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Design methodology for low cost tubular digesters

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ABSTRACT

The aim of this paper is to present a novel, universal, methodology for the design of low cost tubular digesters. This method improves on the established methodology by avoiding assumptions that tend to reduce the final hydraulic retention time (HRT) of digesters once installed. This work recommends designing the digester using trench cross-sectional area and proposes an optimization of the trench dimensions with respect to the angle of the walls and the relationship between the length of the biogas bell and the top width of the trench. The influence of the biogas pressure is considered. A simple geometrical analysis is presented that, by parameterization, can be applied in a wide range of situations.

1. Introduction

Low cost digesters have been implemented in developing countries such as Colombia, Ethiopia, Tanzania, Vietnam, Cambodia, China, Costa Rica, Bolivia, Peru, Ecuador, Argentina, Chile, Mexico, etc. since 1980s (Botero and Preston, 1987; Soeurn, 1994; Solarte, 1995; Sarwatt et al., 1995; Rodriguez and Preston, 1999; Martí-Herrero, 2007; Poggio et al., 2009).

Low cost digesters are characterized by the absence of both active mixing devices and active heating systems and also, consequently, by not needing sophisticated monitoring. Local materials are used for construction, usually plastic bags for the main tank and PVC pipes to carry the biogas. This technology works, with proper adaption, in tropical, continental, and cold climates, usually feed by fresh manure from dairy or pigs (Martí-Herrero, 2007; Martí-Herrero, 2008; Poggio et al., 2009; Ferrer et al., 2011). Due to their simple design and construction from readily-available materials, they are considered appropriate technology.

The "red mud PVC" bag designed in Taiwan (Pound et al., 1981) was the seed for the technical development of this continuous-flow flexible tube. Further development was conducted mainly by Preston in Ethiopia, Botero in Colombia (Botero and Preston, 1987) and Bui Xuan An in Vietnam (Bui et al., 1995). In all cases the digesters were adapted for tropical climates. Martí-Herrero (2007, 2008), in the Altiplano of Bolivia in 2003, adapted Botero's design to cold climates increasing the hydraulic retention time (HRT) to 90 days and adding a greenhouse with high thermal mass adobe walls and straw as insulation in the trench. Poggio et al. (2009), in Perú, proposed adding to the Martí-Herrero model a simple solar heating system, integrated in the design by taking advantage of the structure of the cold climate digester.

There have been scientific publications regarding tubular, non low-cost, digesters dealing with the co-digestion of vegetable wastes by Dinsdale et al. (2000), and on the subject of fruit and vegetable waste treatment by Bouallagui et al. (2003), co-digestion of olive mill wastewater with olive mill solid wastes by Boubaker and Ridha (2007), and operation of a laboratory-scale tubular digester on piggery waste by Floyd and Hawkes (1986).

A few scientific publications in indexed journals exist about low cost tubular digesters which offer analyses of efficiencies and applications. Ong et al. (2000) reports a study to evaluate which layer inside a single-stage digester should be evacuated as effluent in order to improve biogas production, concluding that it was the middle one. Lansing et al. (2008a) published a study about seven low cost digesters in Costa Rica to determine the potential of these systems for treating animal wastewater and producing renewable energy yielding a positive conclusion. In the same year Lansing et al. (2008b) published research on electricity generation from a low cost biodigester as a waste treatment solution for a pig and cow farm, finding that the economic investment could be recovered in 7.6–10.1 years depending on the generator used. Ferrer et al. (2009) reports a study of the viability of ambient temperature anaerobic digestion of pig manure diluted with urine and obtains good results. Lansing et al. (2010a) reported a study in which a small amount of waste cooking grease (2.5% by volume), when added to swine manure more than doubles CH_4 production,

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demonstrating a good opportunity for these digesters to improve their performance while preserving the waste treatment value of the low-cost digestion system (Lansing et al., 2010b).

Ferrer et al. (2011) has recently published the results of two monitored tubular low cost digesters in the Peruvian Andes, obtaining a biogas production rate of around 0.35 $m^3\ kg_{VS}{}^{-1}$, for HRTs of 60 and 90 days, with an organic load rate (OLR) below 0.75 $kg_{VS}\ m^{-3}\ day^{-1}$. Ferrer proposes to investigate HRT below 60 days and OLR above 1 $kg_{VS}\ m^{-3}\ day^{-1}$ in order to "decrease digesters' volume (i.e. costs) and increase biogas production rate" to fulfill the biogas requirements of a family for cooking and lighting. In this sense, Martí-Herrero (2011) communicated that "one of the problems reported from field surveys of this type of digester is that end-users complain that daily biogas yields are less than those indicated by the designers" and observed that two common errors in the design of low cost tubular digesters, also the Peruvian Andes ones, that decrease the real HRT. This observation helps to explain the low biogas production identified by Ferrer and Martí-Herrero.

