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Optimization of the Mixing in a Gas-lift Anaerobic Digester of Municipal Wastewater Sludge

D. Baveli Bahmaei[1], Y. Ajabshirchi[2], Sh. Abdollahpour[3*], S. Abdanan Mehdizadeh[4]

1- PhD Student, Department of Biosystems Engineering, Faculty of Agriculture, University of Tabriz, Tabriz, Iran
2- Professor, Department of Biosystems Engineering, Faculty of Agriculture, University of Tabriz, Tabriz, Iran
3- Associate Professor, Department of Biosystems Engineering, Faculty of Agriculture, University of Tabriz, Tabriz, Iran
4- Associate Professor, Department of Mechanics of Biosystems Engineering, Faculty of Agricultural Engineering and Rural Development, Agricultural Sciences and Natural Resources University of Khuzestan, Ahvaz, Iran
(*- Corresponding Author Email: shams@tabrizu.ac.ir)

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Abstract

This research aims to optimize the mixing process in gas-lift anaerobic digesters of municipal sewage sludge since mixing and maintaining uniform contact between methanogenic bacteria and nutrients is essential. Wastewater municipal sludge sampling was performed at the Ahvaz West treatment plant (Chonibeh, Iran) during the summer of 2022. A Computational Fluid Dynamics (CFD) model was implemented to simulate, optimize, and confirm the simulation process using ANSYS Fluent software 19.0. The velocity of the inlet-gas into the digester was determined and a draft tube and a conical hanging baffle were added to the digester design. Different inlet-gas velocities were investigated to optimize the mixing in the digester. Furthermore, turbulence kinetic energy and other evaluation indexes related to the sludge particles such as their velocity, velocity gradient, and eddy viscosity were studied. The optimal inlet-gas velocity was determined to be 0.3 ms^{-1}. The simulation results were validated using the Particle Image Velocimetry (PIV) method and the correlation between CFD and PIV contours was statistically sufficient (98.8% at the bottom corner of the digester's wall). The results showed that the model used for simulating, optimizing, and verifying the simulation process is valid. It can be recommended for gas-lift anaerobic digesters with the following specifications: cylindrical tank with a height-to-diameter ratio of 1.5, draft tube-to-digester diameter ratio of 0.2, draft tube-to-fluid height ratio of 0.75, the conical hanging baffle distance from the fluid level equal to 0.125 of the fluid height, and its outer diameter-to-digester diameter of 2/3.

Keywords: Computational Fluid Dynamics (CFD), Digestion, Particles Image Velocimetry (PIV), Simulation

Introduction

The performance of an anaerobic digester is affected by several factors, including the retention time of the substrate within the digester and the degree of contact between the incoming substrate and the viable bacterial population. These parameters are determined by the flow pattern, or mixing, in the digester. Complete mixing of the substrate within the digester facilitates the uniform distribution of organisms and heat transfer. This is considered to be essential in high-rate anaerobic digesters (Sawyer & Grumbling, 1960; Meynell, 1976).

Three methods for mixing in anaerobic digesters include gas mixing, mechanical mixing, and pumped recirculation liquid. Gas

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mixing can be performed using either unconfined or confined methods. In unconfined systems, biogas collected at the top of the digester is compressed and discharged through bottom diffusers or top-mounted lances (McFarland, 2001). To make the four gas mixing designs (Bottom diffusers, Gas lift, Cover mounted lances, and Bubble guns) comparable, MEL= 5 Wm^{-3} at TS= 5.4% was used to determine the velocity of the inlet gas. In confined systems, the biogas is released through tubes. The gas lift method in a confined system produces the highest average velocity (0.080 ms^{-1}) under the same mixing power (5 Wm^{-3}). In other words, mixing with the gas lift requires the lowest mixing power under the same average velocity of the flow field, and is the preferred method (Wu, 2014).

The flow pattern, or mixing, inside gas-mixed digesters is affected by several factors including the biogas recycling rate, the clearance of the draft tube at the bottom, the ratio of the draft tube to tank diameter, the slope of the hopper bottom, the position and design of the biogas injection (sparger), and the solids loading rate (Karim *et al*., 2005). Wei, Uijttewaal, Spanjers, Lier, & Kreuk (2023) assessed the impact on the treated sludge's rheology as an important factor affecting the flow optimization and mixing characterization in a full-scale biogas-mixed digester.

Conducting experiments to evaluate the effect of these parameters on mixing in the digester is time-consuming and costly. Therefore, simulation software like ANSYS Fluent is a suitable tool for designing and optimizing mixed gas anaerobic digesters. Wu (2010) presented an Eulerian multiphase flow model for mixing gas in digesters and proposed that the Shear Stress Transport (SST) k–w model with Low-Reynolds corrections would be an appropriate turbulence model to solve gas and non-Newtonian two-phase flows.

Researchers use different indexes to assess the performance of their simulations and to be able to evaluate simulations performed with experimental data. Varma & Al-Dahhan (2007) measured the turbulence kinetic energy and the velocity. Karim, Thoma, & Al-Dahhan (2007) measured the magnitude of axial velocity. Wu (2010) studied the velocity contour, Wu (2014) used the average velocity and the uniformity index of velocity to evaluate the mixing performance, and Daplo *et al*. (2015) used the magnitude of velocity along the vertical axis.

