

CFD Simulation of Methane Optimization at different Slurry Temperature and for different Number of Baffle Plates in Fixed Dome Shaped Digester for Optimum Methane Production

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ABSTRACT

This Paper is numerical study of methane optimization in fixed dome shaped digester. The parameters of study are slurry temperature, and number of baffle plates. Simulated results are validated with the available data provided by the Urja Biotech System Pvt. Ltd.. Results are generated in the form of variation in methane gas generation. Fluent 6.2.16, a finite volume flow solver is used for solving the set of governing equations for the present geometry, in order to compute % of methane collection at the outlet of digester and to visualize the velocity contours in the digester. Large enough cell count and domain size is used to obtain numerical results. Appropriate boundary conditions are imposed under natural mode. Fluid flow characteristics are presented in the form of velocity vectors and velocity contours. Anaerobic processes are used to treat the cow dung for the production of biogas. This paper developed a three-dimensional CFD model to predict the effects of geometry and operating conditions on methane output in fixed dome shaped digester. The work was carried out by changing the number of baffle plates and with different slurry temperatures. The model is based on the principles of conservation of mass, conservation of energy, and species transport with volumetric reaction approach. Here only one chemical reaction is considered out of the 21 different chemical reactions which are used in biogas generation process. k- ϵ model is used to predict the forward reaction rate in the digestion process. The inclusion of baffles in the digester with diameter 15 m increased the methane output for constant slurry temperature. Validation is done with the experimental results provided by Urja Biotech System Pvt. Ltd, Pune. Results are obtained in the form of methane production in the digester.

1. Introduction

Biogas is an important renewable energy source for rural areas in India. It is produced by anaerobic digestion of biological wastes. It is an environment friendly, clean, cheap and versatile fuel. Biogas generally comprise of 55-65 % methane, 35-45 % carbon dioxide, 0.5-1.0 % hydrogen sulfide and traces of water vapor. Average calorific value of biogas is 20 MJ/m³. The use of biogas systems can increase agricultural productivity. All the agricultural residue, and dung generated are available for anaerobic digestion, whereas previously, a portion would be combusted daily for fuel. Therefore more is returned to the land in the form of fertilizer.

A change in feed to the digester can cause various problems in anaerobic digestion, particularly with mixing. A lot of research has been carried out on the anaerobic digestion, and good process monitoring can help, control, optimize and evaluate the biogas process very well. In particular, a new challenge is to optimize the mixing systems in biogas digesters to increase the biogas production rate.

2. Literature Review

Fleming (2002) developed a 3D model of a covered lagoon digester. This complex model incorporated the processes of bulk fluid motion, sedimentation, bubble mixing, bubble entrainment, advection, biological reactions, and heat transfer. The model was validated using performance data from full scale digesters in North Carolina. Forschner et al.

(2004) modeled a horizontal mixing vessel operating as a complete stirred tank reactor (CSTR). Vesvikar and al-Dahhan (2005) performed CFD simulations of an internal airlift loop reactor (ALR); the ALR was cylindrical with a central draft tube. The numerical predictions were compared to experimental results obtained from a lab-scale ALR operating with 5% Total Solid municipal sewage. They considered regions with velocities less than 5% of the maximum velocity to be dead or stagnant; according to this definition, they found that dead space occupied 25.0% to 59.7% of the digester volume for flat-bottomed digesters, and 11.02% to 29.57% for conical-bottomed digesters. They stated that the numerical and experimental results were in good agreement, despite the fact that the fluid properties of water were used in the CFD simulations. Wu and Chen (2008) used CFD to simulate fluid flow in a cylindrical continuous flow reactor. The dimensions of a lab-scale digester, five "scale-up" digesters ranging from 1 to 5 m³, and a 40 m³ pilot-scale digester were used. Hydraulic retention times studied ranged from approximately 4 s for the lab-scale digester to 4000 s for the pilot-scale digester. The properties of both water and liquid manure were used in the simulations and compared. Terashima et al. (2009) developed a 3D model of a mechanically agitated digester with a centrally-located internal draft tube; the rheological properties of digested sludge were incorporated through empirically-determined power law parameters. Meroney and Colorado (2009) simulated four large, circular anaerobic digester tanks with single and multiple draft tube mixers. Ford et al. (2006)

used CFD to model the dynamic response of agitated pulp stock chests to a pseudo-random binary input. The pulp was modeled as a non-Newtonian Bingham Plastic. They found that the reactor designs studied were far from ideal due to a high degree of channeling in the system. Ford et al. (2007) continued this work by studying the effect of impeller speed on degree of channeling.

