Designing of Small Scale Fixed Dome Biogas Digester for Paddy Straw

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Abstract- With the advancement in biogas technology over the years, many biogas reactor designs have been developed so far as a result of alteration in biomass as feed-stocks. The current study is focused on one of the abundant agro-residue in India, paddy straw as waste; mostly burnt in the fields and cause air pollution, soil infertility and depletion of potential energy source. In this prospect, fixed dome digester was selected as foundation for designing and modification in a digester. The modified digester model was designed for thermophilic conditions (50-55ºC) to enhance the biogas yield, provide constant temperature, with a provision of agitation, recycling and insulation. Further the mathematical modeling of fixed dome digester with the capacity 1 to10 m^3/day was performed by considering the gas production rate of 0.012 m^3/day/kg of the biomass of size 1mm. The parameters like diameter, height, active slurry volume, gas storage volume, gas yield, pressure of gas, stress pattern of digester were calculated using the developed mathematical model by scaling- up a lab scale data. For a batch, assuming D: 2H (D = dia; H = height), the feeding of biomass was calculated on wet basis for 1 m^3 and 10 m^3 digesters. A stirrer provided to digester to enhance the mass transfer, gas yield and prevent sludge and scale formation.

Keywords: Biogas-digester, thermophililes, gas production rate, mathematical modeling, paddy straw, biogas.

1. Introduction

Shortage of crude oil and hike in prices lead to the energy crisis not only in Asian countries but also in the Gulf Coast. Besides the gasoline prices in the pre-crisis age is the main reason of the burden on the economic conditions of the world [1,2 and 3] , which further has greater impact on the prices of the goods as shown in Figure 1. All above issues lead to drift the energy policies. The history of last 20 years conveyed the important alterations in the advancements of the energy zone [4]. The lignocellulosic wastes have the ability to generate biogas and bioethanol, which is most significant tool in the hands of the men to fight against the problems of petroleum crisis [5]. Among all mentioned fuels, the biogas technology is one of the cheapest resources of energy according to today's energy scenario.

The biogas is generated through anaerobic digestion process . The digester is a device, where digestion process takes place [6]. Moreover, the structure, operational ethics, performance and application of the digesters vary across the world because biomass specification gets altered from one region to another. Therefore, we can assume from the earlier era to till now, the modeling of biogas digester design technology brings many changes in the fashion of manufacturing new and efficient models for digestion of biomass. Moreover, the design of biogas plant is totally based on the availability of the biomass [7]. Production of new category of biomasses gives new direction to the bio-reactor design in. Time to time modeling of new biogas plant will help in booming gross domestic products by giving power, gas, and employments [8,9 and 10].

A mathematical model depends upon various experimental factors such as hydraulic retention time (HRT), volatile solids and temperature [12]. Further, [13] reported that the retention time is an important factor in mathematical modeling, because it helps to find out flow rate of a process. Besides[14] reported, HRT as a major factor, however, other constraints such as microbial concentration ratio of total volatile fatty acids also affect the modeling of bio-digester.

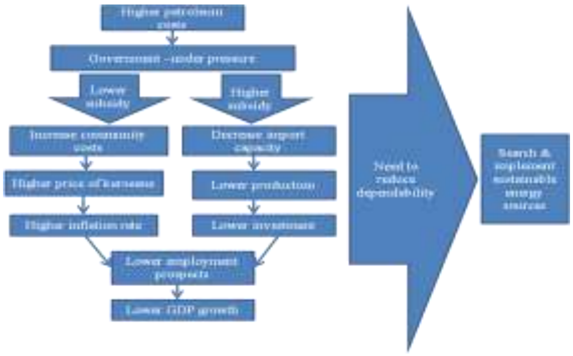

Fig.1.Reasons behind the need of sustainability in energy[11]

Furthermore, reported that kinetics, simulation and feedback control are the base of mathematical modeling [15, 16] . Similarly, [17] reported that simulation is a compulsory tool to find out the formulation of biogas plant. They reported that the rate constant and optimization are the main factors, which are considered before mathematical modeling [18] . Further in the progression of it, [19, 20, 21 and 22] found if the biochemical reaction kinetics were solved mathematically with the help of ordinary differential equations, the error occurred in the structural parameter and mathematically estimated parameters can be solved by method of Monte Carlo Simulation, whereas, [23] reported a non-linear one-dimensional modular dynamic model that was developed by mathematical modeling and used for the simulation, which has given satisfactory result for boosting biogas yield. Meanwhile [24,25, 26 and 27] reported that stability and control of the system is one of the important measures for mathematical designs.