Validating the CFD simulation results is a necessary step. Tracer and non-invasive techniques are the traditional methods of studying gas mixing in anaerobic digesters and are usually used for verifying the CFD simulation results. Vesvikar & Al-Dahhan (2016), Karim *et al*. (2007), and Wu (2010) validated their models against the digester reported by Karim, Varma, Vesvikar, & Al-Dahhan (2004) and verified the flow fields with the measured data from Computer Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT), a non-invasive technique. Dapelo, Alberini, & Bridgeman (2015) used Particle image velocimetry and a high-speed camera to validate an Euler-Lagrange CFD model of unconfined gas mixing in an anaerobic digestion. Hu *et al*. (2021) proposed a novel approach for experimental quantification of mass transfer in a high-solid anaerobic digestor's mixing process using Laser Induced Fluorescence (LIF) technique in a mixing tank equipped with multistage impellers. Flow field was investigated for a better illustration of the mass transfer, thus Particle Image Velocimetry (PIV) and Computational Fluid Dynamics (CFD) techniques were conducted for flow field measurement.

The quality of mixing in a gas-lift anaerobic digester depends on various factors, such as the dimensions of the draft tube and the conical hanging baffle, the position of the baffle relative to the digester bottom, and the angle of the baffle. Baveli Bahmaei, Ajabshirchi, Abdollah poor, & Abdanan Mehdizadeh (2022) performed a numerical study and examined the influence of these factors on the mixing performance using ANSYS Fluent software. The present paper extends their work by optimizing the mixing using the same digester configuration with different inlet-gas velocities. The evaluation criteria for optimization are average velocity, turbulence kinetic energy, average velocity gradient, and eddy viscosity of the sludge. The numerical results are validated using particle image velocimetry (PIV).

Materials and Methods

Methodology

The Computational Fluid Dynamics (CFD) simulations were conducted using ANSYS Fluent software for modeling the inlet-gas anaerobic digester. The initial step involved determining the inlet-gas velocity. Subsequently, the effects of adding the draft tube and the conical hanging baffle to the digester design were analyzed. The optimization of mixing within the digester was achieved by varying the inlet-gas velocities and assessing the change in the evaluation indexes. The turbulence kinetic energy and the behavior of the sludge particles, namely their velocity, velocity gradient, and eddy viscosity were the studied indexes. The contours of the resulting evaluation indexes were analyzed to determine the optimal velocity for mixing. Following the simulation results, a transparent anaerobic digester was constructed and loaded with municipal sewage sludge, operating at optimal inlet-gas velocity. The Particle Image Velocimetry (PIV) method was employed to compare the evaluated index contours of PIV with those of the CFD and to validate the CFD simulation outcomes. A schematic representation of the simulation, optimization, and verification process is presented in Fig. 1.

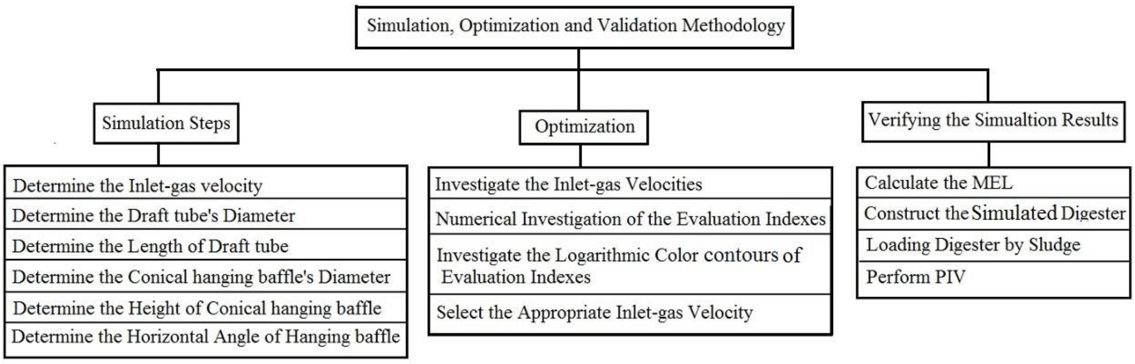


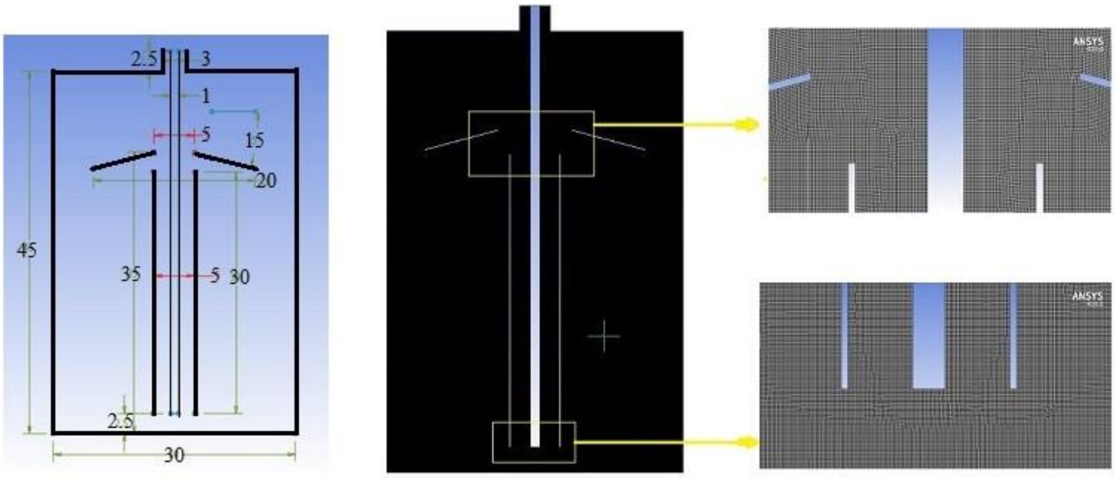
Fig.1. Steps used for the model simulation, optimization, and verification