Anaerobic digestion was affected by many factors, especially impacted by temperature, biogas yield was increased when temperature increasing, but the energy consumption was also greatly enhanced to hold temperature. Therefore, a swine manure related research was carried out to inquire into the optimum digesting temperature during anaerobic digestion of cow dung excrement, providing a scientific guidance to methane fermentation in breeding industry. Figure shows the reaction mechanism of xylose in supercritical water within a temperature interval of 450 and 650 °C proposed by Goodwin and Rorrer.

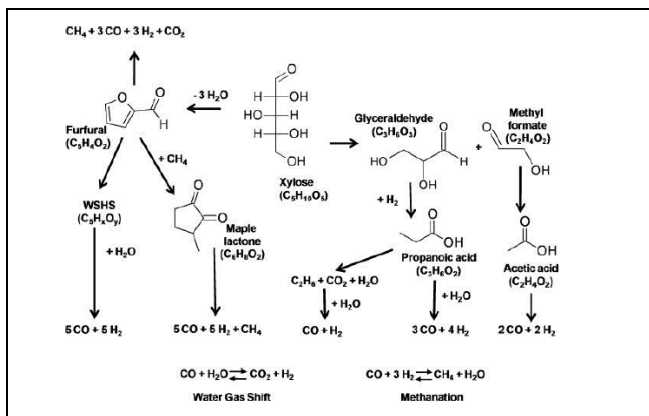


Fig:1 Reaction mechanism of xylose

3. CFD Analysis

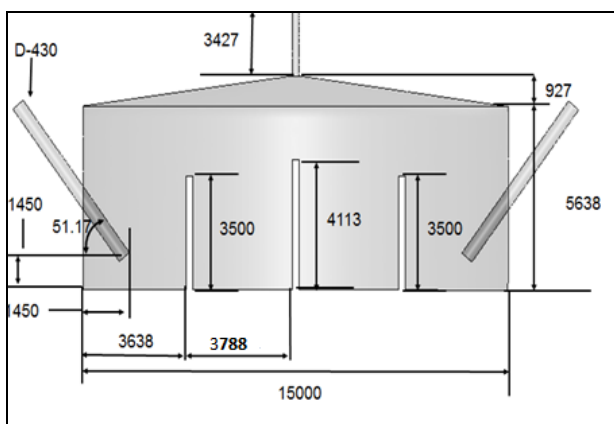


Fig.2 3D Model of Geometry having D 15m.

The study contributes a three-dimensional steady-state computational fluid dynamics (CFD) simulation has been performed for a particular anaerobic digester, in order to visualize the flow patterns and also the amount of methane mass fraction at the outlet of digester. Flow and velocities profiles have been represented inside the digester to identify possible dead zones or stratifications. This paper developed a CFD model to simulate the hydrodynamic characteristics of

single phase flow in biogas digester. This work carried out by changing the no of baffle plates. two different digester diameters for with and without baffles. Species Transport model with volumetric reaction approach was applied to describe the flow of the phases with chemical reaction, using Ansys Fluent. Following objective were defined to simulate, geometry of a real digester which installed by Urja Bio System Pvt .Ltd in order to consider the proposed methodology.

1. To Study the effect of slurry temperature on methane generation in fixed dome type digester.
2. To Study the effect of No. of baffle plates on methane generation.