In recent times, the numbers of biogas plants designs have been carried out using computerized approach of modeling and ample of the software. The main benefits are reduction of errors in calculation and less-time consumption. The abattoir is one kind of a sub programmer for biogas plant calculation, which can record the various conditions like volume, diameter, height etc [28, 29]. Furthermore, in the another study on mathematical model based on the programming in MATLAB, a SIMULAB algorithm, was made and then tested its feasibility for the various initial parametric vectors and further shock conditions were recorded by PID controller [30,31]. Group of researcher also reported that the experimental data is the base of the commercial biogas plant designs. With the help of scale-up techniques, we can assemble the mathematical model on software such as Chem CAD and MATLAB [32]. In the present study based on the lab-scale results, the biogas digester has been scaled-up and the parameters like volume and other dimensions have been calculated.

2. Materials and Methods

Literature reveals paddy is light in weight so it generally floats on the surface of water during digestion processes, many researchers used pretreatment method which is very expensive to conquer this problem so by considering all these, we decided to produce new design, which is based on agriculture waste digestion process, As it was proved that grinded biomass floats above the water, therefore to stop this phenomena we constructed agitator for mixing. This helps in effective mass transfer. The total surface area of the digester is less in order to control heat transfer as the process is totally based on the temperature. We are trying to maintain and control temperature conditions in this design by giving underground lining of bricks cement and concrete. This can be further helpful in research on designing. In this we used scale up techniques on following parameters.

- Scale up volume.
- Scale up water.
- Scale up using Reynolds number.

At laboratory level experiment, we have a the biogas digester (bottle) having capacity of 1 liter with 600ml working volume and 400ml volumetric space for gas collection, was used for anaerobic digestion of paddy straw (size= 1mm). The feedstock was prepared with C/N ratio maintained as 20:1 with 10% solid loading, about 50 grams dry biomass was taken with 1:10 (biomass: water ratio). The biogas yield obtained as 0.484 m^3 Kg^{-1} of volatile solid at 54°C in 23 days incubation period. Average methane and carbon-dioxide composition observed in biogas was 53.35% and 46.58%, respectively. The temperature variation ranged from 50°C to 54°C to check the tolerance and performance in respect to biogas production with thermophilic consortia. The biogas production from rice straw was observed highest in comparison to mesophilic conditions.

3. Design of Dome Digester

3.1 Experimental Data Analysis

Experimental data which is used for Pilot plant calculations given as following on dry basis.

50gram biomass (water + paddy straw) produced 13940ml of gas

50gram →0.050kg → 13940 kg/23days →0.606lt/day
1kg produced = 0.606/0.050×1= 12.12lt/day
12.12lt/ day →0.012cum/day

Based on above data we calculated the gas production rate per kilograms of a particular process within a body of digester as it is very from one biomass to another biomass. The gas production rate is per day per kilogram taken as the base of whole pilot plant calculation. Here we used mathematical calculation for 10 m^3 cylindrical fixed dome digester we knew for 10 cubic meter capacity digester requirement of biomass is 834 kg on wet basis. Which was comprises the following parts

- Inlet cylindrical Tank
- Digester volume
- Dome (gas volume)
- Outlet Chamber
- Agitator

Mathematical Design for 10 m^3/day production of biogas pilot plant

1. Gas production rate (G)

$$G = W \times 0.012 \tag{1}$$

Where W is weight of biomass and G is gas production rate. Design for G = 10m^3/day so put this value in equation no. (1)

$$10 = W \times 0.012 \tag{2}$$

On solving equation no (2) We get,

$$W = 843 kg \tag{3}$$

2. Active slurry volume (Vs), the volume of digester which is filled by undigested feed (paddy straw + water) is calculated by using following formula.

$$V_S = HRT \times {}^{2W}\!/_{1000} \tag{4}$$

Where HRT is the hydraulic retention time of biomass inside the digester for 23 days and density is assumed to equivalent of water.

