Improving the performance of mechanical stirring in biogas plant by computational fluid dynamics (CFD)

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Abstract: Stirring of material in biogas plant needs to be done to provide desirable contact between microorganisms and substrate which can improve digestion process. In the present study, computational fluid dynamics (CFD) was used to determine a suitable mechanical stirrer for biogas plant and simulate the flow pattern of cow manure. In order to select optimum design of impeller, three types of impeller including six-blade turbine, four-blade turbine and six-flat-blade disc turbine were evaluated. Simulations were undertaken utilizing Fluent 15.0 software with a multiple reference frame approach via standard *k*-*ε* turbulence model under steady-state conditions. According to the simulation results, six-blade turbine impeller is more appropriate than the two other impellers. The results further indicated that, this type of stirrer offers suitable mixing both at the center and on the lateral walls of the reactor, reducing dead spaces and improving mass and heat transfers inside the reactor.

Keywords: anaerobic digestion, cow manure, flow pattern, simulation, stirred tank

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1 Introduction

Biogas is a renewable energy source that is produced through anaerobic digestion of organic waste. The production of biogas is influenced by many operational parameters, including temperature, pH, stirring, organic loading rate, hydraulic retention time, etc. (Yadvika et al., 2004; Shen et al., 2013). Stirring is an important operation that homogenizes anaerobic bacteria, nutrients, and temperature throughout the reactor to maximize biogas production. The importance of mixing in achieving efficient substrate conversion has been reported by several researchers (McMahon et al., 2001; Stroot et al., 2001; Kim et al., 2002; Karim et al., 2005; Vavilin and Angelidaki, 2005; Vedrenne et al., 2008). Various methods have been proposed to undertake mixing operation within biogas reactors. Mechanical mixing, spargers and jets are common choices for stirring purposes (Kapraju et al., 2008; Karim et al., 2005).

Considering the variety of the processes and different purposes in which they are serving, stirrers have been developed with a large number of different geometries. Mechanical stirring represents one of the most efficient and inexpensive mixing methods. Although the significance of the mixing to achieve optimal process performance and biogas production is well known, an obvious agreement on a single optimal mixing regime is yet to be achieved. In-reactor mixing and contacting can be undertaken in a continuous and alternating way. Adequate mixing is important to minimize capital and operating costs, enhance process efficiency when mass transfer is limited, and hence increase overall profitability. The efficiency of the stirring process using a mechanical stirrer depends on the corresponding Reynolds number to the impeller for both laminar and turbulent flow regimes. The main mixing mechanism includes physical movement of materials among various parts of the entire body driven by the impeller rotating force. Successful accomplishment of some of stirring process stages is

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related to the way the fluid is stirred and mixed. Mixing refers to the stirring of one or more non-similar materials to obtain physical and chemical uniformity. Since diffusivity in a liquid is very limited, mixing of liquids is principally performed by stirring the liquid inside a tank. Optimal design of stirrer and mixing operation efficiency represent important factors for production quality and production costs. The flow pattern in stirred tanks is a complex phenomenon as there is a turbulent rotational flow within a zone around the impeller.

In recent years, computational fluid dynamics (CFD) methods have been increasingly substituted to empirical experiments for the evaluation of flow fields and optimal flow pattern as well as impeller and tank geometries (Shekhar and Jayanti, 2002). CFD is a technique utilized to analyze systems including fluid flow, heat transfer and associated phenomena such as chemical reactions based on computer-aided simulations (Dehghani, 2008). Being a powerful methodology, CFD covers a wide spectrum of industrial and non-industrial applications. Mechanical stirred-tank reactors are widely used in industries working with multi-phase systems. Numerous industrial applications have been reported for these reactors (Nigam and Schumpe, 1996). In 2010, Shirmohammadpour et al. (2010) investigated the mixing inside a multiple-impeller industrial reactor equipped with three marine impellers, using CFD modeling technique. Li et al. (2004) studied hydrodynamic behavior of a stirred tank equipped with a curved-shaped stirrer. Their results showed that CFD simulation can be used to properly predict radial and axial velocities. Ahmed et al. (2010) studied different flow configurations in a stirred-tank gas-liquid reactor equipped with two Rushton type turbine stirrers. Ding et al. (2010) showed that the type and rotating speed of the impeller affect the resulting flow pattern significantly, and proposed optimal impeller for bio-hydrogen production accordingly. A comparison between simulation results and experimental data indicated, clearly, that the optimized impeller could achieve better velocity distribution within the reactor at lower velocities (Ding et al., 2010). Numerous factors affect the modeling of stirred-tank reactors including adequate meshing density, spatting methods, blade rotation model, and finally, the fluid turbulence model, to name the most important ones. In spite of the fact that much research has been done on the mixing strategy in anaerobic digesters, a clear image of the effects of the mixing in anaerobic digestion in manure is not provided yet. Therefore, stirring systems are still an important component of biogas plants (Stroot et al., 2001; Karim et al., 2005). In another research, CFD was used to investigate different modes of mixing and consumed power in single and multiple digesters. Cow manure and silage maize were used as the reactor feed, with the stirred reactor serving as the digester. The results indicated that the so-called standard k-ε model outperformed other turbulence models (Zhang et al., 2016).