Configuration

Figure 1 shows the fixed dome type of digester used, by Urja Bio System Pvt. Ltd, digester consisting of a main tank with baffles to maintain the flow, a screw pump to feed the biomass, and storage to collect the stable product. The gas is released from a top pipe of the digester. The diameter of digesters is 15 m, height of digester is 6 m, including the roof. The tank's internal volume is about 450 m³. The inlet pipe diameter is 0.43 m inclined with 51 deg. In this study, the pump located in the front of the digester to feed the biomass is not modelled, its pressure effect is included while simulation, also acted as a pusher to push the sludge inside the digester. Due to limitations of time constrained, actual chemical properties of volumetric reactions getting in digester, there is need to consider some assumptions, which is listed as below

Assumptions

1. 3-D, steady state with Heat flow and species transport through the digester.
2. Adiabatic conditions for the digester cover, walls, and floor.
3. Liquid manure is considered to be Newtonian.
4. pH range is between 6.5 and 7.5
5. Species reaction takes place only in one step, i.e., reactants are directly converted into final product without intermediate products.
6. The model is single phase, in which phase-interaction is negligible, and thus, rise of biogas to the surface has no effect on manure transport.

Governing Equations

The model is based on the principles of conservation of mass, conservation of energy, and species transport with volumetric reaction approach, equation to get the desired results

These equations are described below

Mass conservation equation

The conservation of mass or continuity equation used is expressed as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u) = 0 \dots\dots\dots(1)$$

Momentum Equation

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\vec{\tau}) + \rho \vec{g} + \vec{F} \dots\dots\dots(2)$$

Here, $\vec{\tau}$ is stress tensor and given as

$$\bar{\tau} = \mu \left[(\nabla \bar{v} + \nabla \bar{v}^T) - \frac{2}{3} \nabla \cdot \bar{v} I \right] \quad \text{Energy Equation}$$

The energy equation used is of the form (Patankar 1980):

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x} (u_i (\rho E + p)) = \frac{\partial}{\partial x} (k_{eff} \frac{\partial T}{\partial x} - \sum_j h_j \hat{j}_j) + u_j (\tau_{ij})_{eff} + S_h \dots (3)$$

Where, the first three terms on the right-hand side of the equal sign represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. Sh includes heat of chemical reaction and any other volumetric heat sources.

Species transport equations

The species transport equations for liquid manure can be written in a general form as (Patankar 1980):

$$\frac{\partial}{\partial t} (\rho Y_i) + \frac{\partial}{\partial x_i} (\rho u_i Y_i) + \frac{\partial}{\partial x_i} (J_i) + R_i \dots (4)$$

For mass diffusion in laminar flow, the diffusion flux, J_i, is computed as

$$J_i = -\rho D_{i,m} \frac{\partial y_i}{\partial x_i} \dots (5)$$

Chemical reaction equations

The initial conversion of raw waste to soluble organics can be expressed as (Chang 2004)

Modeling reaction rate

The reaction rate can be computed using the Arrhenius expression as

$$R_i = M_{w,i} \sum_{r=1}^{NR} R_{i,r} \dots (6)$$

Where, R_{i,r} is molar rate of creation or destruction of species i in reaction r, which is calculated as:

$$\hat{R}_{i,r} = (v_{i,r}'' - v_{i,r}') (k_{f,r} \prod_{j=1}^{NR} [C_{j,r}]^{\nu_{j,r}'}) \dots (7)$$

Information for k_{f,r} is not available in the literature. In this study, k_{f,r} is calculated by using first-order BOD removal rate in an ideal plug-flow reactor (Metcalf and Eddy 2003) as:

$$\frac{C}{C_0} = \exp(-k_{f,r} T) \dots (8)$$

Where, C/C₀ is percentage remaining of (CO₂).

Grid Generation

The modeling of this problem is done by using Ansys workbench while meshing by Ansys ICEM software. The tetra meshing type is created by using Ansys ICEM software. Set the nomenclature as per requirement. The Global mesh size given around max element of 60 with 0.4 scale factor, and tri mesh type is selected for shell surface mesh. Tetra mesh type with robust octree method is selected for volume mesh. Part mesh setup is used to set individual meshing parameters for each part. Volume mesh is computed by using tetra type of meshing, using automated algorithm used in Ansys ICEM software. Once created meshing, the mesh is checked by using parameters like skewness, angle, orthogonal quality, negative volume. Angle should be less than 15, orthogonal quality is valid if get till 0.1, while the domain should free from negative volume.