CFD simulation

A commercial CFD software, ANSYS Fluent (version 19.0) was utilized to create a two-dimensional geometry in the design modeler, generate mesh, and solve the two-phase Eulerian model flow using the Eulerian multiphase approach. This two-dimensional model can be applied to digesters that are symmetrical around their vertical axis, like cylinders (Yang *et al*., 2015). Simulations were performed under unsteady-state conditions using Double Precision, Serial, Pressure-Based, and Implicit settings. The two-phase liquid-gas Eulerian Model of Viscous-SST k-omega (with sludge as the primary phase and biogas as the secondary phase) and low-Re correction were employed. At each time step, the iterative calculation was accepted as converged if all residuals fell below 1×10^{-3}. Final convergence was achieved when the average velocity of the liquid phase remained unchanged (Wu, 2014).

Geometry, Computational domain, and mesh

The geometry of the digester used in this research is based on a previously simulated geometry by Baveli Bahmaei *et al*. (2022) and the six steps of digester simulation are outlined in Fig. 1. The digester consists of a cylindrical tank with a flat bottom, height of 45 cm, and a diameter of 30 cm which results in a height to diameter ratio of 1.5. The draft tube diameter to digester diameter is 0.2 (5 cm) and the draft tube height to fluid height is 0.75 (30 cm). The conical hanging baffle distance from the fluid level is equal to 0.125 of the fluid height (5 cm), its outer diameter to digester diameter is 2/3 (20 cm) and has a horizontal angle of 15 degrees (Fig. 2). The mesh size function was set to curative, max face size was set to 0.0007, and the number of nodes and elements were 267083 and 264281, respectively. Discretization error estimation was calculated based on the method proposed by Celik *et al*. (2008).



(a) (b)

Fig.2. The digester used for mixing optimization: (a) Geometry, and (b) Meshing; values are in cm and degrees

Evaluation indexes

Sludge velocity

The velocity contour and streamlines were utilized in steps 1 to 6 of the simulation (Fig. 1) to determine the inlet-gas velocity, draft tube, and conical hanging baffle characteristics. The uniformity of contours and streamlines, as well as their contribution to uniformity within the digester, were considered (please refer to Baveli Bahmaei *et al*. (2022) for more details). Sludge velocity was used as one of the validation indexes for investigating the mixing quality in a simulated gas-lift anaerobic digester and for selecting the appropriate inlet-gas velocity. The velocity value was compared with the sludge's sedimentation velocity. Whenever the velocity was less than the sedimentation velocity, it indicated that the sludge particles would sediment in the digester.

Sludge velocity gradient

The sludge velocity gradient was used as a validation index for assessing the quality of mixing. This parameter is defined as a custom field function in the main menu of ANSYS Fluent as shown in Eq. 1 and measures the local velocity gradient of a mixture in multiphase flow using the SST k-w model as defined by Wu (2014).

$$G_L = \sqrt{\frac{\rho\omega\beta^* k}{\eta}} \tag{1}$$

Where ρ and η are the density and the non-Newtonian viscosity in the liquid phase, respectively. β^* is 0.09 and ω and k are the specific dissipation rate and the turbulence kinetic energy of the mixture, respectively. G_L is the local velocity gradient and will be called the velocity gradient hereafter.

Turbulence kinetic energy

Turbulence kinetic energy is used as one of the indexes that investigates the mixing quality in simulation results and is defined in Eq. 2.

$$G_k = -\rho\overline{u_i'u_j'}\frac{\partial u_j}{\partial x_i} \tag{2}$$

Reynolds stresses ($-\rho\overline{u_i'u_j'}$) is defined in Eq. 3 using the Boussinesq hypothesis related to the mean velocity gradient.

$$-\rho\overline{u_i'u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \tag{3}$$

Where μ_t is the turbulent viscosity, k is the turbulence kinetic energy, and u (Eq. 4) is the velocity component.

$$u_i = \bar{u}_i + u_i' \tag{4}$$

Where $\bar{u}_i$ and u_i' are the mean and fluctuating velocity components respectively (i=1, 2, 3).

Sludge eddy viscosity

Mixing quality can also be investigated using sludge eddy viscosity. Sludge eddy viscosity is the proportionality factor in describing the turbulent energy transfer in the form of moving eddies, giving rise to tangential stresses. Eddy viscosity is defined in Eq. 5 (Menter, 1993):

$$v_T = \frac{\mu_T}{\rho} = \frac{k}{\omega} \tag{5}$$

Mixing Energy Level

The Mixing Energy Level (MEL) can be estimated using Eq. 6 (Stukenberg, Clark, Sandino, & Naydo, 1992).

$$MEL = \frac{E}{V} \tag{6}$$

Where V denotes the effective volume of the digester and E denotes the energy consumption. Energy consumption for the gas-sparging (Eq. 7) was evaluated based on the power input formula (McFarland, 2001).

$$E = P_1 \cdot Q \cdot ln\left(\frac{P_2}{P_1}\right) \tag{7}$$

Where Q denotes the gas flow rate, and P_1 and P_2 are the absolute pressure in the tank headspace and at the gas-sparging inlet, respectively.