Alvarez et al. (2006) reported the results of the evaluation of the effects of pressure (495 and 760 mm Hg), temperature (11 and 35 °C), HRT (20 and 50 days), and manure content in the slurry (10%, 20% and 50%) respect to productivity and methane yields from cow and llama manure digestion. This conditions are referred to high altitude cold climate conditions as Peruvian Andes or the Bolivian Altiplano. Alvarez determined that the effect of the pressure is not significant while the main factor to achieve a better productivity and methane yield is the temperature. The temperature in low cost digesters has been increased taking advantage from passive heating devices as greenhouses, thermal inertia and insulation, as there are no active heating devices in low cost digesters (Martí-Herrero, 2008), but further research must be done in order to improve the thermal performance. The HRT and OLR appears on second and third place of influence on methane yield, and on inverse order for methane production. Increasing HRT and/or OLR will result in higher productivity and methane yields. The OLR is more related to the operational phase, to the content of VS on the different available substrates and the dilution with water of the slurry. Other factors as C/N ratio or PH of the different substrates can also affect the productivity and methane yields of the digester. These both factors use to be corrected by the digester user adding paper or rice shells to increase C/N ratio on pig and human manure, or adding calcium carbonate (agricultural lime) to reach a proper PH when it is low. So OLR, C/N or PH are parameters to be considered but dependent to the type of substrate to be used and the operational phase. The HRT is directly dependent to the temperature and design phase, and in order to standardize and industrialize low cost digesters become a critical factor to be considered.

The aim of this paper is to develop a new, universal, methodology for the design of low cost tubular digester. The old common design methodology, employed by all the authors (Botero and Preston, 1987; Bui et al., 1995; Sarwatt et al., 1995; Rodriguez and Preston, 1999; Aguilar, 2001; Martí-Herrero, 2008; Poggio et al., 2009), assumes that the final liquid volume is determined by the cylinder shape of the tubular plastic whilst, in reality, the critical factor is the trench dimensions, as reported by Martí-Herrero (2011). This erroneous assumption results in a reduction of the HRT once the digester is placed in the trench. How to determinate the cost-effective dimensions of the trench and to keep the HRT once the low cost tubular digester is installed and working affected by the biogas pressure?

In this paper, a geometrical analysis of the low cost tubular digester is realized, and a general methodology to determine the optimum dimension for the trench is proposed. The advantage over the old method is that the designed HRT is achieved once the digester is installed. The gap filled in the body of knowledge is the explanation of why actual HRT has tended to be lower than expected.

2. Old common design methodology

As there is no information in peer-reviewed journals about the design and dimensioning of low cost digesters, the primary source of information on the subject is the Internet. Low-cost tubular digesters are generally made of sheet plastic (low-density polyethylene (LDPE), high-density polyethylene (HDPE) or polyvinyl chloride (PVC)), and hence they are flexible and take the form of the container in which they are installed; most commonly in a trench in the ground. On the Internet (Botero and Preston, 1987; Bui et al. 1995; Sarwatt et al., 1995; Rodriguez and Preston, 1999; Aguilar, 2001; Martí-Herrero, 2008; Poggio et al., 2009), specific trench dimensions can be found for various circumferences of plastics used.

The methodologies reported for the design a low-cost tubular digester use the cylindrical volume that the tubular plastic forms as the central parameter. This total volume is separated into two phases—liquid and gas. Depending on the author, the liquid volume is reported as 80% of total cylindrical volume (Bui et al., 1995; Sarwatt et al., 1995; Rodriguez and Preston, 1999; Poggio et al., 2009) or 75% (Botero and Preston, 1987; Aguilar, 2001; Martí-Herrero, 2008). The liquid volume is supposed to fill the volume of the trench in which the digester is situated. In order to obtain the total volume, the cross section of the cylinder is multiplied by the length of the digester, assuming that this volume will remain unchanged after the digester is placed in the trench. The dimensions of the trench are given in each case as 'recommended', but no methodology or justification is provided. However, these dimensions are critical because, in practice, they determinate the real liquid volume.

Martí-Herrero (2011) reported that the recommended dimensions, in most cases studied, are not consistent with the circumference of the plastic. Also, in the cases where the data is coherent, the loss of HRT, due a lower final liquid volume (once the digester is placed in the trench), ranges from 6% to 51% compared to the HRT expected by the design. In the same report Martí-Herrero highlighted that the biogas pressure influences the final HRT and can result in a reduction of between 15% and 17% compared to the theoretical value expected by design.

