Implementation of a momentum-consistent actuator line model for anaerobic digester flow simulations

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Background

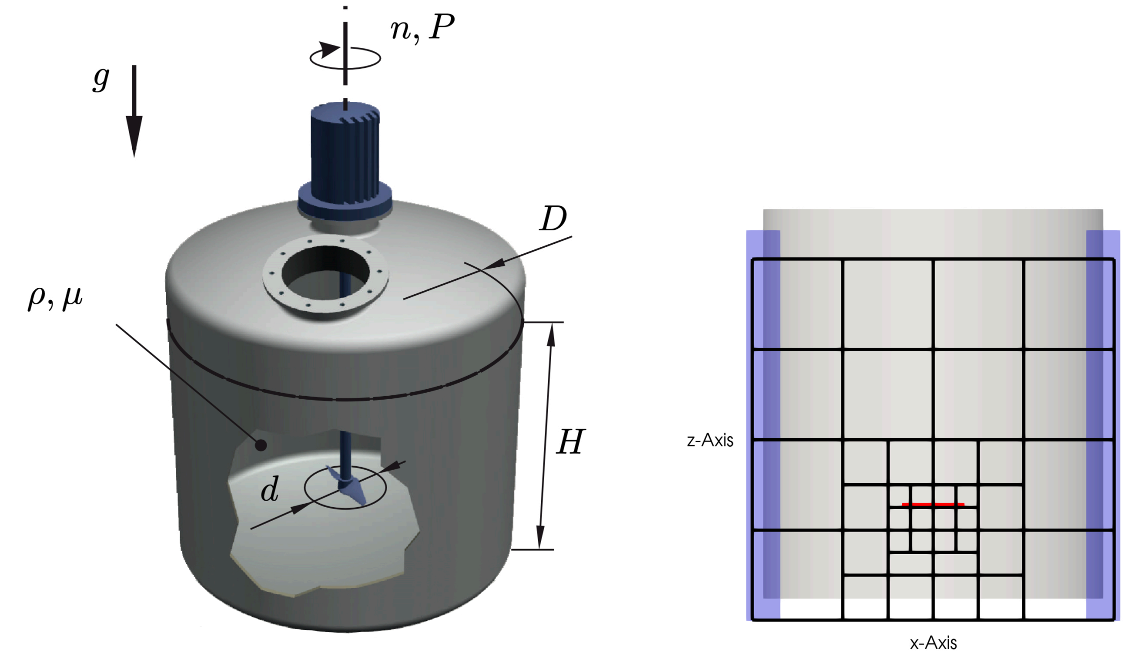
Wastewater treatment plays a critical role in safeguarding both the environment and human health, and its importance has been magnified by rapid global population growth. As a byproduct wastewater treatment produces biologically active sludges, which need to be treated and stabilised before further processing or final disposal. Large wastewater treatment plants make use of anaerobic digesters (AD) to microbially convert the biodegradable fractions of these sludges to methane and carbon dioxide. Generally, mixing inside ADs is of critical importance to ensure a homogeneous distribution of nutrients, pH and temperature for optimal operational efficiency and to prevent the excessive sedimentation. However, many wastewater plant operators are inclined to shut down their mixing units or refuse to replace them, arguing that the high investment and operating costs do not justify the benefits of mixing. To facilitate a shift towards a more sustainable and long-term oriented mindset, significantly improved quantitative understanding in the flow states and the transport processes inside ADs is essential.

Recently, a collaborative research effort in the high-fidelity investigation of the turbulent flow inside an AD was made between Professorship of Hydromechanics of TUM, and Dr.-Ing. Steinle Ingenieurgesellschaft für Abwassertechnik mbH. Consequently, mixing of wastewater sludge inside a mechanically stirred anaerobic digestion tank with a height and diameter of 15.7 m was numerically investigated applying the Large Eddy Simulation (LES) approach and our in-house turbulent flow solver MGLET. In the simulations a mechanical mixer was modelled both as an actuator disc and line that induce an axial downward flow by applying a volume force to the right-hand side of the momentum equations. It was demonstrated that the cell-based actuator line model is clearly superior to the more simplistic momentum disc approach in capturing highly unsteady nature of the flow inside the digester. Important dynamical insights including fine-scale turbulent statistics have been obtained through the (to our knowledge) first of its kind simulations [Pulber, 2023].