Particle image velocimetry

According to the methods used by Raffel, Willert, & Kompenhans (1998) and Dawkins, Cain, & Roberts (2012), the particle image velocimetry (PIV) process involves taking two images (I_1 and I_2) separated by time Δt. Both images were then divided into smaller regions, also known as sub-windows, interrogation-windows, or interrogation-regions. Each sub-window in the first image is compared with the corresponding sub-window in the second image. The sub-window with position indexes i and j in the first image is denoted as $I_1^{i.j}$ and the corresponding sub-window in the second image is denoted as $I_2^{i.j}$. Afterward, a search algorithm was performed to identify a displacement pattern in $I_1^{i.j}$. To do this, the squared Euclidean distance between the two sub-windows was defined in Eq. 8.

$$R_e(s.t) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left[I_1^{i.j}(m.n) - I_2^{i.j}(m-s.n-t)\right]^2 \tag{8}$$

This formula calculates the sum of the squared differences between all of the possible $I_1^{i.j}$ and $I_2^{i.j}$ sub-windows. In other words, it looks for the position where the sub-windows were the "least unlike". Expanding the square parentheses in Eq. 8 would result in Eq. 9.

$$\begin{aligned} R_e(s.t) &= \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left[I_1^{i.j}(s.t) - I_2^{i.j}(m-s.n-t)\right]^2 \\ &= \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I_1^{i.j}(m.n)^2 - 2I_1^{i.j}(s.t) \cdot I_2^{i.j}(m-s.n-t) + I_2^{i.j}(m-s.n-t)^2 \end{aligned} \tag{9}$$

It should be noted that the first term, $I_1^{i.j}(m.n)^2$, is a constant since it does not depend on s or t. The last term, $I_2^{i.j}(m-s.n-t)^2$, depends on s, t, and only the second image. To sum up, only the middle term deals with both of the images and this term (without the -2), as defined in Eq. 10, is usually referred to as cross-correlation (or circular cross-correlation).

$$R(s.t) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I_1^{i.j}(m.n) \cdot I_2^{i.j}(m-s.n-t) \tag{10}$$

Results and Discussion

The mixing conditions in the digester were investigated using different inlet-gas velocities. Simulations were performed using inlet-gas velocities of 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 ms^{-1} to study the mixing quality in a cylindrical digester, details of which are indicated in Fig. 2.

Investigation of the evaluation indexes

The values of the investigated indexes and Mixing Energy Levels (MEL) for each of the gas-inlet velocities are shown in Table 1.

Table 1- Evaluated indexes and MEL for verifying the mixing quality in the gas-lift anaerobic digester for different inlet-gas velocities

Inlet-gas velocity (ms^{-1})	**Sludge velocity (ms^{-1})**			**Turbulence kinetic energy (m^{2}s^{-2})**		**Average velocity gradient (s^{-1})**		**Sludge eddy viscosity (Pa s)**		**MEL**
	min. E-6	**Ave.**	**max.**	**min. E-14**	**max.**	**min. E-6**	**max.**	**min. E-17**	**max.**	
0.05	2.23	0.0236	0.30	1.0	3.8E-07	6.6	0.07	5.85	3.0E-08	0.505
0.1	10.72	0.0291	0.43	1.0	8.3E-07	18	0.14	5.91	8.0E-07	1.01
0.2	1.40	0.0287	0.66	1.0	64E-07	29	0.29	7.75	1.8E-05	2.02
0.3	2.61	0.0322	0.83	8.1	0.011	359	285.23	64.50	73E-05	3.03
0.4	3.92	0.0375	1.16	120	0.17	1398	449.68	974.12	0.65	4.04
0.5	2.26	0.0443	1.29	4400	0.21	8370	536.97	34911.40	0.63	5.05
0.6	9.53	0.0453	1.49	1900	0.26	5461	672.24	14858.50	0.74	6.06

Sludge velocity

Table 1 shows the minimum, average, and maximum values of sludge velocity for different inlet-gas velocities. The minimum sludge velocities were achieved in local and face options. The maximum velocity appears inside the draft tube, while the minimum value appears near the digester walls and at the bottom. The maximum velocity varies from 0.3 to 1.49 ms^{-1} for the studied inlet velocities and the average velocity only varies about 0.022 ms^{-1}. This indicates that the velocity of the particles in all internal parts of the digester does not increase proportionally with the increase in the inlet-gas velocity. This could be due to the formation of short-circuiting in the digester in areas where more mixing takes place. Because sludge is a non-Newtonian fluid and more mixing causes more decrease in its viscosity.

Since the maximum sedimentation velocity in sludge particles is 4.7E-5 ms^{-1} (Baveli Bahmaei *et al.*, 2022), to prevent particle sedimentation, the minimum sludge velocity should be greater than 4.7E-5 ms^{-1}. However, when considering the minimum fluid velocities at different inlet-gas velocities, this goal is not achieved thoroughly at any of the studied inlet-gas velocities. On the other hand, increasing the inlet-gas velocity in gas-lift anaerobic digesters is limited due to the biological nature of anaerobic digestion. Therefore, a balance must be struck between increasing the mixing rate and reducing the particle sedimentation to maintain the conditions that prevent disruption of the biological process of anaerobic digestion.