The complaints about lower daily biogas production rates than those indicated by the designer, can be related to the issues reported by Martí-Herrero (2011) about design considerations and the high HRT and low OLR identify by Ferrer et al. (2009). These complaints can also be related to other factors associated to user behavior that also adversely affect production rates, such as not loading the digester with fresh manure every day or loading less manure than recommended. Other factors as the quality of the substrate used are hardly modified, and C/N ratio or PH can be corrected by user as commented before.

3. Sizing tubular low cost digesters

3.1. Available circumference

The low-cost tubular digester is limited by the dimensions of the LDPE, HDPE and PVC plastics available in the local market. Generally LDPE plastic is manufactured in tubular form with circumferences of 2, 4, 5, or 8 m. HDPE plastics, in the Bolivian market, can be found in flat sheets 7 m in width, and the PVC ones are often 1.4 m wide, so the possible circumferences must be a multiple of these measurements assuming they are joined edgewise to form a tube.

The available circumference must be distributed, in the optimum fashion, between the perimeters of the trench ($a + 2A$) which determines the liquid volume, and the biogas bell length (L_{bell}) which determines the biogas volume (see Fig. 1).

3.2. Shape of the trench

The trench of a tubular digester determines its liquid volume. The ideal optimum cross-sectional shape of the trench would be circular, keeping the original form of the plastic and taking advantage of the full available capacity. But, due to the fact that a circular shaped trench is challenging to dig, in rural areas the trend is to dig polygonal shapes. The more sides a polygon has, the closer it approximates a circular shape and cross sectional area. But an octagonal or hexagonal shape is just as challenging to build in rural areas as a circular shape. Thus trapezoidal shapes are typically dug, as they are the easiest and most common shape and also as this is the shape proposed by all the authors.

3.3. Volume of a tubular digester situated in a trapezoidal trench

The total volume V_{BDG} is given by the cross section of the circular segment, CS_{bell}, plus the trapezoidal cross section, CS_{trench}, multiplied by the length of the digester, L.

$$V_{BDG} = (CS_{bell} + CS_{trench}) \cdot L \quad (1)$$

where CS_{bell} is:

$$CS_{bell} = (\pi \cdot R_{bell}^2 \cdot n/360 - (b \cdot h)/2) \quad (2)$$

R_{bell} is the radius of the bell, n the angle of the bell arc, b the length of the chord (that corresponds with the upper width of the trench) and h is the height of triangle OPQ from Fig. 1. h can be calculated using the Pythagoran Theorem.

CS_{trench} is:

$$CS_{trench} = p(b + a)/2 \quad (3)$$

where p is the depth and a is the lower width of the trench.

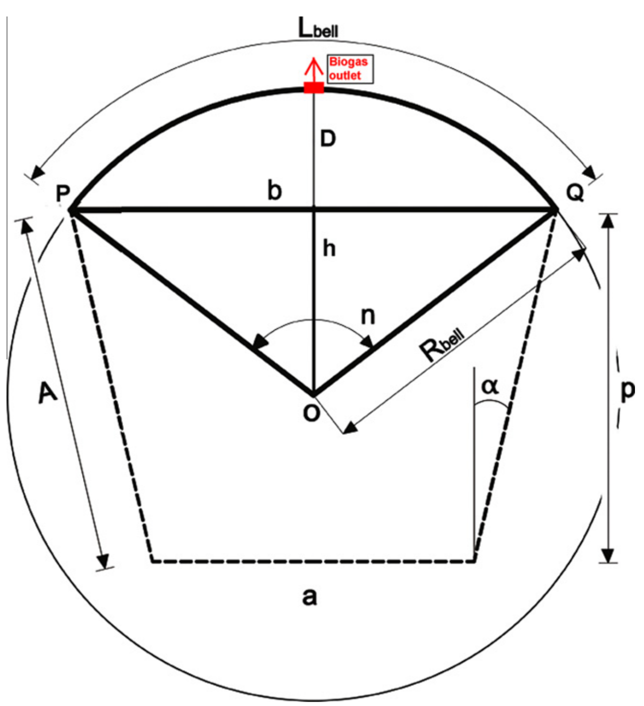

Fig. 1. Geometrical parameters for the tubular low cost digester installed in a trench.

4. Parametric dimensions of a tubular low cost digester

In order to generate universal methodology, independent of the circumference of plastic available, C, a parametric study is proposed. All values are divided by the radius r of the plastic tube.

$$c = 2\pi r \quad (4)$$

So the factors are:

$$f_b = b/r \quad (5)$$
$$f_a = a/r \quad (6)$$
$$f_p = p/r \quad (7)$$

4.1. Dimensions for the biogas bell

The dimension of the biogas bell determines the capacity of the digester to store biogas. In some cases larger biogas bells will be desired. In other cases external biogas reservoirs will be used, and the biogas bell can be kept smaller. In all cases it is important to maintain a minimum biogas bell size in order to avoid possible blockage of the biogas flow out of the tube in the upper part of the bell which can be caused by two main factors: (a) the formation of foam obstructing the biogas outlet and (b) obstruction of the biogas outlet by suspended solids in the surface of the liquid phase, in situations where the biogas pressure is low.

