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Multiphase modeling of settling and suspension in anaerobic digester

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HIGHLIGHTS

- Develop biowaste fluid dynamics for collision, aggregation and breakup of clusters.
- Explore the mechanisms of settling and suspension in anaerobic digester.
- Biowaste particles tended to have fluid properties.
- Aided with CFD simulation, the scale-up effect was reduced.

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ABSTRACT

Effective suspension and settling are critical for controlling biomass retention in a bioreactor. In this paper, a multi-fluid model with kinetic theory of granular flow (KTGF) was established to describe these phenomena in the biowaste particles flow in anaerobic digesters. Solid retention time (SRT) was added as a parameter into anaerobic digestion No.1 (ADM1) model to evaluate its effect on the biogas productivity. The model was experimentally validated in a liquid–gas–solid column reactor with gas and solid volume fraction and granular temperature as the major variables. The wastewater residence time distribution was also determined through modeling and measurement to evaluate the mixing pattern in the pilot column reactor. The effect of restitution coefficient on flow behavior of biowaste particles, particles settling and suspension were predicted. Settling and suspension processes of anaerobic digesters were simulated for lab and pilot-scale reactors with comparisons made for reactor configuration and geometry model, respectively. This study demonstrated that the multi-fluid model with KTGF could provide better understanding of impact of suspension and settling upon retaining biomass particles in the anaerobic digesters.

1. Introduction

Public awareness of the need to reduce global warming and the drastic increases in oil price have encouraged many countries around the world to adopt new energy policies that promote renewable energy applications to meet energy demands and to protect the environment [1,2]. Anaerobic digestion (AD) is a promising biochemical process for production of renewable energy, stabilization of waste streams, and recycling nutrients from organic wastes [3,4]. Retention times of solid and liquid in an anaerobic digester are critical parameter for design and operation of a high rate digester. For example, in wastewater treatment, high rate digesters are commonly designed to retain anaerobic biomass particles including the particulate substrates and the attached microorganisms [5]. As these digesters work a very short hydraulic retention time (HRT) which is less than the maximum growth rate for methanogens, mechanisms are required to maintain biomass in the reactor [6]. Suspension and settling of the biomass particles are essential mechanisms, which significantly affect the operation of anaerobic digesters. In particular, microorganism attachment on particle surfaces needs effective suspension and settling to gain adequate contact and longer retention so that reactor performance can be improved [7]. Suspension and settling of the biomass particles involves solid–liquid–gas flow, in particular the non-linear interactions among the particles and between the particles and fluid [8]. Although some models such as gravity settling theory [9], selection pressure [10], and primary settling efficiency [11], were developed to simulate the settling process in waste water treatment processes, the complicated phase interaction was not considered in these models. To better understand these complex processes, it is necessary to apply advanced modeling methods.

With the advancement of computer performance in the last decades, many researchers have turned to computational fluid dynamics (CFD) to predict flow fields and improve mixing

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performance in anaerobic digesters [12,13]. The earlier relevant studies focused on change of velocity distribution in anaerobic digesters. However, this variable did not completely describe flow fields within the reactors because the complex flow and phase structure could not be completely revealed. Our earlier studies even with the introduction of non-Newtonian fluid theory into CFD simulation of manure slurry [14,15] did not explain the flow phenomena of suspension and settling in anaerobic digester because wastewater and biomass particles were assumed to share one phase. Some researchers [16,17] developed a three-fluid model (gas–liquid–solid) to describe the hydrodynamics in an upflow anaerobic sludge blanket (UASB) reactor. Their model, nonetheless, did not describe biomass particle momentum exchange due to translation and collision [18]. To date, few studies of multiphase flow have focused on biomass particles [8].

Kinetic theory of granular flow (KTGF) is a recognized approach for consideration of collision, aggregation and breakup of particle clusters [19]. Introduced into a two-fluid model, KTGF has been extensively applied into the simulation of gas–solid [20,21], liquid–solid [22] and liquid–gas–solid fluidization [23]. Gidaspow et al. [22,24] further introduced KTGF into non-Newtonian blood flow where plasma and red blood cells (RBCs) were considered as two phase to describe the Fahraeus–Lindqvist effect. Like glass beads in previous studies, RCBs were also assumed to be partial elastic particles. However, unlike the rigid particles (glass beads and sand particles) in gas–solid fluidization, most of the biowaste particles (manure and activated sludge particles) are soft and deformable and trend towards inelastic [25]. Parameters of KTGF must be adjusted to better account for such unique biowaste particle flow phenomena.