Turbulence kinetic energy

The minimum and maximum values of turbulence kinetic energy for different inlet-gas velocities are shown in Table 1. Minimum turbulence kinetic energy varies between 1E-14 and 4.4E-11 m^{2}s^{-2} for inlet-gas velocities of

0.05 and 0.5 ms^{-1}, respectively and the maximum varies from 3.8E-7 m^2s^{-2} in 0.05 ms^{-1} velocity to 0.26 m^2s^{-2} in 0.6 ms^{-1} velocity. The produced turbulence kinetic energy is very low for the first three inlet-gas velocities (0.05, 0.1, and 0.2 ms^{-1}), has a medium value for the inlet-gas velocity of 0.3 ms^{-1}, and is high with close values for the remaining three velocities (0.4, 0.5, and 0.6 ms^{-1}). Turbulence kinetic energy of different inlet-gas velocities is presented in Fig. 3. Higher turbulence kinetic energy causes more intense mixing and the destruction of flocs, which disrupts the anaerobic digestion process.

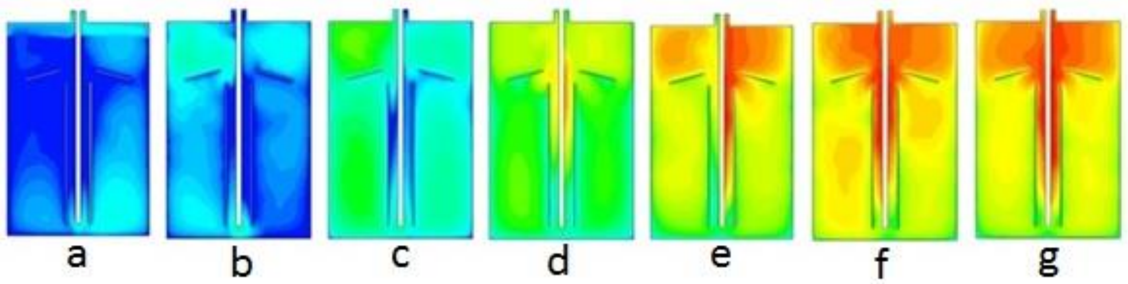


Fig.3. Turbulence kinetic energy contours (logarithmic color) for different inlet-gas velocities; (a) 0.05, (b) 0.1, (c) 0.2, (d) 0.3, (e) 0.4, (f) 0.5, and (g) 0.6 ms^{-1}

Average velocity gradient

The average velocity gradient generates the turbulence kinetic energy and therefore, their results are similar. Results of the average velocity gradient for the studied inlet-gas velocities are presented in Fig. 4. The minimum average velocity gradient varies from 6.6E-12 to 84E-10 s^{-1} for different inlet-gas velocities (Table 1). The maximum average velocity gradient varies from 0.07 to 672.24 s^{-1} for inlet-gas velocities of 0.05 to 0.6 ms^{-1}. The average velocity gradient is low for the first three inlet-gas velocities (0.05, 0.1, and 0.2 ms^{-1}) and high for the last three of them (0.4, 0.5, and 0.6 ms^{-1}). It has a medium value for the inlet-gas velocity of 0.3 ms^{-1}.

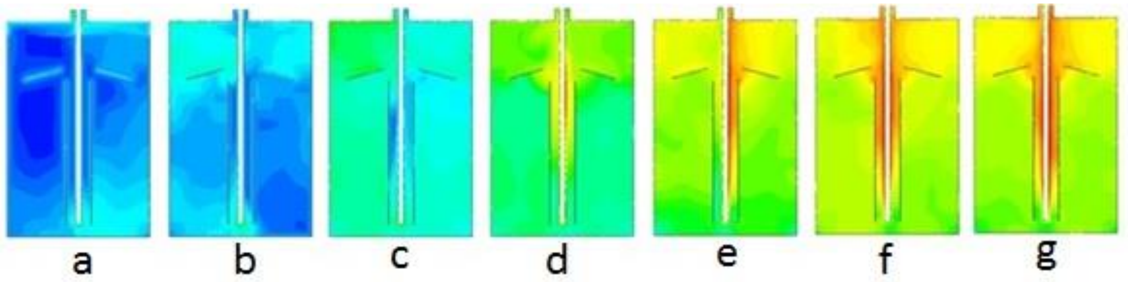


Fig.4. Average velocity gradient contours (logarithmic color) for different inlet-gas velocities; (a) 0.05, (b) 0.1, (c) 0.2, (d) 0.3, (e) 0.4, (f) 0.5, and (g) 0.6 ms^{-1}

Sludge eddy viscosity

Sludge eddy viscosity is a proportionality factor describing the turbulent energy transfer as a result of moving eddies, giving rise to tangential stresses. The results of sludge eddy viscosity for different inlet-gas velocities are presented in Fig. 5. The minimum and maximum values of sludge eddy viscosity for different inlet-gas velocities are shown in Table 1. Minimum sludge eddy viscosity varies from 5.85E-17 to 14.86E-14 Pa s, and the maximum varies from 3.0E-8 to 0.74 Pa s as the velocity increases from 0.05 to 0.6 ms^{-1}. Sludge eddy viscosity produced by the first four inlet-gas velocities (0.05, 0.1, 0.2, and 0.3 ms^{-1}) has low values and the last three velocities (0.4, 0.5, and 0.6) are high and have close values. Higher eddy viscosity indicates higher amounts of moving eddies and high tangential stresses in the sludge that can lead to the destruction of flocs and disrupt the biological process of digestion. Therefore, in terms of sludge eddy viscosity index, an inlet-gas velocity of 0.3 ms^{-1} was appropriate.