From Equation No.4

$$V_S = 23 \times {}^{2\times 834}\!/_{1000} \tag{5}$$

$$V_S = 38.36 m^3 \tag{6}$$

3. Calculation of Height & diameter of digester (H: D), in biogas digester the ratio of height and diameter usually set as D: 2H because it is directly proportional to the cost of the digester. As we know the volume of cylinder is found by following formula.

$$V_S = {}^{\Pi}\!/_{4} \times H \times D^2 \tag{7}$$

$$H = \left({}^{V_S}\!/_{\Pi}\right)^{1/3} \tag{8}$$

$$H = \left({}^{38.36}\!/_{3.14}\right)^{1/3} \tag{9}$$

$$H = 2.30 m \tag{10}$$

$$D = 2 \times 2.30 = 4.60 m \tag{11}$$

4. Slurry displacement inside digester (d), the slurry displacement inside the digester depending upon the gas usage pattern during cooking. The pressure of the gas pushes the digested slurry down. The following assumption considered:

Cooking is usually done 2 times in a day.50% of the gas produced in a day is available for one cooking span. Assume the cooking spans are 3 hours.
Thus the slurry displacement is depending upon, the gas storage volume V_{sd} so we have to equate the all above factors and gas storage volume in equation No. 12.

$$\left({}^{3}\!/_{24}\right) \times G \times V_{Sd} = 0.5G \tag{12}$$

$$V_{Sd} = 0.375G \cong 0.4G \tag{13}$$

$$d = \left({}^{\Pi}\!/_{4}\right) \times D^2 d = V_{Sd} = 0.4G \tag{14}$$

$$V_S = HRT \times {}^{2W}\!/_{1000} \tag{15}$$

$$V_S = 23 \times {}^{2\times G}\!/_{1000} \times {}^{1000}\!/_{0.012} \tag{16}$$

$$V_S = 3.8G \tag{17}$$

$$V_{Sd} = {}^{\Pi}\!/_{4} \times D^2 d \tag{18}$$

On equating equation (15) and (18) we get result by putting these values in equation (19).

$${}^{\Pi}\!/_{4} \times D^2 d = {}^{\Pi}\!/_{4} \times {}^{D^2 \times H}\!/_{3.8G} = 0.4G \tag{19}$$

On simplifying equation No (19)

$$d = {}^{H}\!/_{3.8} \times 0.4 \tag{20}$$

$$d = 2.30/3.8 \times 0.4 = 0.24m \quad (21)$$

5. Slurry displacement height (h) in inlet & outlet tanks depends upon following factors.

   Maximum pressure attained by the gas is equal to the pressure of water (slurry) column above the lowest slurry level in the inlet/outlet tanks.

   Pressure is usually selected to be 0.85m water gauge as a safe limit for brick/concrete dome. Thus:

$$h + d = 0.85 \quad (22)$$

$$h = 0.85 - 0.24 = 0.61m \quad (23)$$

6. Length (l) & breath (b) of outlet tanks: in the case of bio-digester the outlet is depends upon following assumptions.

   It is usually a rectangular shape with l = 1.5b is assumed. Outlet cross-sectional areas are selected identical. So the equation of rectangle,

$$2 \times l \times b \times h = V_{Sd} = 0.4G \quad \textbf{(24)}$$

   The above relation is obtained by equating the volume of slurry displaced downwards inside the digester to the total volume of slurry displaced upwards in the inlet & outlet tanks. Substituting l = 1.5 b in above equation (23)

$$2 \times 1.5b \times b \times h = V_{Sd} = 0.2G \quad (25)$$

$$3b^2 \times h = 0.2G \quad (26)$$

$$b = \left(0.2G/3h\right)^{1/2} \quad (27)$$

   The above equation is valid for inlet and out both, if both are rectangular, but we use only outlet is rectangular. So we modified this equation further for single tank.