The effect of mixing on anaerobic digestion from manure was investigated at laboratory and pilot scales at 55ºC, wherein the effects of three mixing modes, namely continuous, alternating and minimized mixings, were studied and it was found that the mode and intensity of mixing affect anaerobic digestion of manure. The results of the research on pilot scale indicated a 7% increase in biogas performance in alternating mixing approach as compared to that of the continuous mixing approach (Kaparaju et al., 2008). In a 1.5 m^3 reactor fed by cow manure, effects of continuous and alternating mixing on biogas production performance were investigated at the controlled temperature of 37ºC and for retention times of 10 and 20 days. The results revealed that, when the retention time was set to 10 days, the rate of backflow was of slight effect on the biogas production, with the continuous backflow failed to improve the reactor performance. Moreover, backflow was found to be of no effect on the reactor performance for the retention time of 20 days (Rico et al., 2011).

The aim of present study is to select of proper impeller design for mixing cow manure in a batch reactor using CFD.

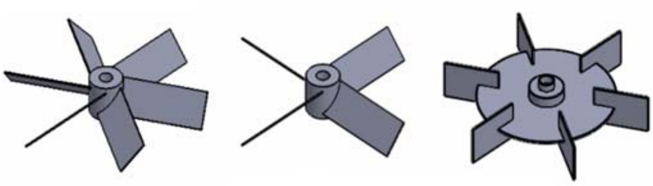
2 Materials and methods

This study was carried out to design proper stirrer for a full-scale pilot biogas plant (1200 L) built at the Biosystems Engineering Workshop, University of Kurdistan. The reactor was built from stainless steel and operated with a working volume of 800 L. Fresh cow manure was considered as substrate for the biogas plant.

Effective stirring of fluids to provide adequate mixing and movement requires an extensive analysis of capacity, viscosity, and dynamic response of the fluid, so that based on the results of such an analysis one can obtain the corresponding stirrer's power and shaft speed as well as blade size to the considered conditions.

2.1 Design of impeller

In order to select proper turbine stirrer, the corresponding impeller system should be designed properly. Further, the impeller design is in such a way that the applied shear stress to the fluid is reduced to keep the bacteria inside the reactor from being eliminated. The design encompasses the type of turbine, number of turbines, location-within-the-assembly of the blade and its diameter. For this purpose, three types of impeller were designed in the Solidworks software, on which geometry the proceeding analyses were based. Figure 1 shows three types of impeller designed including six-blade turbine impeller, four-blade turbine impeller, and six-flat-blade disc turbine impeller with a radius of 10 cm. As can be seen on the following figure, in these stirrers, a set of flat blades at a pitch angle of about 45° producing an inter axial-radial flow were used. This contributed into enhanced stirring as well as mass and heat transfer. Pitched blades are often used in bio-reactors which are sensitive to shear stress.



a. Six-blade turbine impeller b. Four-blade turbine impeller c. Six-flat-blade disc turbine impeller

Figure 1 A view of the three types of designed impeller

The stirrers are commonly used in non-continuous reactors, although those can be used in continuous stirred tank reactors (CSTR) as well (Li et al., 2004; Mirro and Voll, 2009). The ratio of blade diameter to reactor diameter (d/D) is an important parameter because it affects flow pattern and power input and consequently mixing efficiency. d/D values of 0.3-0.5 have been studied and used in design and operation of conventional stirred tanks. Table 1 provides the geometrical dimensions for the designed impellers.

