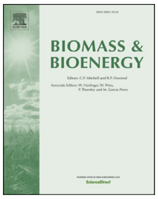
Biomass and Bioenergy 84 (2016) 98–106

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe



Research paper

Hydrodynamics investigation of laboratory-scale Internal Gas-lift loop anaerobic digester using non-invasive CAPRT technique

Mehul S. Vesvikar, Muthanna Al-Dahhan*

Washington University in St. Louis, School of Engineering & Applied Science, Department of Energy, Environmental & Chemical Engineering, Chemical Reaction Engineering Laboratory, Brauer Hall, Campus Box 1180, One Brookings Drive, St. Louis, Missouri, 63130, USA

ARTICLE INFO

Article history:
Received 7 March 2015
Received in revised form
3 November 2015
Accepted 13 November 2015
Available online 7 December 2015

Keywords:
Flow pattern
Draft tube
Sparger
Mean circulation time
Dead volume
Mixing

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.

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

---

* Corresponding author. Present Address: Missouri University of Science and Technology, Chemical and Biochemical Engineering Department, 110E, Bertelsmeyer Hall, Rolla, MO, 65409, USA.

E-mail addresses: mehulsv@gmail.com (M.S. Vesvikar), aldahhanm@mst.edu (M. Al-Dahhan).

http://dx.doi.org/10.1016/j.biombioe.2015.11.014

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 h 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 ±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 L. 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.

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 $cm^3\ s^{-1}$ to 50 $cm^3\ s^{-1}$ (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 $cm^3\ s^{-1}$ 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.