$$l \times b \times h = V_{Sd} \quad (28)$$

$$1.5b \times b \times h = 0.2G \quad (29)$$

$$1.5b^2 \times h = 0.2G \quad (30)$$

$$b = \left(0.2G/1.5h\right)^{1/2} \quad (31)$$

   In case, where the inlet pipe diameter is 15-20cm. Then the area of outlet should be double to accommodate the slurry displacement. On substituted the values of G and h in equation No. 32

$$b = \left(0.2 \times 10/1.5 \times 0.61\right)^{1/2} \quad (32)$$

$$b = 1.09m \quad (33)$$

$$l = 1.5 \times 1.09 = 1.63m \quad (34)$$

7. Inlet and outlet were the essential part of a digester. The mixing was done at inlet tank and outlet contained the digested biomass (both act as storage tanks), which can be further used as the manure. Here we design a cylindrical inlet having area 1.77m², and the outlet usually have rectangular shape. Calculation was done by the relation that obtained by equating the volume of slurry displaced downwards inside the digester, to the total volume of slurry displaced upwards in the outlet tanks

   Inlet tank calculation: The inlet tank is set cylindrical in shape for this digester. Now calculate the area and volume of inlet cylindrical tank.

$$Area = \Pi/4 \times d^2 \quad (35)$$

$$b = 1.77m^2 \quad (36)$$

$$Volume = Area \times Height \quad (37)$$

$$V = 1.77 \times 2.50 = 4.42m^3 \quad (38)$$

   If diameters of inlet pipe are not available in the range of ±15-20cm.Then inlet & outlet tanks are not same dimensions. Inlet diameter is slightly higher because we use it for storage tank also.

8. The gas collection space is known as Dome, so to find out the height of dome we have to detected the volume of dome [V_d,]which was a section of sphere was given as

$$V_d = \left(\Pi/6\right) dh \left[3\left(D/2\right)^2 + d^2 h\right] \quad (39)$$

   Total volume of gas space G. Slurry or gas displacement volume V_d is already fixed as 0.4G which is remaining gas space volume.

   Volume of dome

$$(G - 0.4G) Or (0.6G) \quad (40)$$

$$06G = \left(\Pi/6\right) dh \left[3\left(D/2\right)^2 + d^2 h \right] \quad (41)$$

dh is find out by solving above equation. Using iteration,

$$P = 0.75D^2 \quad (42)$$

$$p = 0.45 \times (4.60)^2 = 15.87m \quad (43)$$

$$q = -0.6\left(6/\Pi\right) G \quad (44)$$

$$q = -0.6 \times 1.90 \times 10 = 11.4m \quad (45)$$

$$R = \left(P/3\right)^3 + \left(q/2\right)^2 \quad (46)$$

$$R = \left(15.87/3\right)^3 + \left(11.4/2\right)^2 \quad (47)$$

$$R = (5.29)^3 + (5.7)^2 = 180.49m \quad (48)$$

$$\sqrt{R} = \sqrt{180.49} = 13.43 \quad (49)$$

$$A = [\left(q/2\right) + \sqrt{R}]^{1/3} \quad (50)$$

$$A = [(-5.7) + 13.43]^{1/3} \quad (51)$$

$$A = 2.58 \quad (52)$$

$$B = [\left(-q/2\right) + \sqrt{R}]^{1/3} \quad (53)$$

$$B = [(-5.7) + \sqrt{13.43}]^{1/3} \quad (54)$$

$$B = -6.37m \quad (55)$$

$$dh = A + B = 0.72m \quad (56)$$

9. Radius of dome r, Radius of dome means radius of sphere

$$r = [\left(D/2\right)^2 + d^2h/2dh \quad (57)$$

$$r = [\left(4.60/2\right)^2 + 0.72/2 \times 0.72 \quad (58)$$

$$r = 4.03m \quad (59)$$

Other dimension

The size of inlet & outlet opening (these were called boxes connect the inlet/outlet tanks to digester) in digester were normally 0.6 m* 0.6 m for digester of any capacity.