Table 1 Geometrical dimensions of the designed impellers

Type of impeller	Blade length, cm	Blade width, cm	Blade thickness, cm	Blade angle, deg	Disc diameter, cm
six-blade turbine impeller	13	5	0.2	45	-
four-blade turbine impeller	13	5	0.2	45	-
six-flat-blade disc turbine impeller	7	5	0.2	-	30

2.2 Power properties

As an important principle in choosing appropriate stirring system, consumed power by mixing process is largely dependent on the mixing intensity and fluid flow conditions. The required power to achieve a desired stirring speed depends on the frictional force and fluid movement form against the impeller rotational resistance, with the friction and fluid movement form resulted in the development of some torque on the shaft of the stirrer. Input power of a stirrer can be empirically calculated by measuring the torque (*T*) (Shirmohammadpour et al., 2010).

2.3 Relation between impellers' power and speed for mixing

When designing any impeller-driven mixing system, a reasonably accurate estimation of the power/speed curve is necessary for the selection of the power unit by which the expected mixing performance can be provided. Therefore, choosing an appropriate power unit may incur high purchasing costs or increase the probability of failure due to overloading operations. However, required information can be acquired via full-scale experiments, based on which information one will be able to undertake the best design strategy (Cumby, 1990; Dickey, 2001). Power consumption of stirrer can be evaluated from Equation (1).

$$P = 2\,\pi\,N_i\,T \tag{1}$$

where, P denotes the stirrer power (W); T is stirrer torque (N.m), and N_i refers to the stirrer speed (rpm). When more than one fluid is stirred mechanically, corresponding Reynolds number (N_{Re}) is defined as in Equation (2).

$$N_{Re} = \frac{\rho D_i^2 N_i}{\mu} \tag{2}$$

where, N_i and D_i denote rotation speed (rpm) and diameter of impeller (m) and ρ is the fluid density (kg m^{-3}). Moreover, μ represents the fluid viscosity (Pa s) at each shear rate which can be calculated form Equation (3).

$$\dot{\gamma} = k_s N_i \tag{3}$$

where, k_s is the consistency coefficient (Pa s^n), and $\dot{\gamma}$ is shear rate (s^{-1}). Power number (N_p) (dimensionless number) and flow number (N_Q) in stirred tanks can be obtained using Equation (4) and (5).

$$N_P = \frac{P}{\rho N_i^3 D_i^5} \tag{4}$$

$$N_Q = \frac{Q}{N_i D_i^3} \tag{5}$$

N_Q is the flow number (dimensionless number) and Q refers to the flow rate (m^3 sec^{-1}). For turbines N_Q is calculated as 0.7- 2.9.

In present study, an electric motor with a power of 0.75 kW and a maximum rotational speed of 1400 rpm and a gearbox with transmission ratio of 1:10 for increasing stirrer torque, was used to provide the required driving power for six-blade turbine stirrer.

2.4 CFD method

Fluent 15.0 software package was utilized in the present study. Single phase model was used for the simulations in this research, so as to reduce computational costs of the system. In this model, the solid particles together with liquid phase are taken as a single homogeneous phase of the density and viscosity of the solid-liquid mixture. In cases where volumetric percent load of the solid particles is close to that of the fluid in the reactor, one can use the so-called pseudo-single phase model. Furthermore, the smaller the size of solid parties and the lower the density difference between solid and liquid phases, the more reasonable would be the use of the pseudo-single phase model. Because in this case the two-phase mixture of liquid and solid, homogeneous and its behavior is very close to the behavior of a single-phase mixture. Density and viscosity of the cow manure diluted with water were considered as 1000.36 (kg m^{-3}) and 0.070 (Pa s), respectively (El-mashad et al., 2005), with the volumetric percent of the phases being 50% for either of the liquid and solid phases (Wu, 2010). As such, pseudo-single phase model was used to lower computational costs. Indeed, the considered system is a single-phase stirred-tank reactor. The reactor contained a liquid (slurry). Performing a CFD simulation encompasses several stages including pre-processing, model start-up, calculation iteration, and post-processing of the results. Entire calculation domain was decomposed into several sub-domains among which, the impeller sub-domain, as moving zone, was the only one that was modeled using Tet/Hybrid meshing. The model start-up is briefly described in the following:

- Defining a three-dimensional, steady, implicit and pressure-based solver,
- Defining a turbulence model from the panel of viscous model,
- Activating the fluid properties with the conditions of turbulent flow using the text command: definition / models / viscous / turbulence model,

And then defining the material

- Defining operational conditions by activating the gravity,
- Defining boundary conditions,
- Adjusting the value of rotation speed and direction and determining the rotating regions using the rotating reference frame model at a given rotation speed,
- Determining the zero normal gradient for all variables at the liquid surface (symmetry boundary),
- Flow fields Initialization,
- Activating the monitoring of residuals and surface monitoring for an instance of the impeller's blades (torque),
- Solving flow fields until achieving a convergence,
- Set the time step size.