In this study, CFD was used to evaluate the biomass retention physical process while the anaerobic digestion No.1 (ADM1) model was used to evaluate the biomass retention biochemical process. Since the time scales of CFD and ADM1 are much different, they were calculated separately. A multi-fluid model with KTGF was established to describe the settling and suspension of dairy manure waste particles in the bottle reactors of lab scale and the pilot column reactor, respectively. Since intermittent mixing was used in the anaerobic digesters, the settling process was simulated at the laminar flow without agitation while the suspension process was simulated at the turbulent flow with a jet agitation. Separate momentum balances equations were solved for the continuous flowing liquid phase and for the discrete gas and solid phases. Residence time distribution was measured and predicted to understand the dispersion feature of the pilot column digester. Solid retention time (SRT) was added into the ADM1 model to evaluate the effect on the biogas productivity in bottle and column reactors.

2. Materials and methods

2.1. Experimental section

2.1.1. Laboratory and pilot scale anaerobic digesters

Anaerobic digesters were constructed from 1 L glass bottle reactor (lab-scale) and 70 L steel column reactor (pilot-scale). The glass bottle dimensions were 11.7 cm in height and 7.62 cm in diameter. The bottle reactor was agitated on a 150 rpm shaker for 10 min per 2 h. The steel column reactor height was 100 cm, the diameter was 30 cm, the cone height was 7.6 cm, and the cone bottom diameter was 3.8 cm. The wastewater was injected into the column reactor from the bottom inlet as mixing mechanism. The wastewater flowed out from the side outlet while the gas went out from the top outlet. The wastewater was recycled back to agitate the column reactor for 10 min per 2 h. Fig. 1 shows the schematic of a gas–liquid–solid column anaerobic reactor including different simulation procedures for multi-phase flow field and biochemical and physico-chemical conversion process. The same simulation procedures were also applied into the bottle reactor.

In the anaerobic digesters, dairy manure and anaerobic sludge were inoculated at a 1:1 volume ratio. The feeding concentration of dairy manure was 9.1 g/L total solids (TSs). In the anaerobic digesters, the solid content was maintained at an average of 5%TS. After the dairy manure and fiber particles settled in the digesters, there was a 25% TS accumulation at the bottom. The SRT value was adequately controlled by regular discharge of solids at 10 d from the digesters while HRT was 6 d [7]. The source of flushed dairy manure was the Washington State University Dairy Center in Pullman, WA, USA. Anaerobic sludge was sampled from a 35 °C anaerobic digester operating within the Pullman wastewater treatment plant. Dairy manure particle average density was measured as 1700 kg/m^3 with its particle size distribution shown in Table 1. The samples were taken from top, middle and bottom of the bottle reactor, respectively before digestion [26]. The particle sizes were calculated by weighted average. Table 1 shows that 70.06% particles at the range of 0.04–0.06 mm had not settled down from the top of the bottle reactor.

2.1.2. Analytic methods

A single-phase (wastewater only) system was used to measure residence time distribution in the column reactor for flow pattern validation and reactor design evaluation. There was no inoculum in the wastewater system and the initial system pH was maintained at 7.0. Therefore, acetic acid did not give perturbation in the measurement. 50 mL acetic acid was used as a pulse tracer to measure residence time distribution in the column reactor. A pH probe was used to receive the signal at the exit of the column reactor and pH was monitored on-line with an OM-CP-PH101 pH and Temperature Data Logger connected to an OMEGA®PHE-4200 pH probe.

TS was determined according to standard methods [27]. Maximum packing limit was measured by the maximum TS packing at the reactor bottom because of gravity. This method gives a range of results instead of accurate value.

In the digestion process, biogas production was measured using Wet Tip Gas Meters (wettipgasmeter.com).

2.2. Models and solution

2.2.1. Assumptions

The model was constructed to describe multi-phase flow characteristics including liquid (wastewater), gas (biogas) and solid (dairy manure fiber and biomass particles) in anaerobic digesters. An Eulerian treatment was used for each phase. Since the biowaste particle flow is very complex, necessary assumptions were made in this study to obtain some reasonable solutions in AD reactors. However, these assumptions could lead to uncertainty and limitation for the applicability of the presented multi-fluid model with KTGF. Further research is needed to determine complex mechanisms for the constitutive relationship in a multi-phase AD system.

The main assumptions were as follows:

(a) Liquid (wastewater) had the same properties as water (35 °C), i.e. Newtonian fluid. This assumption requires low TS (<1%) in the liquid phase. The small size and electrical charge in the wastewater affect particle sedimentation in the liquid phase. This leads to an increase of TS and generates colloidal suspension. The fluid properties are changed with an increase of TS, and may transit from Newtonian fluid to non-Newtonian fluid. The constitutive equation of shear stress for a non-compressive Newtonian fluid may not be suitable for wastewater with high concentration of colloidal solids.