G (Gas production rate) = 10cum/day
Vs (Active slurry volume) = 38.36cum/day
H (Height of cylindrical digester) = 2.30m
D (Diameter of digester) = 4.60m
d (slurry displacement) = 0.24m
h (height of slurry displacement) = 0.61m
b (Breath of outlet rectangular tank) = 1.09m
l (Length of outlet rectangular tank) = 1.63m
h_o (Height of outlet rectangular tank) = 2.25 m
D_c (diameter of cylindrical inlet) = 1.5m
H_c (Height of cylindrical inlet) = 4m
dh (Height of spherical dome) = 0.72m
r (Radius of spherical dome) = 4.03m

This size is selected so that a man can go inside the digester during construction period

The digester walls were 230mm thick (full bricks) and the wall of the inlet & outlet boxes (below the inlet) 115mm thick (half bricks). For plain bottom thickness was 115mm (half bricks).

Volume of digester = $\frac{\pi}{4}$ D^2*h = 38.20 m^3

The cylindrical and spherical equation of mathematics was used to solve the theoretical calculations, which mainly affect the process parameters like volume, mixing, temperature etc. With the help of conventional engineering approach we used lay-lout for analyzing and designing including all the dimensions with front view, side view and top view, so each and every internal and external part of the biogas reactor is visible clearly.

All design parameter of 10m^3/day biogas plant analyzed listed below and design layout in Figure 2(a) to 2(d).

The detailed biogas plant information of the volume, height, diameter, dome, digester volume and total input is given for the plant capacity 1m^3/day to 10m^3/day is mentioned in table 1.

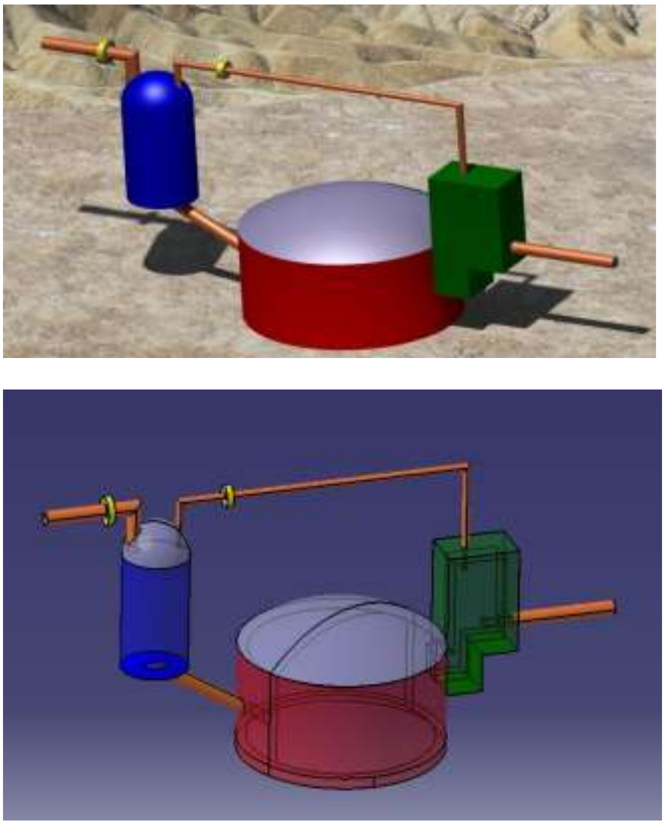

Fig. 2 (a). External and internal views of biogas plant from different angles.

Table 1. Biogas plant with various capacities and respective output are for fixed dome having capacity 1 to 10 cubic meters.