After initializing the conditions, for each case, computation time required is around 20 Hrs. to get the desired accuracy. The accuracy of 10⁻⁴ was considered for getting solution convergence. After getting convergence the results are described below.

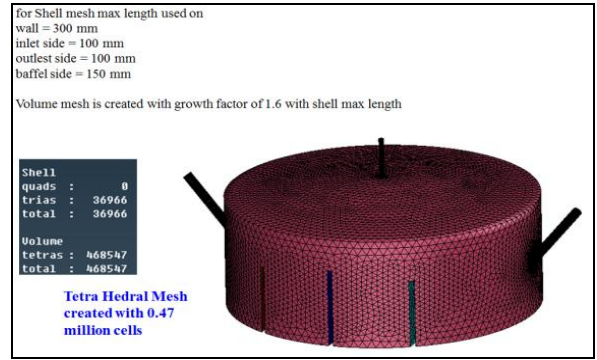


Fig.4. Meshing for Geometry having diameter 15 m

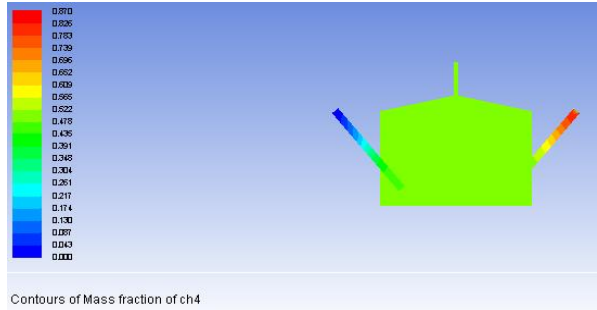


Fig.5. Contours of Mass fraction of CH₄ for without baffle plates

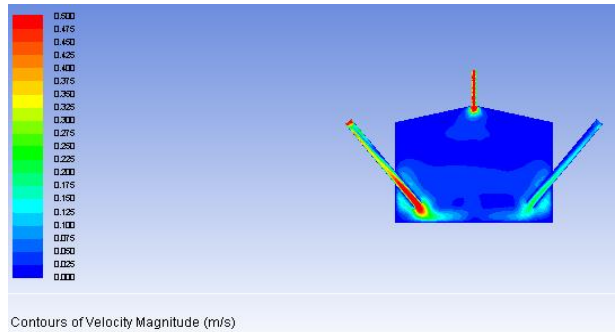


Fig.6. Contours of Velocity on Plane for without baffle plates.

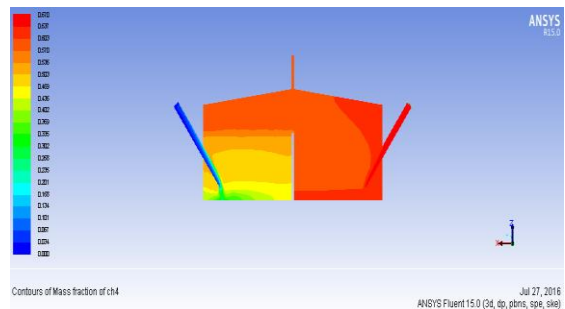


Fig.7. Contours of Mass fraction of CH₄ for one baffle plate

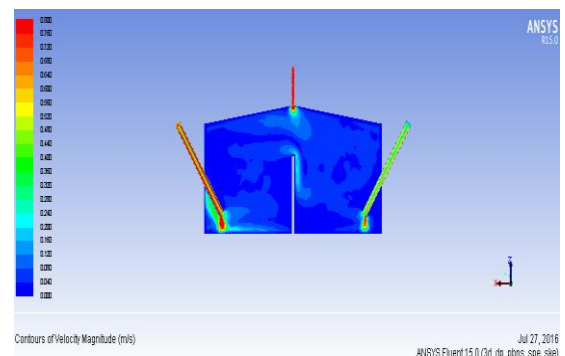


Fig.8. Contours of Velocity on Plane for one baffle plate.

