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Research paper

Euler-Lagrange Computational Fluid Dynamics simulation of a full-scale unconfined anaerobic digester for wastewater sludge treatment

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ABSTRACT

For the first time, an Euler-Lagrange model for Computational Fluid Dynamics (CFD) is used to model a full-scale gas-mixed anaerobic digester. The design and operation parameters of a digester from a wastewater treatment works are modelled, and mixing is assessed through a novel, multi-facetted approach consisting of the simultaneous analysis of (*i*) velocity, shear rate and viscosity flow patterns, (*ii*) domain characterization following the average shear rate value, and (*iii*) concentration of a non-diffusive scalar tracer. The influence of sludge's non-Newtonian behaviour on flow patterns and its consequential impact on mixing quality were discussed for the first time. Recommendations to enhance mixing effectiveness are given: (*i*) a lower gas mixing input power can be used in the digester modelled within this work without a significant change in mixing quality, and (*ii*) biogas injection should be periodically switched between different nozzle series placed at different distances from the centre.

1. Introduction

This paper considers the Computational Fluid Dynamics (CFD) modelling of a full-scale gas-mixed anaerobic digester. The purpose of this work was to develop recommendations to minimize the input mixing power without compromising, and indeed enhancing, biogas yield for the scenario considered. This was done by progressively lowering the mixing input power while analysing the resulting flow patterns. This work is based on Dapelo et al. [1], but the current article also includes: (*i*) a systematic assessment of the model mesh-independence through the Grid Convergence Index (GCI) as proposed by Roache [2]; (*ii*) a more complete analysis of the flow patterns by comparison of velocity and viscosity plots; (*iii*) additional simulations to track the distribution of a non-diffusive scalar field to be used as a virtual tracer and to reproduce the Herschel–Bulkley rheology; (*iv*) an analysis of the presence of low-viscosity corridors in the digester, and their detrimental effect on mixing; (*v*) an assessment of a mitigation strategy consisting of abruptly switching biogas injection between two nozzle series at regular intervals; and (*vi*) an alternative approach to calculate the value of minimum power per unit volume necessary for a satisfactory level of mixing computed in the original conference paper is presented here.

Wastewater treatment is an energy-intensive operation. Energy use at wastewater treatment works (WwTWs) which come under the auspices of the Urban Wastewater Treatment Directive (UWwTD) and for which EU Member States returned data exceeds 23,800 GWh per annum [3]. Energy consumption has increased significantly in the last two decades, and further increases of 60% are forecast in the next 10–15 years, primarily due to tightened regulation of effluent discharges from WwTWs (e.g. Water Framework Directive, WFD) [4]. WFD impacts will not be truly appreciated for many years, but the UK water industry forecasts a GBP 100M energy cost increase from implementation of more stringent treatment standards [5]. However, predictions show that by 2030 the world will have to produce 50% more food and energy and provide 30% more water [6], while mitigating and adapting to climate change, threatening to create a "perfect storm" of global events. Therefore, we must address the explicit link between wastewater and energy.

Renewable energy resources development is an integral part of several EU Governments' environmental strategies. Mesophilic anaerobic digestion (MAD) is the most widespread technology for sludge treatment, the by-product of wastewater treatment, in which sludge is mixed with anaerobic bacteria to break down biodegradable material and produce a methane-rich biogas. The

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current drive to maximise energy recovery means biogas is increasingly harnessed via combined heat and power technology. So, we need to optimise MAD reactor (digester) and mixing performance to maximize energy recovery.

In order to predict confidently optimum digester mixing, we need to determine to what extent biogas output is influenced by flow patterns in a digester; flow patterns which are determined by physical parameters of the digesters, inflow mode, sludge rheology and, crucially, mixing regimes. Yet research is lacking in this area. Traditional approaches to digester design are firmly rooted in empiricism and rule of thumb rather than science, and design standards focus only on treated sludge quality, not quality and gas yield/energy consumption.

Although the importance of thorough mixing has been recognized, recent studies [7–11], have questioned traditional approaches. A consistent body of literature[12–20] has shown that computational fluid dynamics (CFD) offers significant potential for understanding flow patterns of the non-Newtonian sewage sludge within digesters. However, there are clear limitations with the work undertaken to date; for example, while much work has been done to understand mechanical mixing, gas mixing remains poorly studied.Although it is recognized that mechanical mixing is the most efficient mode of mixing [16,21], gas mixing is not prone to problems specific to mechanical mixing such as wear and expensive maintenance due to the presence of moving elements (e.g., impellers, shafts, ball bearings) inside the digester. Hence, there is a clear industrial interest in investigating gas mixing. Despite this, only Vesvikar and Al-Dahhan [12], Wu [16], Wu [22] and Wu [23] have proposed robust multiphase models. Karim et al. [13] adopted a simplified approach by considering *de facto* a single-phase model and reproducing the effect of the bubbles through appropriate boundary conditions, but such approach is valid only for the specific case of the draft-tube digester they considered.