G m^3/day	Vs m	H & D m	Displacement m	Dome (H) m	Dome (R) m
1	3.86	H-1.07 D-2.14	d-0.11 h-0.74	0.33	1.79
2	7.65	H-1.36 D-2.69	d-0.14 h-0.71	0.41	2.37
3	11.5	H-1.54 D-3.08	d-0.16 h-0.69	0.46	2.78
4	15.36	H-1.69 D-3.39	d-0.17 h-0.68	0.51	3.06
5	19.18	H-1.82 D-3.65	d-0.19 h-0.66	0.56	3.14
6	23	H-1.94 D-3.88	d-0.20 h-0.65	0.61	3.18
7	26.86	H-2.04 D-4.09	d-0.21 h-0.64	0.63	3.63
8	30.68	H-2.13 D-4.27	d-0.22 h-0.63	0.65	3.83
9	34.5	H-2.22 D-4.44	d-0.23 h-0.62	0.68	3.96
10	38.36	H-2.30 D-4.60	d-0.24 h-0.61	0.72	4.03

Design of agitator

In laboratory experiment we was observed that in digester bottle the biomass and water get separated after some time and made the 2 unusual layers. The gas get trapped in the layer of biomass which is only escaped by the shaking as the result of it the whole mass transfer in the digester was not uniform.

The agitator helped in proper mass transfer by uniform distribution of mixture inside the digester. It facilitated in uniform distribution of temperature.

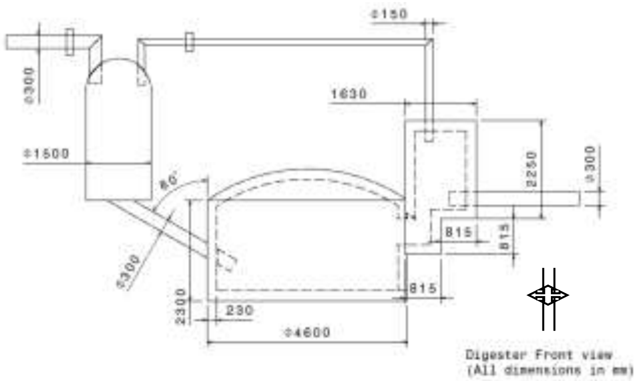

Fig. 2(b). Biogas Digester front view with dimensions.

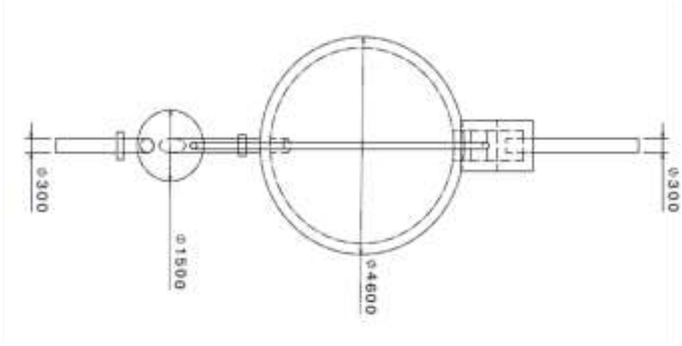

Fig.2(c). Top view of biogas digester.

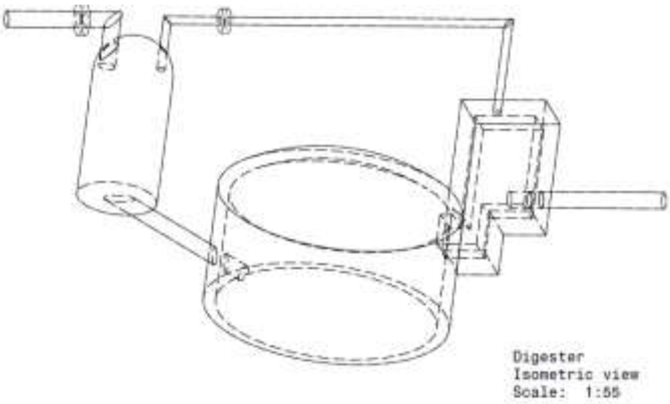

Fig.2(d). Isometric view of biogas digester.

Calculation for the three blade type agitator were determined by governing the rules of impeller designing, which were calculated based on the total height of digester = H+H_D= 3.02m and diameter of digester (D) = 4.60m.

$$\frac{D_a}{D} = \frac{1}{3} = 0.53m \qquad (60)$$

Then the following are obtained and given in the Figures 3(a) and (b).