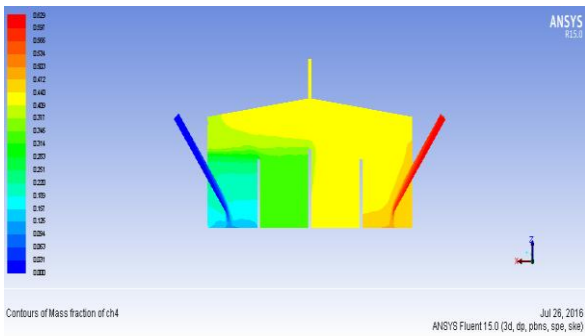


Fig.9 Contours of Mass fraction of CH₄ for three baffle plates

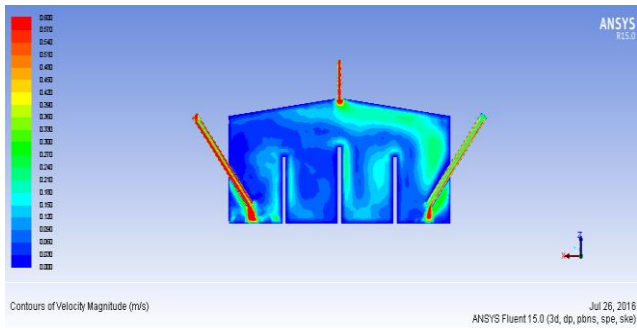


Fig.10. Contours of Velocity on Plane for three baffle plates.

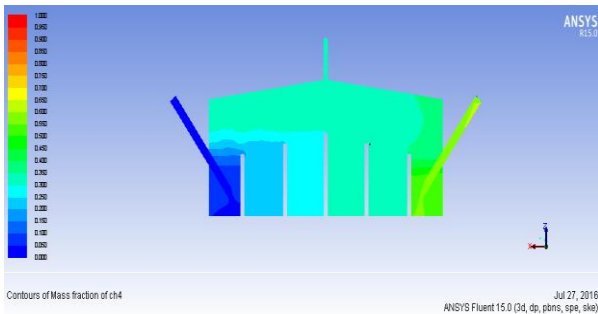


Fig.11. Contours of Mass fraction of CH₄ for five baffle plates

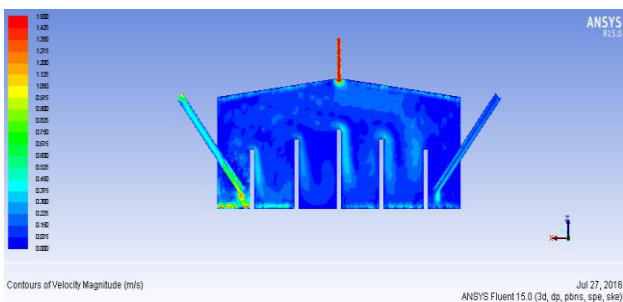


Fig.12. Contours of Velocity on Plane for five baffle plates.

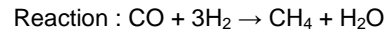
4. Experimental Verification

Table 1. Experimental values from Urja Biotech System, Pune.

Sr No	Parameters	Experimental Values from Urja Biotech system	Numerical Values
1	Pressure at gas outlet	102.796 kPa	101.325 kPa
2	Mass flow rate of Biogas	0.00487 kg/sec	0.00367 kg/sec
3	Inlet temperature of slurry	20 0C– 27 0C	300C
4	Temperature Inside the digester	38 0C – 40 0C	39.850C

In the experiment the information about the above parameters are given by the Urja Biotech system ,pvt .ltd.,Pune. The model is single phase, in which phase-interaction is negligible, and thus, rise of biogas to the surface has no effect on manure transport. Discretized 3D model is simulated by using Ansys Fluent 16.0 software. Computations are performed by varying slurry temperatures ranging from 20⁰C to 40⁰C All simulations used a generalized coordinate, finite volume code (Ansys Fluent 16) with Simple pressure velocity coupling with first order upwind for momentum, kinetic energy and dissipation rate is used.

