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Evaluation of a transparent analog fluid of digested sludge: Xanthan gum aqueous Solution

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Abstract

To verify the accuracy and reliability of the computational fluid dynamics simulation of sludge anaerobic digester, fluid flow visualization experiment is a reliable approach. However, it cannot be used for anaerobic digester due to the opaque nature of sludge. Xanthan gum (XG) aqueous solution was selected as the analog fluid of the digested sludge (DS) due to its good optical clarity and good stability. The rheological properties of DS and the XG aqueous solution were measured by applying a rotational viscometer and the measuring results qualitatively and quantitatively compared by graphics and mathematical statistics analysis. The experimental results revealed the rheological behaviour of XG aqueous solution was similar to DS. They were both typical pseudo-plastic non-Newtonian fluid and showed the same trend in the rheological curves with similar curvatures. Carreau model (R^2=0.9578) was proposed to describe the rheological behaviour and calculate the rheological parameters of the analog fluid. The limiting viscosity of the XG aqueous solution linearly increased with the increases of the concentration within the concentration range of 0.20g/L~1.60g/L. According to the linear relationship, 0.50g/L, 1.00g/L and 1.50g/L XG aqueous solution were selected to compare with DS. The result of Welch's t-test demonstrated that there is no significant difference in the rheological parameters of DS and the 1.00g/L XG aqueous solution at the significant level of α=0.05, which indicated the feasibility of choosing the 1.00g/L XG aqueous solution as transparent analog fluid of DS, and build a foundation for visualization experiment in anaerobic digester.

Keywords: digested sludge; analog fuild; xanthan gum aqueous solution; rheological properties; Carreau model;Welch's t-test; CFD simulation.

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Nomenclature

XG	Xanthan Gum	γ	shear rate [s^{-1}]
CFD	Computational Fluid Dynamics	η	viscosity [Pa·s]
DS	Digested Sludge	η_0	zero shear viscosity [Pa·s]
PIV	Particle Image Velocitometry	η_∞	limit viscosity [Pa·s]
LDV	Laser Dpoppler Velocimetry	η_p	plastic viscosity [Pa·s]
CARPT	Computer Automated Radioactive Particle Tracking	τ	shear stress [Pa]
CMC	Carboxyl Methyl Cellulose	τ_0	yield stress [Pa]
H-B	Hershel-Bulkly model	k	fluid consistency index [$Pa\cdot s^n$]
Ostwald	Ostwald de Vaele model	n	flow behaviour index
λ	time constant	m	dimensionless exponent

1. Introduction

Anaerobic digestion is a wide spread technology for stabilizing and reducing the excess sludge from wastewater treatment plants[1, 2]. It has been praised as a cost-effective process due to its capacity to degrade organic matter by converting organic compounds into a valuable biogas composed of methane and carbon dioxide under anaerobic conditions, which represents a source of renewable energy[3, 4]. Since the 1880s, anaerobic digestion technology has been used for sludge treatment. However, the failure rate for anaerobic digesters is still very high, the common operation issues including stratification and formation of a surface crust in the reactor which are believed to be mainly due to poor design, construction, as well as inadequate mixing[5]. Furthermore, with the development of dry or high-solid anaerobic technologies, the high viscosity caused by high total solids concentration can severely reduce the mass and heat transfer among enzymes, bacteria and substrates in the digester[6, 7]. Proper mixing is regarded as an important means to optimal performance and operation since mixing creates a homogeneous substrate preventing stratification and formation of a surface crust, and ensures solids remain in suspension. Mixing also enables heat transfer, particle size reduction at digestion progresses and release of produced gas from the digester[8]. Therefore, to enhance the overall performance of a selected digester configuration and design, it is important to understand and quantify its mixing and flow pattern[9]. Chemical tracer techniques were used measuring the mixing behaviour and confirming system mixing efficiency in the earlier studies on digesters[10]. These research methods, however, are quite time-consuming and expensive for test. What is more, they cannot offer complete information of flow field and turbulence parameters (kinetic energy, stresses, etc.) in the reactors[10].

Computational fluid dynamics (CFD) technique is a powerful numerical tool that can efficiently develop both spatial and temporal field solution of fluid pressure, temperature and velocity, and have been proven its effectiveness in the analysis and design of engineered systems[11]. CFD-based computer simulations overcome the experimental difficulties and have been used for characterizing, analysing and optimizing flow pattern inside anaerobic digesters[12]. Brideman[13] modelled the mechanical mixing of sewage sludge in a cylindrical digester at laboratory scale, and the velocity magnitude and volume of stagnant zones are obtained in the simulation. Wu[14] simulated the flow fields and mixing energy level in egg-shaped anaerobic digesters that mixing by mechanical draft tube, and made comparisons of two mixing types and two digester shapes by CFD simulation. The states-of -art of CFD used to investigate bioreactors have already reviewed in his recent article[12]. Although CFD-based simulation has been widely used, its users and developers still face a same critical issue: How to assess the accuracy of the simulation solution? Verification and validation are certainly the primary means to assess the accuracy and reliability in computational simulations[15]. In the previous studies, the accuracy of a CFD simulation was assessed by comparison with experimental data, the existing measurements including chemical tracer techniques[16], Particle Image Velocitometry (DPIV), Laser Ddoppler Velocimetry (LDV) [17], and Computer Automated Radioactive Particle Tracking (CARPT) [10] etc. Common optical techniques, such as PIV and DIV etc., have been widely used due to describing the flow information directly and the measuring instruments obtained easily. But they are not suitable for anaerobic digesters due to the opaque nature of sludge. Therefore, we need to find a transparent analog fluid to carry out the PIV or LDV experiment for sludge, and thus to further verify the accuracy and reliability of the CFD simulation results.