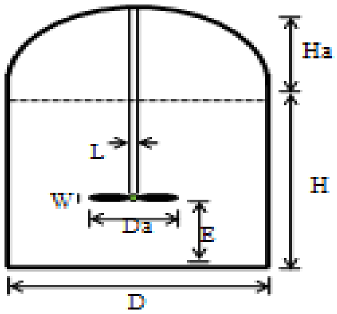

Fig.3 (a). Biogas plant represent impeller front view

Fig.3 (b). Biogas plant with impeller top view inside digester

Height calculation of impeller, H but Total height can be calculated by following relationship in this digester, H= Height of impeller in Cylinder + Height of dome

$$\frac{H}{D_a} = \frac{1}{1} = 2.25m \qquad (61)$$

J Calculation for design parameter

$$\frac{J}{D} = \frac{1}{12} = 0.38m \qquad (62)$$

E, Empty space below the impeller can be calculated by following equation.

E= Total height- Impeller height

$$E = 0.77m \qquad (63)$$

Width of the impeller, w

$$\frac{W}{D_a} = \frac{1}{5} = 0.46m \qquad (64)$$

L, diameter of impeller supporting pipe or width.

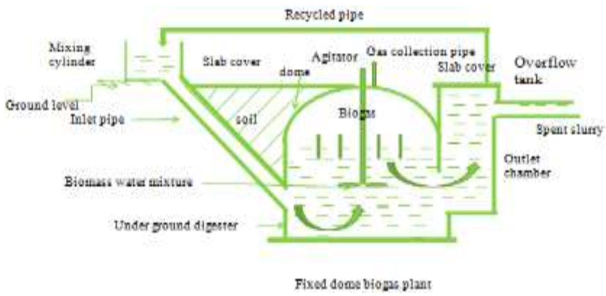

Fig.4. Modified fixed dome model.

The Reynolds numbers dimensionless quantity that was used to predict the flow patterns inside the digester moreover its represents the fluid properties such as density and viscosity. Our calculated value is 7108.74 for 500rpm, which is not above than 10 000 so the system is not fully turbulent. It has smooth turbulent flow inside the digester, which leads to effective mass transfers by eddies.

4. Results and Discussion

This design is quite different from the fixed dome model, used for the digestion of cow dung [33].We have judged all parameters in experiment and its effect on the process of anaerobic digestion of paddy straw. Further by knowing unique characteristics of paddy straw, we tried to modify the fixed dome reactor.

We used underground recycled fixed dome cylindrical digester having spherical dome. This has been selected for the reason that relatively small amounts of slurry (a mixture of biomass and Hot water) are added daily. The water was separated from outlet tank and recycled with the help of pump. The slurry having large amount of living micro-organisms which can helps in the further digestion. The ground preserve the heat in it for long time so it provides a kind of insulation to the outer volume of the digester, size of inlet was changed as we compare with others fixed dome type models because it also acted as a space for soaking with hot water as well as storage space. The reactor was also used batch or continuous operation so we have to add feed on daily basis which is 36.23 kg/day in order to boost up the gas production rate per kg. The gas production rate of paddy in kilograms was 0.012 m^3/kg (from batch type operation) and then we produced the overall procedure to find out the structural identical of digester. Researchers reported methane emission of a fixed dome biogas plant in plain areas was 83.1 $g\ m^{-2}\ d^{-1}$ and 43.1 $g\ m^{-2}\ d^{-1}$ in the hilly areas but in this design we will expected to obtain yield obtained more than 0.484 $m^3\ Kg^{-1}$ of volatile solid [34].

5. Conclusion

From above studies it is concluded that the fabricated digesters are the need of the hour to innovate both larger and smaller size design of fixed dome biogas plants for paddy straw. It is vital to ensure that the most efficient way to enhance methane production from most abundant waste in Punjab such as paddy. The use of the design of experiments method allowed us to analyze the effect of the parameters taken into account as well as their interactions. Lab scale data of biogas digester model can be used for construction and fabrication of bigger sized biogas plants. However for bigger size fixed plants; calculations, innovative civil designs are to be created. This paper proposes that type of theoretical design model using fixed dome cylindrical and hemisphere equations which are to be solved using mathematical modeling and draft layout using designing software. These designs will bring down the heat transfer when compared to floating type of designs.

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