As examples, see fig. 1a for a conceptual mixing tank, whereas fig. 1b represents the 3D simulation domain projected onto a 2D plane through the middle of the cylindrical digester tank. Each black square depicts a grid box, which consists of $36 \times 36 \times 36$ finite volume cells. The colour distributions in fig. 2a and fig. 2b show the average velocity magnitude and turbulent kinetic energy respectively simulated with the actuator line model, together with the streamlines from the mean velocity field. Figure 3 visualises an instantaneous distribution of turbulent vortices and shear-dominated regions by means of the Q-criterion [Jeong and Hussain, 1995].

The proposed project aims to extend the above study and improve the actuator line model by defining a more consistent momentum injection rate. The implementation will be based on the open-source version of MGLET[1], in emphasis of collaboration and knowledge sharing with broader audiences. The simulation results will be compared with the outcomes from the previous investigation, and the final set of simulations should be performed for an extended parameter space and the refined grid resolutions.

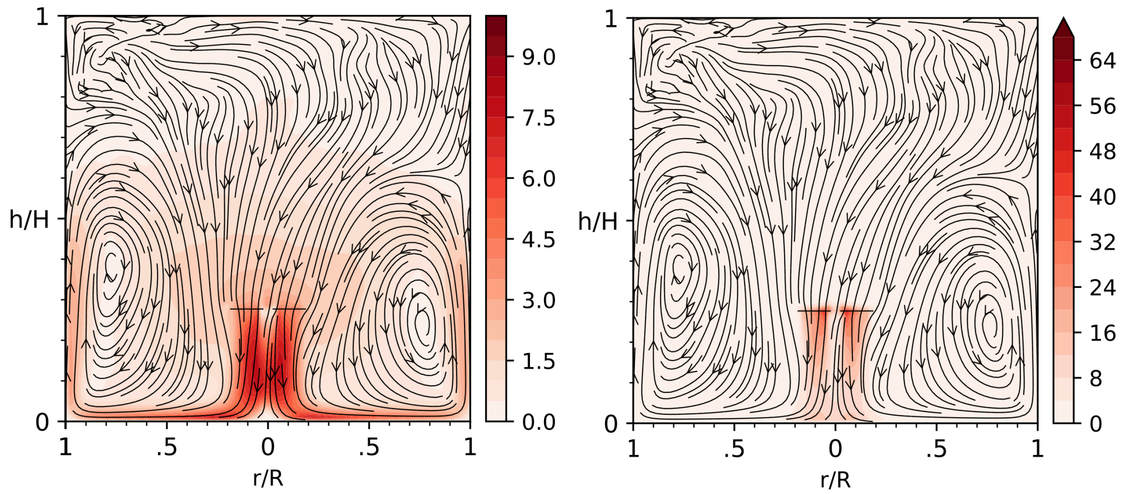
[1] `https://github.com/tum-hydromechanics/tum-mglet-base`



(a) Conceptual mixing tank [Reviol, 2021]

(b) Numerical Domain of mixing tank (blue = baffles, red = actuator, black = grid)

Figure 1: Mixing tank setup with spatial discretisation



(a) Average velocity magnitude (with streamlines)

(b) Turbulent kinetic energy (with streamlines)