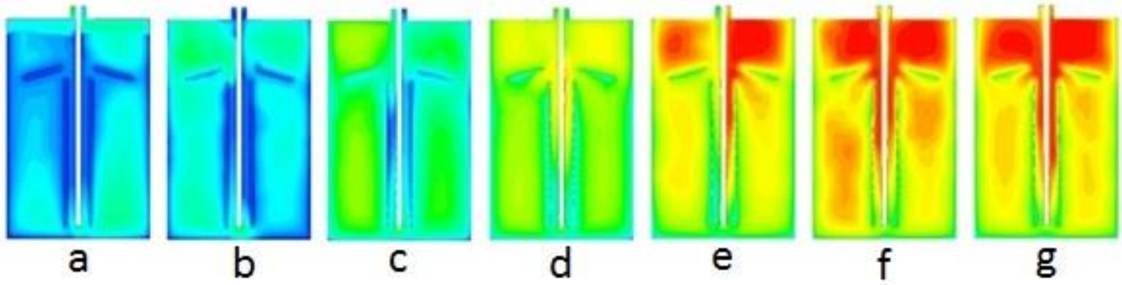


Fig.5. Sludge eddy viscosity contours (logarithmic color) for different inlet-gas velocities; (a) 0.05, (b) 0.1, (c) 0.2, (d) 0.3, (e) 0.4, (f) 0.5, and (g) 0.6 ms^{-1}

Selecting the appropriate inlet-gas velocity

The investigation of the evaluation indexes revealed that a balance between the mixing intensity and sludge sedimentation must be maintained. Higher mixing intensity can result in broken flocs and impairs anaerobic digestion. If a high inlet-gas velocity is selected for mixing, it can disrupt the biological process of anaerobic digestion. On the other hand, if the velocity is too low, the particle sedimentation rate will increase and proper mixing will not occur.

Analyzing sludge velocity, turbulence kinetic energy, average velocity gradient, and eddy viscosity showed that selecting an inlet-gas velocity of 0.3 ms^{-1} is the most appropriate option. The results of CFD simulations for the investigated evaluation indexes for an inlet-gas velocity of 0.3 ms^{-1} are shown in Fig. 6.

The sludge velocity contour presented in Fig. 6 indicates that in most of the digester zones, zones 4 and 5 with yellow and red colors, the particle velocity is greater than 1.75E-3 ms^{-1}. Considering the maximum sludge sedimentation velocity for the largest sludge particle (47 E-6 ms^{-1} for particle size of 2 mm) (Baveli Bahmaei *et al.*, 2022), particle sedimentation in the digester is very low. Even in zone 3 with a green color, the sludge velocity was larger than 9.9E-5 ms^{-1}. Only in zones 2 and 1 where sludge velocity is lower than 9.9E-5 ms^{-1}, there is a possibility of sedimentation of particles larger than 0.85 mm, which comprise 17% of the total particles in the sludge (Baveli Bahmaei *et al.*, 2022). However, zones 1 and 2 cover a very small percentage of the digester volume, indicating good mixing conditions.

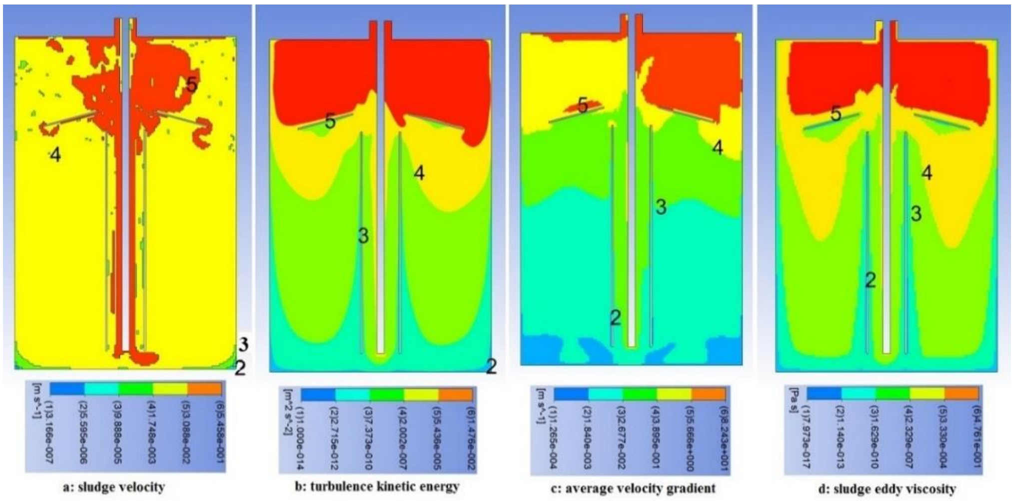


Fig.6. The resulting evaluation indexes in the digester; gas inlet velocity= 0.3 ms^{-1}

Gas-sparging intensity determines the amount of injected biogas for mixing and is an important operational assessment parameter. Based on the compressor's capacity, the injected biogas flow rate for the inlet-gas velocity of 0.3 ms^{-1} was calculated to be 0.085 m^3h^{-1} in the studied digester. In the actual experiment, 0.085 m^3h^{-1} yielded a *MEL* of 3.3 Wm^{-3}, which was close to 2.2 Wm^{-3} that was reported in another full-scale gas-mixed digester (Dapelo & Bridgeman, 2018). However, this value is still much lower than the recommended range (5-8 Wm^{-3}) needed for proper mixing (U. EPA, 1979). To match the recommended range, the inlet-gas velocity should be increased to over 0.7 ms^{-1}. This alteration requires additional investment in the studied digester, and the technical adjustments and the much higher energy consumption may challenge the biogas production process altogether. Therefore, increasing the inlet-gas velocity is not an efficient strategy for enhancing the flow and mixing, and the recommended *MEL* criterion appears unsuitable for the studied digester.

