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

Lili Li[1], Kun Wang[1], Liangliang Wei[1], Qingliang Zhao[1*], Huimin Zhou[1], Junqiu Jiang[1]

[1]Key Laboratory of Urban Water Resource and Environment, School of Environment, Harbin Institute of Technology, Harbin 150090, China

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

Presenting author email: qlzhao@hit.edu.cn

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_L), 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_{vsr} and B_{isr}) 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 ± 1 °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).

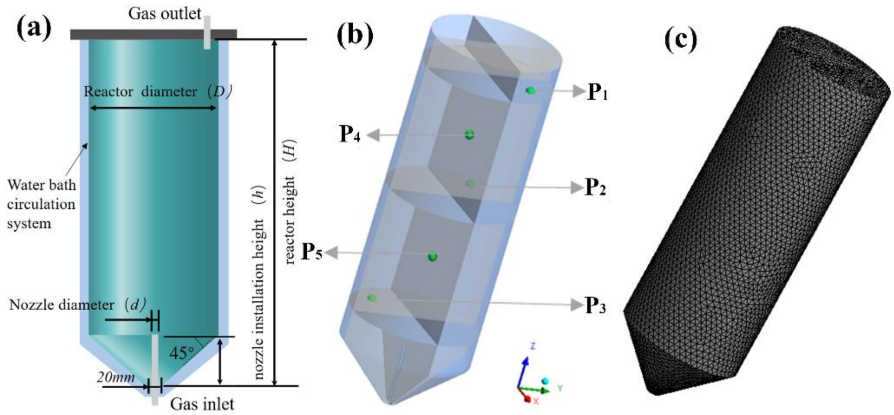

Fig.1 Diagram of (a) digester; (b) monitoring point locations with single nozzle; (c) meshing of the physical model

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 velocity), correspondingly the smaller dead zone and higher G_L. 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 charactered by high average velocity, low dead zone value and high G_L, 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_L 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_L 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.

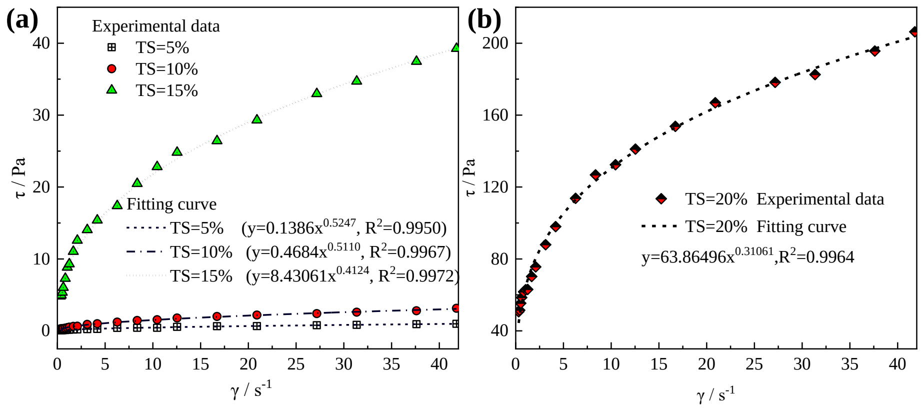

Fig.2 Rheological properties of liquid food waste. (a) TS=5%, 10% and 15%; (b) TS=20%

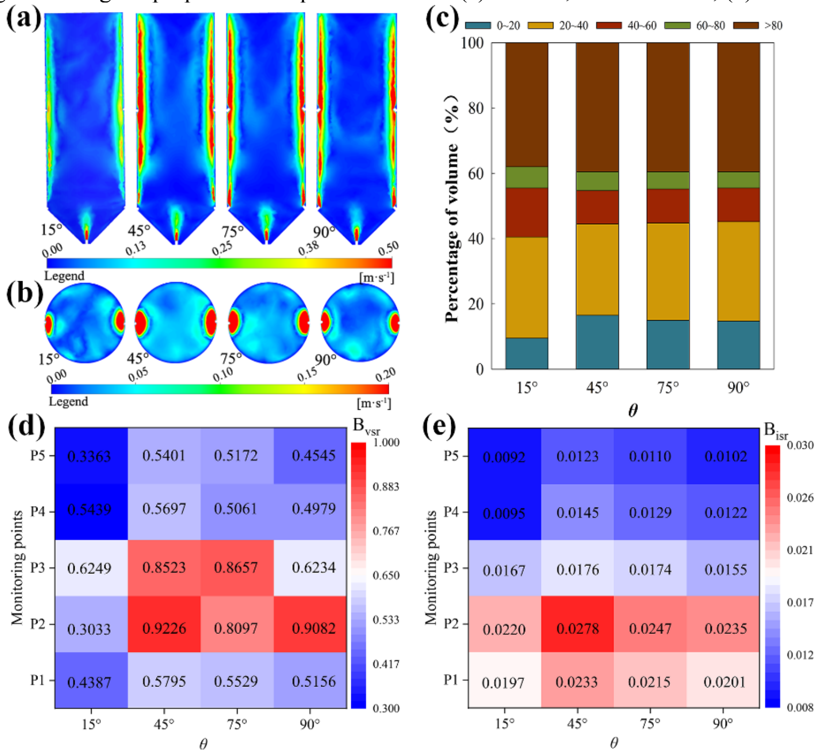

Fig.3 Mixing quality evaluation with different inlet angle of discharge nozzles. (a) velocity magnitude from *XZ* plane; (b) velocity magnitude from *Z*=0.25 m plane; (c) Percentage of local G_L volume; (d) B_{vsr} and (e) B_{isr} at different monitoring points.

Acknowledgments

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

References

Angelonidi, E., Smith, S.R., 2015. A comparison of wet and dry anaerobic digestion processes for the treatment of municipal solid waste and food waste. *Water Environ J*. 29, 549-557.https://doi.org/10.1111/wej.12130.

Latha, K., Velraj, R., Shanmugam, P., et al., 2019. Mixing strategies of high solids anaerobic co-digestion using food waste with sewage sludge for enhanced biogas production. *J Clean Prod*. 210, 388-400.https://doi.org/10.1016/j.jclepro.2018.10.219.

Rocamora, I., Wagland, S.T., Villa, R., et al., 2020. Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. *Bioresource Technol*. 299.https://doi.org/ARTN 12268110.1016/j.biortech.2019.122681.

Trad, Z., Fontaine, J.P., Larroche, C., et al., 2016. Multiscale mixing analysis and modeling of biohydrogen production by dark fermentation. *Renew Energ*. 98, 264-282

Zhuo, Y., Han, Y., Qu, Q.L., et al., 2018. Pre-separation of ammonium content during high solid thermal-alkaline pretreatment to mitigate ammonia inhibition: Kinetics and feasibility analysis. *Water Res*. 139, 363-371.https://doi.org/10.1016/j.watres.2018.03.064.

Zou, H., Ding, S.C., Zhang, W.Y., et al., 2016. Study on influence factors in bacillus thuringiensisproduction by semi-solid state fermentation usingfoodwaste. *The Tenth International Conference on Waste Management and Technology*. 31, 127-135.https://doi.org/10.1016/j.proenv.2016.02.018.