Figure 2: Examplory simulation results

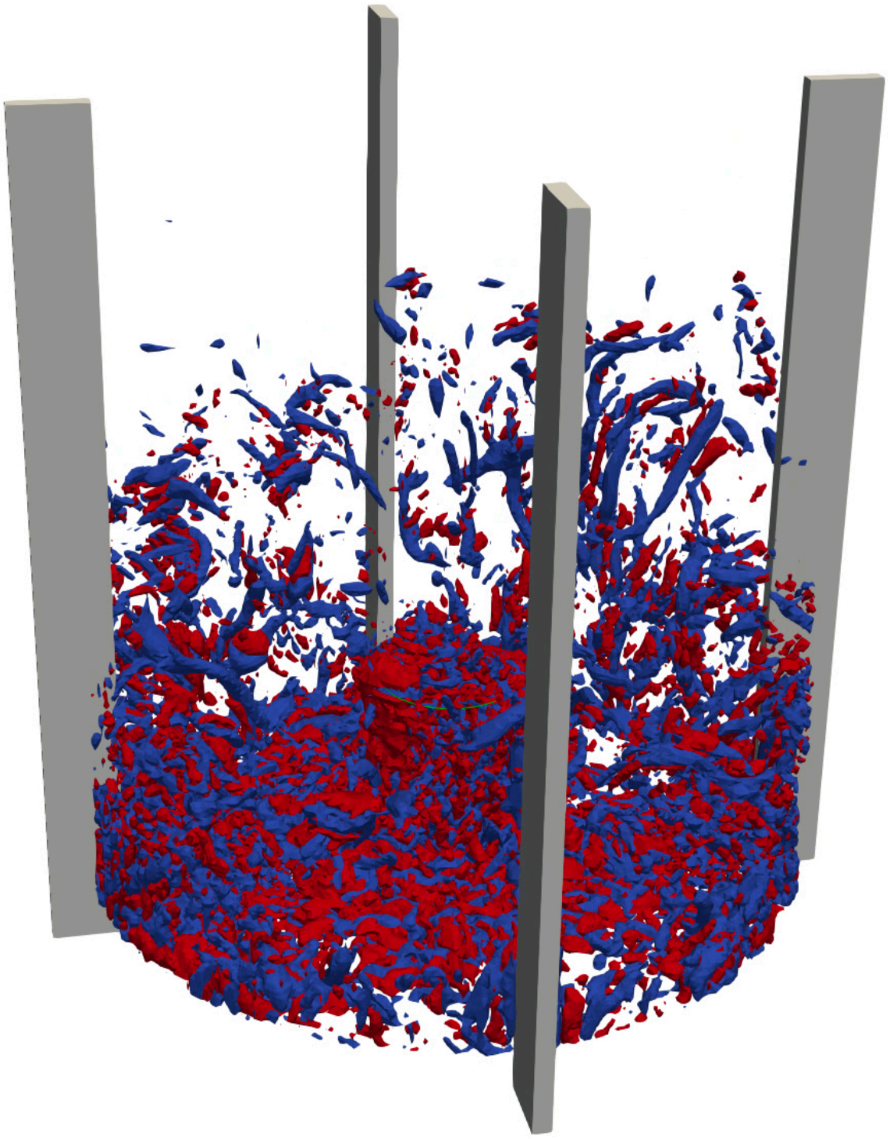


Figure 3: Q-criterion, blue = +40000, red = -40000
(snapshot from simulation video)

Tasks

- conduct literature review on related numerical as well as experimental works that investigate actuator line models (e.g. Troldborg [2009], Stevens et al. [2018])
- conduct literature review on related numerical works that investigate mechanical mixing in anaerobic digesters (e.g. Wu [2012])
- conduct literature review on related experimental works that investigate mixing in stirred vessels (e.g. Ascanio [2015], Kresta et al. [2015])
- develop and implement a momentum-preserving actuator line model using the open-source version of MGLET
- validate the implementation, document
- perform a series of LES simulations and compare the results with the ones from the previous implementation

Required skills

- basic knowledge in fluid dynamics and CFD
- basic knowledge in UNIX/Linux system
- experience in scripting languages (e.g. MATLAB, Python, R)
- sufficient communication skill in English

Recommended skills

- interest in waste water treatment
- basic knowledge in compiled languages (e.g. FORTRAN, C/C++)
- experience in CFD application (e.g. OpenFOAM, Fluent)

Benefits for applicant

- interdisciplinary experience (university & industry)
- in-depth supervision in wastewater treatment
- in-depth supervision in turbulence research
- practical experience in CFD
- practical experience in scientific and high-performance computing

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References

Gabriel Ascanio. Mixing time in stirred vessels: A review of experimental techniques. *Chinese Journal of Chemical Engineering*, 23(7):1065–1076, 2015.

Jinhee Jeong and Fazle Hussain. On the identification of a vortex. *J. Fluid Mech.*, 285(-1): 69–94, apr 1995. ISSN 0022-1120. doi:10.1017/S0022112095000462. URL `http://journals.cambridge.org/abstract{_}S0022112095000462`.

Suzanne M Kresta, Arthur W Etchells III, David S Dickey, Victor A Atiemo-Obeng, et al. *Advances in industrial mixing: a companion to the handbook of industrial mixing*. John Wiley & Sons, 2015.

Eduard Pulber. LES of anaerobic digester mixing using the Actuator Line Model. Master's thesis, Technical University of Munich, 2023.

Thomas Reviol. *A design process for propellers for the agitation of high viscous fluids based on the design analysis of wind turbine blades*. PhD thesis, Technische Universität Kaiserslautern, 2021.

Richard JAM Stevens, Luis A Martínez-Tossas, and Charles Meneveau. Comparison of wind farm large eddy simulations using actuator disk and actuator line models with wind tunnel experiments. *Renewable energy*, 116:470–478, 2018.

Niels Troldborg. Actuator line modeling of wind turbine wakes. 2009.

Binxin Wu. Large eddy simulation of mechanical mixing in anaerobic digesters. *Biotechnology and Bioengineering*, 109(3):804–812, 2012.