is evident by comparing flow patterns (Fig. 5) that the digester with D/T of 0.5 is mixed more homogeneously thorough out the volume than the digester with D/T of 0.75. The change in sparger design also shows no significant effect on dead zone volume (experiment L1 and L5).

Due to the arbitrary value selected for limiting liquid velocity to calculate the dead zone volume, the dead zone volume is not a suitable parameter to quantify mixing. Instead of using an arbitrary value, the limiting velocity could be fixed by using terminal settling velocity of solids in the slurry. However, the solids present in the slurry vary greatly in size, shape and density, microorganisms form flocs and also disintegrate, solids change characteristics as they are digested. These problems make it very difficult to select a criterion to fix the value of limiting liquid velocity for calculating dead zones. Instead, another parameter, mean circulation time, could be used to quantify mixing in digesters.

3.6 Mean circulation time

In practice, IGLR type anaerobic digesters are commonly operated in semi-batch condition [5,38,74]. Specific amount of feed is added at fixed interval according to the desired Hydraulic Retention Time (HRT). So it is necessary for efficient digester operation that the added feed is mixed homogeneously with entire contents of the digester quickly to prevent localized increase in pH caused by excess formation of volatile acids [67]. In such cases, circulation time can be used to quantify mixing and for comparison of mixing performance of digesters at different scales.

Mean circulation time can be evaluated by mapping the trajectory (circulation loop) of the radioactive particle, starting from a given plane in the lower part of the draft tube and ending at the same plane after it has travelled through riser and downcomer. For each CARPT experiment, more than 5000 trajectories were identified. Circulation Time Density Function (CTDF) [44] of experiment L1 (Fig. 9) shows that the circulation time of tracer particle (representing liquid element) can vary from about 5 seconds to about 1000 seconds, with higher frequency ranging from 5 to 100 seconds. Very high circulation times (greater than 200 seconds) represent that the tracer particle was trapped in dead space where there is no flow or very low liquid velocities. The

mean circulation time (79 seconds) signifies that on average a tracer particle, thus liquid element or solid particle, takes 79 seconds to complete one circulation loop in the digester.

Fig. 9 here

Increase in gas superficial velocity and D/T ratio decreases the circulation time (Table 1), because of the increase in liquid velocity. The lowest circulation time observed in D/T of 0.75 is not a result of overall increase in liquid circulation but because of increased circulation only inside the riser (Fig. 5). Thus comparing the flow patterns and mean circulation time, we can conclude that configuration with D/T ratio of 0.5 provides better circulation. There is no significant effect of sparger geometry on mean circulation times, may be because of smaller D/T ratio (of 0.25).

4 Conclusions

Since the mixing performance of gas lift loop reactor (GLR) is governed by the reactor geometry and the operating variables, the results obtained through CARPT experiments can be used as general guideline for designing and modeling the lab-scale internal GLR type anaerobic digester. Quantifying mixing is a herculean task and cannot be accurately predicted through a single parameter, thus both liquid flow pattern and mean circulation time must be used for this purpose. On the other hand a more intuitive parameter such as dead zone volume does not necessarily quantify mixing correctly. Advanced technique such as CARPT cannot be used to study every reactor configuration but it is a valuable tool to benchmark Computational Fluid Dynamics (CFD) models for digester design and scale-up studies.

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Table 1: Details of CARPT experiments for IGLR type digester

Expt no.	Gas flow rate (cm ³ s ⁻¹)	Total solids in the slurry (g L ⁻¹)	<i>D/T</i> ratio	Sparger geometry	% Dead volume	Mean Circulation time (seconds)
L1	16.66	100	0.25	Cross	60	79
L2	50	100	0.25	Cross	52	58
L3	16.66	100	0.5	Cross	47	60
L4	16.66	100	0.75	Cross	42	43
L5	16.66	100	0.25	Single point	55	76

Figureg

Fig 1

Fig 2

Fig 3

Fig 4

Fig 5

Fig 6a

Fig 6b

Fig 7

Fig 8

Fig 9