Vesvikar and Al-Dahhan [12], Wu [16] and Wu [22] used the Euler-Euler model for their simulations. It is well-known that the Euler-Euler model can handle very complex fluids, but needs a relevant quantity of empirical information to close the momentum equations, and for this reason Andersson et al. [24] recommends it only when other models are not available. A novel Euler-Lagrangian CFD model introduced in [25] to simulate the gas mixing of sludge for anaerobic digestion is described in which fluid motion is driven by momentum transfer from the bubbles to the liquid. The bubbles rise in columns via buoyancy and transfer momentum to the surrounding sludge. This momentum transfer takes place due to the push force that the bubbles exert to the surrounding liquid, and the riptide effect arising from the low-pressure region created by the motion of the bubbles. This model successfully described a laboratory-scale setup with a much reduced amount of empirical information when compared to the Euler-Euler model. Validations were performed through Particle Image Velocimetry [25] and Positron Emission Particle Tracking [26] techniques.

Sludge is opaque, corrosive and biochemically hazardous: this makes experiments difficult to perform and therefore makes the use of CFD more valuable, but for the same reason it makes also the process of validation more difficult. The only experiments—and, consequently, validations—reported in the literature on full-scale anaerobic digesters consist of the introduction of a tracer fluid at the inlet and its detection at the outlet [14,15]. They are costly experiments and only give a "black box" representation of the flow through the digester. Other approaches consist of comparing dimensionless groups calculated from specifications such as the power absorbed by the impeller [27–29]. Craig et al. [19] and Hurtado et al. [20] reported the validation performed by Meroney and Colorado [14], but did not perform any of their own. An alternative approach consists of providing a validation for a CFD model through laboratory-scale experiments, and then, applying the validated model to a set of full-scale scenarios. This approach has the advantage of informing modelling strategies involved in the full-scale simulations, such as bubble injection methods, boundary conditions or multiphase momentum transfers, and was followed in the work presented here.

Within this work, the model of Dapelo et al. [25] was applied to examine the mixing regime of a full-scale anaerobic digester. In gas-mixed digesters, biogas is taken from the top and pumped into the sludge at the base through a series of nozzles. The outcome of the simulations was analysed through a novel multi-facetted approach. First, velocity, shear rate and apparent viscosity flow patterns were considered, with the latter being examined for the first time. Then, the computational domain was divided into high, medium, low and very low shear rate zones and each zone's relative occupancy was reported, similar to how [17] considered the velocity magnitude. Finally, the concentration of a non-diffusive scalar tracer was studied. The flow patterns analysis reported for the first time the effect of non-Newtonian rheology on mixing; in particular, the issue of low-viscosity corridors was identified as a possible condition for detrimental, short-circuited mixing. The assessment of the shear rate relative occupancies showed that mixing is not significantly altered if mixing input power is lowered to a minimum acceptable level. The study of the tracer concentration made it possible to assess a mitigation strategy for the low-viscosity corridors. In practice, it was suggested to arrange a second series of concentric nozzles at a different radius from the tank centre, and to switch biogas injection between the original and the new series at regular time intervals.

2. CFD modelling

Sludge is a complex material, which displays a broad range of multiphase and rheological phenomena. In order to successfully model sludge within CFD work, it is necessary to introduce a series of assumptions and simplifications, depending on the type of sludge and the aims of the CFD study.

2.1. Multiphase dynamics

Sludge is a mixture of water, biogas, flocculant and sedimenting debris, both organic and inert. The dimensions of the debris varies from molecules to sand and grit of approximately one millimetre. The dimension of the debris can increase to centimetres, if silage or food waste are added as in the case of agricultural digesters. In addition, gas mixing introduces an additional (gaseous) phase.

Given the level of complexity, some simplifying assumptions are necessary for modelling. Firstly, no information on scum or other floating matter is available from the industrial digesters used for the full-scale modelling work presented in this article, and therefore flocculation was ignored for the sake of simplicity. Sedimentation in the digesters is known to take place over a timeframe of years, while the retention times do not exceed one month. The problem of sedimentation within anaerobic digesters is important, complex and deserving of dedicated study. However, the focus of the work presented in this article is biogas yield optimization; hence, it is reasonable to ignore sedimentation. Finally, as wastewater is screened prior to primary sedimentation, it is reasonable to assume that larger debris is removed, and only fragments of the order of one millimetre are present in sewage sludge. As the computational mesh size was expected to be much larger and the trajectories of the single debris were of no interest in the analysis, it was natural to consider sludge as a single phase. The biogas bubbles constituted an obvious exception, as it was their motion that generated the sludge flow patterns.