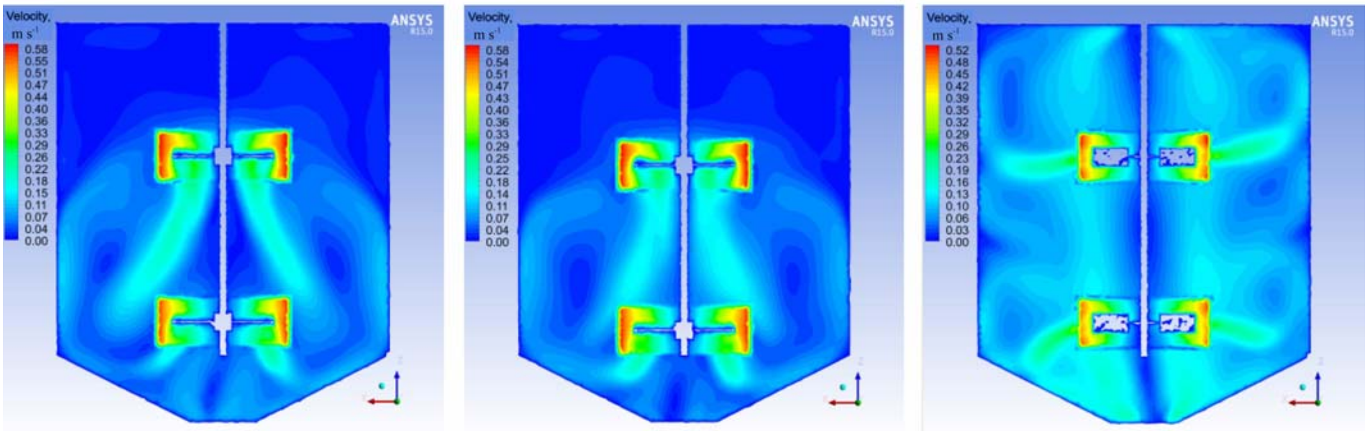
2.4.1 Meshing, boundary conditions and solving model

The considered system was a stirred-tank reactor with an incomplete conical bed of 100 cm in diameter and 150 cm in height. The reactor per time was simulated with one of three mentioned impeller. The stirrer had its axis at the center of the reactor, with two impellers along the axis at a distance of 50 cm from one another and 30 cm from the bottom of the reactor.

Tet/Hybrid meshing was used to mesh the system. Combining structured meshes with unstructured ones, the meshing approach is commonly used for complex geometries. In addition, in order to verify the independence of the results from the number of meshes, in each simulation round, the existing meshing became smaller before relaunching the simulation. No-slip boundary conditions were applied on the walls. In order to discretize the governing equations the system, QUICK approach was followed, with the resulting discrete equations solved by using SIMPLE algorithm. The governing equations were solved via finite volume method for the entire computational domain of the system, and rotating frame model was utilized to simulate rotational behavior of the stirrer. In this method, the computational domain is decomposed into two zones: rotating zone and stationary zone. All simulations were undertaken three-dimensionally, considering steady-state conditions.

3 Results and discussion

Figure 2 presents velocity contours within vertical plane, demonstrating the sweeping ring from top to the bottom of the reactor. According to the simulation results, six-flat-blade disc turbine impeller is more appropriate than the two other impellers.



a. Six-blade turbine impeller b. Four-blade turbine impeller c. Six-flat-blade disc turbine impeller