Particle image velocimetry results

To verify the results of CFD simulations, a digester was constructed with transparent material so that photos of its inside could be easily taken. The transparent pilot-scale digester was built with the optimal characteristics obtained from the CFD simulation results and is shown in Fig. 7. It is made of Polymethyl methacrylate with a thickness of 1.5 mm.

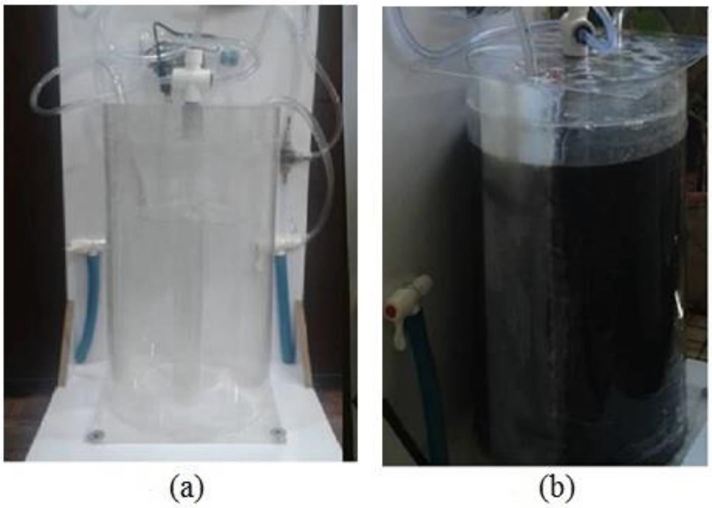

(a) (b)

Fig.7. The transparent digester: (a) empty and (b) filled with municipal wastewater sludge

After selecting the inlet-gas velocity of 0.3 ms^{-1} as the most appropriate inlet-gas velocity, the particle image velocimetry (PIV) was performed. Due to the very dark color of the sludge (see Fig. 7b) and the indistinct particles in the images, a narrow strip of glitter was used along the height of the digester for PIV. The calculated sludge velocity, average velocity gradient, and sludge streamlines are shown in Fig. 8. The average velocity gradient (Fig. 8a) varies from 1.8E-6 to 34.3E-6 s^{-1}, while sludge velocity (Fig .8b) varies from 0 to 1.1×10^{-3} ms^{-1}. The maximum value of average velocity gradient and sludge velocity occurred between 20 to 35 cm from the top of the digester, and the streamline distance is maximum in this zone. As shown in Fig. 8b, in most parts of the digester's wall, the sludge velocity is greater than the minimum sludge velocity achieved from the simulations, indicating that particle sedimentation does not occur. Observing the velocity contour obtained from the PIV shows that the lowest velocity is at the junction of the wall and the bottom of the digester (Fig. 8b). Furthermore since there are no streamlines in this area, the streamlines (Fig. 8c) confirm the results of CFD simulations.

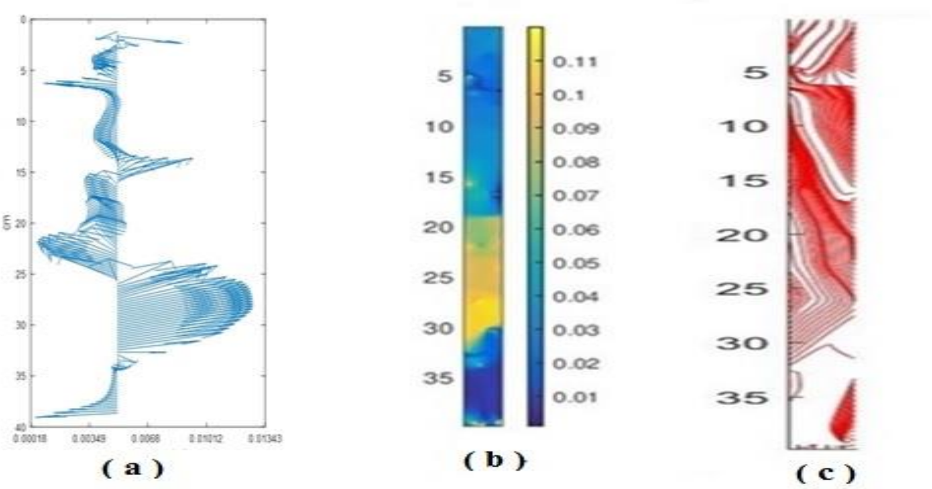


Fig.8. Results of particle image velocimetry (PIV) for inlet gas velocity of 0.3 ms^{-1}: (a) average velocity gradient (s^{-1}), (b) sludge velocity (cms^{-1}), and (c) streamline of particles in sludge

Conclusion

This study aimed to optimize mixing in gas-lift anaerobic municipal sewage sludge digesters. The model was built, simulated, and optimized, and the results were subsequently confirmed by building and testing the actual digester.

