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CFD simulation of gas mixing in anaerobic digesters

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ABSTRACT

A computational fluid dynamics (CFD) model that characterizes gas mixing in anaerobic digesters was developed. The four gas mixing designs studied are: (1) unconfined mixing by two bottom diffusers, (2) confined mixing by one draft tube, (3) unconfined mixing by two cover mounted lances, and (4) confined mixing by two bubble guns. The flow fields for each design were obtained by solving an Eulerian multiphase flow model, assuming that the liquid phase is a non-Newtonian power-law fluid. The commercial CFD software, *Fluent 14.5*, was applied to simulate gas–liquid two-phase flow in the digester. A qualitative description of the fluid motion due to the generation of gas bubbles and quantitative identification of the flow fields of the liquid phase were made to compare the four mixing designs, in which the average velocity and a uniformity index for velocity were used to evaluate the mixing performance for each design. In addition, the velocity gradient for gas mixing along with its application to calculate the breakup number of a floc was investigated. Further, the mixing intensity that impacts the biological process and the justification of the simulation results were discussed.

1. Introduction

There is an increasing interest in organic matter treatment by anaerobic digestion across a wide range of fields including food waste, sewage sludge, and animal manure, etc. The performance of anaerobic digesters is influenced by the degree of contact between substrate and anaerobic bacteria, and the extent of this contact is heavily dependent on mixing in the digesters. The importance of mixing in the conversion of biomass to methane is well recognized, even though the optimum mixing level remains a subject of much debate (Karim et al., 2005). Proper mixing can not only prevent substrate clogging in the digesters, but also maintain uniform conditions for heat and mass transfer.

Basically, mixing can be accomplished by three methods including pumped circulation, mechanical agitation, and recycling of biogas. No matter which method is employed, natural mixing always occurs in a digester because of rising gas bubbles and the thermal convection currents caused by the addition of heat, but this mixing intensity is not adequate to ensure stable digestion process performance at high loading rates. Therefore a mixing system needs to be installed to create a homogeneous environment throughout the digester, so that the digester volume can be fully utilized (Schlicht, 1999).

Gas mixing systems in digesters may be unconfined or confined. Biogas is collected at the top of the digesters, compressed and then discharged through bottom diffusers or top-mounted lances for unconfined systems or released through tubes for confined systems. The schematic diagram of four gas mixing designs is shown in Fig. 1 (McFarland, 2001). Gas mixing is in principle similar to multiphase flow in vertical pipes. Dziubinski et al. (2004) summarized five basic gas–liquid two-phase flow structures as: (1) discrete gas bubbles in a continuous fluid (bubbly flow), (2) large bubbles in a continuous fluid (slug flow), (3) the entrance regime for the development of slug flow (froth flow), (4) liquid along the pipe wall while gas inside the liquid annulus (annular flow), and (5) gas dispersed in liquid (dispersed flow).

Gas mixing in anaerobic digesters has traditionally been studied using both tracer and non-invasive techniques. Verhoff et al. (1974) measured fluoride concentration as a function of time to assess mixing effectiveness in a digestion tank with gas lift mixers. Monteith and Stephenson (1981) did tracer experiments to analyze residence time distribution in two gas-mixed digesters, and reported that inefficient mixing could reduce the effective volume of a digester by as much as 70%. Karim et al. (2004) used computer automated radioactive particle tracking (CARPT) and computed tomography (CT) to measure velocity, turbulent kinetic energy, and gas holdup in a digester with a gas sparger. Later, Varma and Al-Dahhan (2007) extended the work done by Karim et al. (2004) to examine the hydrodynamic performance for the digester with multiple spargers.