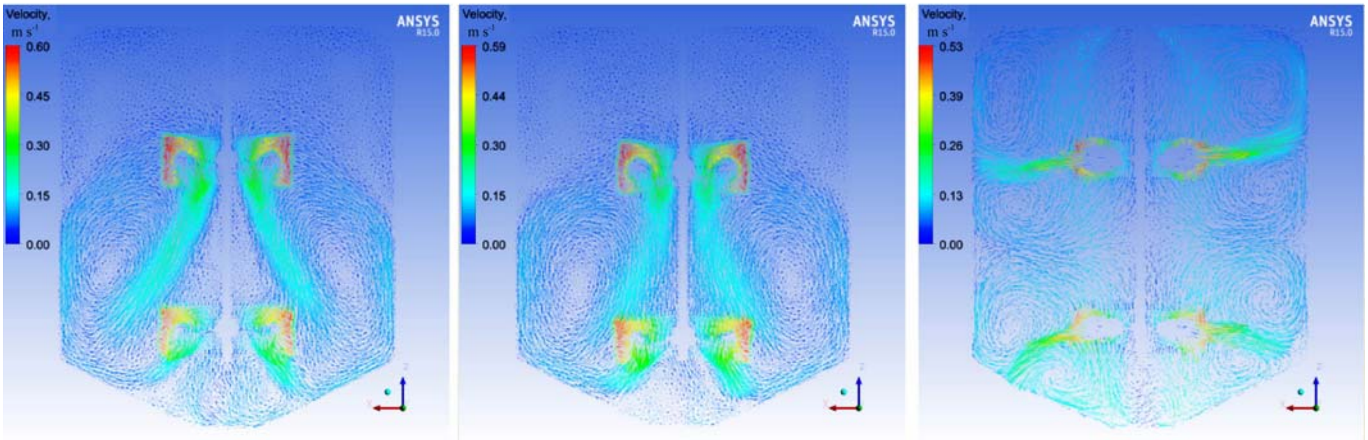
Figure 2 Velocity contours in the vertical plane of symmetry

As can be seen in the Figure 2, the rings on the lower part of the impeller hit the bottom of the tank before being diverted toward the walls around, with the outflow from the impellers generating several vortexes along their way backward. As was mentioned before, the impellers drive the flow toward the surrounding walls and then a major portion of the fluid ascend along the wall. Due to the produced radial pressure gradient by tangential movement, this flow returns toward central axis of the tank and, finally, due to gravity, returns toward the stirrer in the form of a depression.

The pitched-blade impeller with angled blades generates both axial and radial flow in low- to medium-viscosity fluids with a down-pumping flow. The impeller produces slightly higher shear at its blade surface than a hydrofoil impeller does, which gives a good balance between pumping and shear action. So this is considered to be a good general-purpose impeller.

Vector variations in velocity field across the vertical plane of symmetry for six-blade turbine impeller are shown in Figure 3. The variations indicate that, a part of the flow move upward while the other part goes down. Further, the velocity vectors reveal chaotic nature of the flow for lower velocities. With reference to the speed contour, the magnitude of velocity is maximal at the blade tips. An axial rotating ring can be observed considering the direction of the outgoing vectors. In Figure 3, the generated rotational rings around each impeller are evident. The rings are generated above and below each of the impellers. Velocity vectors across the horizontal plane well confirm the rotational nature of the flow which is, indeed, of a vortex form. The following figure presents a close view of the velocity vectors across the vertical plane of symmetry. Average flow is determined by the circular movement established in absence of baffles or any other obstacle. According to the

Figure 3, it can be seen that the fluid particle followed a circular path in horizontal plane. Further, based on the figures, one can understand that the circular movement is smaller than the tangential movement at almost anywhere within the fluid. Figure 4 represents the designed stirred reactor for biogas production with six-blade turbine impeller as selected stirrer.



a. Six-blade turbine impeller b. Four-blade turbine impeller c. Six-flat-blade disc turbine impeller

Figure 3 Changes of velocity square in stirred reactor for the speed of 30 rpm in the vertical plane of symmetry

Figure 4 The designed stirred reactor for biogas production, l: 3D drawing, r: photo

4 Conclusion

The main purpose of sludge mixing is to homogenize the biogas reactor’s content and to avoid the sludge deposits in the bottom area (Manea and Robesco, 2012). In present study, the behavior of three types of impeller inside the biogas reactor was simulated using the rotating frame model and standard k-ε turbulence model utilizing Fluent 15.0 Software. The simulation results indicated that, the mixing operation was more appropriate for six-blade turbine impeller and its reaction rate was desirable at the center of the reactor where there was region of high velocity. The success of the six-blade turbine impeller was concluded by surveying the flow pattern provided by CFD. This type of impeller provides an axial flow which is desired for homogeneity of fluid. Axial flow occurs when fluid is pushed up or down along the axis or shaft of the impeller. On the other hand, this impeller also provides the maximum mixing zone. However, hosting regions of low velocity, the zones farther from the stirrer suffered from lower mixing operation performance and reaction rate. Determination of the appropriate impeller is caused to lower power consumption and shorter mixing time. The investigation about the effect of the stirrer velocity, the type of substrate and the direction of stirrer on flow pattern and mixing performance can considered as the subjects for future research.

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