For simulating Fixed Dome shaped Digester, biomass used consists of carbon monoxide and hydrogen, reacts with each other at ambient conditions. Biomass Volumetric flow of 450 m³/day and ambient temperatures of 20⁰ C , 30⁰C, and 40⁰C is considered at inlet. 82 % mass fraction of CO and 18% mass fraction of H₂ is the fraction of total volumetric flow. Species transport model is activated to get the reaction of CO with H₂ as reactant and CH₄ and H₂O as product. K-epsilon turbulence model is used to account the actual turbulence effect occurs in digester. Eddy dissipation rate type is used for volumetric reaction, as the flow inside the digester has turbulence effect when reaction takes place. In eddy dissipation rate type, mixing rate for reactant and product is 4 and 0.2 respectively, as per fluent help manual. Adiabatic conditions are considered for the digester cover, walls, and floor. Simulation consist only one reaction due to time consumption for analyzing the digester.



5. Experimental Result

We observed that by adding the baffles there is increase in methane production rate So we are studying the effect of change in no of baffles on methane production rate by keeping the same slurry temperature 30⁰C and inlet volumetric flow 450 m³/day we got the following results.

Table2. Results for the effect of no. of baffles on methane production rate

No. of Baffle plates	Digester Diameter 15 m		Results
	Input		Output
	Mass flow rate	Slurry Temperature	CFD Results
	Kg /sec	⁰ C	CH ₄ Kg /sec
0	0.0017	30	0.01042
1	0.0017	30	0.0092
3	0.0017	30	0.05931
5	0.0017	30	0.00405

From the table , we observed that up to the three no of baffles methane production increases but after that there is again reduction in the biogas or methane generation rate.

6. Results and Discussion

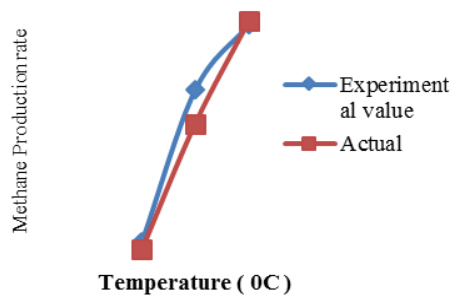


Fig.13 Comparison plot between experimental and actual values of change in methane production rate vs Temperature.

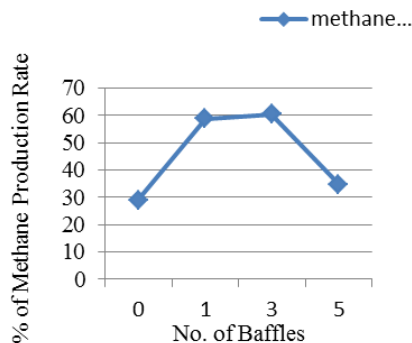


Fig14. Effect of change in no of baffles vs methane production rate

From the above graph, Baffle plates create disturbances to flow which helps in anaerobic digestion and effect on the methane production rate. because of the baffles it creates

disturbance to the flow so it takes some time to flow forward and anaerobic digestion but after increasing baffles up to certain limit it creates some problem of improper mixing and high HRT and that is why methane production get reduced. Production of biogas and methane yield in a certain extent, and fermentation under the higher temperature consumed more energy and less energy benefit.

7. Conclusion

The methane production increases as the temperature increases.

Temperature impacted the digestion time during the anaerobic fermentation, the high the temperature, the faster consumption of material and the shorter digestion time, but the anaerobic microorganisms made more gaseous impurities product in the high-temperature metabolism, which inhibited microbial growth and influenced the production of biogas and methane yield in a certain extent, and fermentation under the higher temperature consumed more energy and less energy benefit.

No of baffles also effect on the methane production rate. By keeping the temperature same and volumetric flow rate same there is change in methane production rate by changing the no. of baffles. But up to 3 baffles there is increase in methane production rate after that for 5 baffles it again reduces methane production rate because of the baffles it creates disturbance to the flow so it takes some time to flow forward and anaerobic digestion but after increasing baffles up to certain limit it creates some problem of improper mixing and that is why methane production get reduced.

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