Besides experimental measurements, computational fluid dynamics (CFD) can be a useful tool for simulation of gas mixing

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Nomenclature

B	breakup number, dimensionless
c	injection - tank bottom clearance, m
C	constant, dimensionless
CARPT	computer automated radioactive particle tracking
CFD	computational fluid dynamics
CT	computed tomography
d	diameter of gas injection, m
d_f	floc diameter, m
E	mixing power, W
F	rupture force, N
$\vec{F}$	force, N m^{-3}
g	gravity, m s^{-2}
G	average velocity gradient, s^{-1}
G_L	local velocity gradient, s^{-1}
HGZ	high velocity gradient zone
J	aggregate strength, N
k	consistency coefficient, Pa s^n
k	turbulent kinetic energy, m^2 s^{-2}
LGZ	low velocity gradient zone
m	number of nozzles
$\dot{m}$	mass transfer rate, kg m^{-3} s^{-1}
MEL	mixing energy level, W/m^3
MGZ	medium velocity gradient zone
n	number of mesh cells
n	number of phases
n	power-law index
No	number of gas injections
p	pressure, Pa
P	pressure, Pa
Q	volumetric flow rate, m^3 s^{-1}
$\vec{R}$	interaction force, N m^{-3}
S	source term, kg m^{-3} s^{-1}
SST	shear stress transport
t	time, s
TS	total solids
UI	uniformity index
v	velocity magnitude, m s^{-1}
$\bar{v}$	average velocity, m s^{-1}
$\vec{v}$	velocity vector, m s^{-1}
V	volume, m^3
x, y, z	Cartesian coordinates

Greek letters

α	volume fraction, dimensionless
β^*	coefficient, dimensionless
$\dot{\gamma}$	shear rate, s^{-1}
ε	dissipation rate of turbulent kinetic energy, m^2 s^{-3}
η	non-Newtonian viscosity, Pa s
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
σ	hydrodynamic stress, N m^{-2}
$\bar{\bar{\tau}}$	stress–strain tensor, N m^{-2}
ω	specific dissipation rate, s^{-1}

subscript

i	mesh cell
inj	gas injection
isr	inertial subrange
p, q	phase
vsr	viscous subrange

in digesters. Vesvikar and Al-Dahhan (2005) simulated air–water two-phase flow in the digester from Karim et al. (2004), and verified the flow fields with the measured data from CARPT and CT. Latha et al. (2009) developed a Lagrangian discrete phase model that describes gas mixing for anaerobic biohydrogen production from municipal and industrial solid wastes, and made a comparison of mixing behaviors for Newtonian and non-Newtonian fluids in a lab-scale reactor. Wu (2010a) presented an Eulerian multiphase flow model to solve gas mixing in digesters, and proposed that the shear stress transport (SST) k–ω model with low-Reynolds-number corrections could be an appropriate turbulence model to solve gas and non-Newtonian two-phase flow.

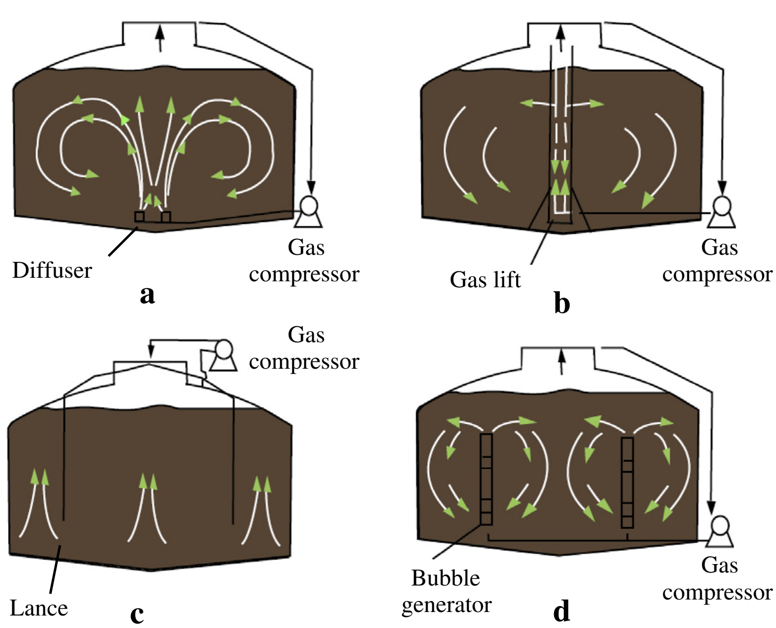

Fig. 1. Schematic diagram of four gas mixing designs: (a) bottom diffusers, (b) gas lift, (c) cover mounted lances, and (d) bubble guns.