CFD simulation and evaluation of the mixing efficiency of gas and non-Newtonian fluid during high solid anaerobic digestion

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Keywords: non-Newtonian fluid, two phase flow, gas mixing, high solid anaerobic digestion, CFD

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Anaerobic digestion has been highly considered as one of the most effective approaches for sustainable energy production during food waste management. High solid anaerobic digestion (HS-AD) (i.e., more than 10% total solids within reactor) exhibits the advantages such as flexible feedstock types, small reactor volume, high organics loading, less heat consumption, and easy operation than the traditional liquid AD (Angelonidi and Smith, 2015; Rocamora et al., 2020; Zhuo et al., 2018; Zou et al., 2016). Substrates mixing of the HS-AS should be comprehensive considering the operational parameters optimizing, bioreactor type designing and fluid properties, closely related to the overall flow structure and all the hydrodynamic properties of the flow (Trad et al., 2016). The enhancement of mixing efficiency becomes critical rate-limiting factor in HS-AD systems operating at high organic loads and short residence time (Latha et al., 2019), however the flow characteristics of gas mixing in HS-AD reactors still remains unclear. The mixing efficiency varies widely depending on the equipment used and the geometry of the digester. Therefore, it is practically urgent to refine the design and operation of mixing in anaerobic digesters using CFD techniques to optimize the balance between the input mixing energy and the biogas output. To assess the anaerobic digestion mixing scenarios, quantitative mixing criteria, including uniformity index (UI), dead volume and average shear rate, have been previously adopted in anaerobic digestion. However, statistical analysis of mixing in anaerobic digesters should consider not only the homogeneity of mixing inside the reactor, but also the breakup mechanism of gas mixing as it enters the reactor interior.

Here, a two-phase Euler-Euler model was applied to analyze the hydrodynamics of different anaerobic digesters, with varied geometric configurations and mixing energy, to establish the best-case scenario in response to inadequate modeling of gas mixing of HS-AD. Furthermore, the effects of geometry and mixing efficiency on digester performance, including flow patterns, average velocity, energy consumption, dead volume, UI, and velocity gradient \( G_h \), were comprehensively analyzed via the combination analysis of the quantitative and qualitative mixing indexes. At the end, the applicability of the indexes was discussed. Moreover, breakup number \( (B_{u0} \text{ and } B_{u1}) \) was introduced to analyze the effect of mixing on flocs growth. The construction and shape of plexiglass double layer reactor using a water bath jacket to maintain a constant temperature \( (37 \pm 1 \degree C) \) were given in Fig. 1. To better analyze the effects of different geometric configurations and mixing indexes, five representative monitoring points selected for this study were \( P_1 \) (0.05, 0.05, 0.45), \( P_2 \) (-0.05, 0.05, 0.25), \( P_3 \) (-0.05, -0.05, 0.05), \( P_4 \) (0.0, 0.35), and \( P_5 \) (0.0, 0.15 as shown in Fig.1(b).

![Diagram of (a) digester, (b) monitoring point locations with single nozzle; (c) meshing of the physical model](image)

Experimental results showed that the food waste slurry exhibited pseudoplastic characteristics and the non-Newtonian fluid characteristics (Fig. 2). The higher the reactor diameters, the greater consumption of the input energy (under the same level inlet mixing), correspondingly the smaller dead zone and higher \( G_h \). However, a larger input energy did not mean a more uniform mixing. Under the condition of certain input energy, the gas dispersed inlet was better than the centralized inlet for mixing. Thus, the symmetrical nozzles were arranged in the digester with a spacing of 180° and an angle of 45° between the inlet of each nozzle and the reactor wall (Fig. 3). The high mixing intensity was characterized by high average velocity, low dead zone value and high \( G_h \), which was not theoretically corresponded to a homogeneous mixing system. While the homogeneity of the system could be mirrored by the distribution of local \( G_h \) and UI. The more uniform the energy distribution, the smaller its effect on flocs growth.

In summary, CFD simulation of gas and non-Newtonian fluid during HS-AD could be used to to establish the best-case mixing scenario, the distribution of local \( G_h \) and UI were proved to be effective indicators for evaluating the homogeneity of HS-AD mixing. The results offer the possibility of further optimal scale-up design of the bioreactor.
Fig. 2. Rheological properties of liquid food waste. (a) TS=5%, 10% and 15%; (b) TS=20%

Fig. 3. Mixing quality evaluation with different inlet angle of discharge nozzles. (a) velocity magnitude from XZ plane; (b) velocity magnitude from Z=0.25 m plane; (c) Percentage of local Gi volume; (d) B_air and (e) B_gas at different monitoring points.

Acknowledgments
This research was funded under the auspices of the National Key Research and Development Program of China (No.2018YFC1900902).

References