To optimize mixing in the digester, different inlet-gas velocities were investigated, and sludge particle velocity, the gradient of sludge particle velocity, the turbulence kinetic energy, and the eddy viscosity of the sludge particles were evaluated. The contours of these evaluation indexes were analyzed to determine the appropriate velocity for optimal mixing, which was found to be 0.3 ms^{-1}.

Based on the simulation results and particle sedimentation velocity in the sludge, it was expected that the sedimentation of the particles would not occur in the digester at the selected inlet-gas velocity; except for large sludge particles in the small triangular section near the junction of the wall and the bottom of the digester. Subsequently, a transparent anaerobic digester was constructed and loaded with municipal sewage sludge, operating at the optimal inlet-gas velocity of 0.3 ms^{-1}. Particle Image Velocimetry (PIV) was employed to calculate sludge velocity, average sludge gradient, and streamlines and to validate simulation outcomes. According to the results of the Particle Image Velocimetry (PIV), in most parts of the digestion wall length, the sludge velocity is greater than the minimum sludge velocity achieved in the simulations. Moreover, the velocity contour obtained from the PIV shows that the lowest velocity is at the junction of the wall to the bottom of the digester and streamlines also showed that there are no streamlines in this area. Overall, the PIV method successfully validated the CFD simulation and showed sufficient agreement between the simulation and the experiment. The results showed that the model used for simulating, optimizing, and verifying the simulation process was successful and can be recommended for similar gas-lift anaerobic digesters, which consist of a cylindrical tank with a flat bottom and a height-to-diameter ratio of 1.5. The draft tube diameter should be 0.2 times the digester diameter and the draft tube height should be 0.75 times the fluid height. The conical hanging baffle’s distance from the fluid level should be equal to 0.125 times the fluid height, and its outer diameter should be 2/3 of the digester’s diameter.

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بهینه‌سازی هم‌زنی در هاضم بی هوازی گاز- بالابر لجن فاضلاب شهری

داود باولی بهمئی[1]، یحیی عجب شیرچی[2]، شمس اله عبداله پور[3*]، سامان آبدانان مهدی زاده[4]

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چکیده

این تحقیق با هدف بهینه‌سازی هم‌زنی در هاضم‌های بی‌هوازی گاز–بالابر لجن فاضلاب شهری انجام شد، زیرا همزنی یکنواخت برای ارتباط مؤثر بین باکتری‌های متانوژن و مواد مغذی مهم است. نمونه‌برداری لجن فاضلاب شهری در تصفیه‌خانه غرب اهواز (چنیبه) در تابستان ۱۴۰۱ انجام شد. یک مدل برای شبیه‌سازی، بهینه‌سازی و تایید فرآیند شبیه‌سازی با استفاده از دینامیک سیالات محاسباتی (CFD) توسط نرم‌افزار ANSYS Fluent 19.0 ارائه شد. سرعت گاز ورودی به هاضم تعیین شد و یک لوله گاز- بالابر و بافل آویزان مخروطی به طرح هاضم اضافه شد. سرعت‌های مختلف گاز ورودی برای بهینه‌سازی اختلاط در هاضم مورد بررسی قرار گرفت و شاخص‌های ارزیابی مانند سرعت ذرات لجن، گرادیان سرعت ذرات لجن، انرژی جنبشی تلاطم و ویسکوزیته گردابی ذرات لجن مورد ارزیابی قرار گرفت. سرعت بهینه گاز ورودی ۰/۳ ms^{-1} تعیین شد. نتایج شبیه‌سازی با استفاده از روش سرعت‌سنجی تصویری ذرات (PIV) تأیید شد و درصد همبستگی کافی بین کانتورهای CFD و PIV وجود داشت (۹۸/۸٪ در محل اتصال دیواره به کف هاضم). نتایج نشان داد که مدل مورداستفاده برای شبیه‌سازی، بهینه‌سازی و تأیید فرآیند شبیه‌سازی موفق بوده است و می‌توان آن را برای هاضم‌های بی‌هوازی گاز- بالابر استوانه‌ای شکل با نسبت ارتفاع به قطر ۱/۵، نسبت قطر لوله گاز- بالابر به قطر هاضم ۰/۲، نسبت ارتفاع لوله گاز- بالابر به ارتفاع سیال ۰/۷۵، فاصله بافل آویزان مخروطی از سطح سیال ۰/۱۲۵ برابر ارتفاع سیال و قطر بیرونی بافل به قطر هاضم ۲/۳ توصیه کرد.

واژه‌های کلیدی: دینامیک سیالات محاسباتی (CFD)، سرعت‌سنجی تصویر ذرات (PIV)، شبیه‌سازی، هضم

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[1] دانشجوی دکتری، گروه مهندسی بیوسیستم، دانشکده کشاورزی، دانشگاه تبریز، تبریز، ایران
[2] استاد، گروه مهندسی بیوسیستم، دانشکده کشاورزی، دانشگاه تبریز، تبریز، ایران
[3] دانشیار، گروه مهندسی بیوسیستم، دانشکده کشاورزی، دانشگاه تبریز، تبریز، ایران
[4] دانشیار، گروه مهندسی مکانیک بیوسیستم، دانشکده مهندسی زراعی و عمران روستائی، دانشگاه علوم کشاورزی و منابع طبیعی خوزستان، اهواز، ایران
(*- نویسنده مسئول: Email: shams@tabrizu.ac.ir)

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