The length of the bell arc, L_{bell}, has the mathematical expression:

$$L_{bell} = 2 \cdot \pi \cdot R_{bell} \cdot n/360 \quad (8)$$

R_{bell} and b are related by:

$$R_{bell} = (b/2)/\sin(n/2) \quad (9)$$

Combining Eqs. 8 and 9 the following is obtained:

$$n = \frac{L_{bell} \cdot 360 \cdot \sin(n/2)}{\pi \cdot b} \quad (10)$$

And L_{bell} can be related to b through a factor f_{bell}:

$$f_{bell} = L_{bell}/b \quad (11)$$

So, it is found that the angle n of the bell arc is a function of f_{bell}, as shown in Eq. 12.

$$n = (f_{bell} \cdot 360/\pi)\sin(n/2) \quad (12)$$

Using an iteration of Eq. 12, the angle n can be obtained for each f_{bell}, being f_{bell} the determining factor which characterizes the biogas bell. In Table 1 some results are shown. The curve plotted with these results can be fitted to a 6th-degree polynomial equation, with $R^2 = 1$ and valid for the range $1 < f_{bell} < 3$, as follows:

$$n = -25,085f_{bell}^6 + 333,74f_{bell}^5 - 1835,2f_{bell}^4 + 5352,7f_{bell}^3 - 8787,9f_{bell}^2 + 7829,3f_{bell} \quad (13)$$

The cross section of the biogas can be related to the tubular one, using R_{bell} from Eq. 8 and Pythagoras theorem for h (see Fig. 1):

$$\frac{CS_{bell}}{CS_{tubular}} = (f_b^2/4\pi) \cdot (360f_{bell}^2/\pi n - \sqrt{(360f_{bell}/\pi n)^2 - 1}) \quad (14)$$

So, if f_{bell} is determined, n can be estimated by Eq. 13. f_b will be explained below and will be a function of f_{bell} and α. So $CS_{bell}/CS_{tubular}$ is function of (f_{bell}, α).

Table 1
Different values of f_{bell} and its corresponding angle n.

f_{bell} (L_{bell}/b)	1.1	1.2	1.3	1.5	1.75	2	2.5
Angle n (°)	86	118	140	171	198	217	244

4.2. Dimensions of the trench

The dimensions of the trench are determined by the angles of the walls α, and the desired capacity of the biogas bell, related to $f_{bell.}$, once α is determinate.

A trapezoidal shape is used commonly in civil engineering when designing retaining walls. The desired angle α is not universal and, depending the type of soil, a different angle α could be required. So α is considered a determinant parameter for the sizing of the digester.

In this case, the trigonometric relationship is fulfilled:

$$\sin\alpha = [(b-a)/2]/A \tag{15}$$

where A is the apothem.

The circumference of the available plastic is distributed as follows:

$$C = 2\cdot A + a + L_{bell} \tag{16}$$

Combining Eqs. 15 and 16 a can be isolated, and dividing by r the next expression is obtained:

$$f_a = [f_b - (2\pi - f_b\cdot f_{bell})\sin x]/(1-\sin x) \tag{17}$$

The depth of the trench, p, can be expressed by f_p as:

$$f_p = (f_b + f_a)/(2\cdot\tan\alpha) \tag{18}$$

And defining the factor $f_A = A/r$, this gives:

$$f_A = (2\pi - f_a - f_b\cdot f_{bell})/2 \tag{19}$$

Finally, the trapezoidal cross section can be related to the tubular one:

$$\frac{CS_{trench}}{CS_{tubular}} = \frac{f_b^2 - f_a^2}{4\pi\cdot\tan\alpha} \tag{20}$$

where f_a is a function of (f_{bell},f_b,α) as shown in Eq. 17. So CS_{trench}/$CS_{tubular}$ is function of the three parameters (f_{bell},f_b,α) defined before.

5. Optimization of the dimensions of the trench

The optimum trench is the one with the largest trapezoidal cross section area CS_{trench}, constrained by the circumference of the plastic available C, and defined by the angle α of the walls and the ratio f_{bell}.

Using Eq. 20 for each (f_{bell},α) the optimum f_b value can be calculated, that is the one which will generate the highest CS_{trench}/$CS_{tubular}$.

In Fig. 2, the variation of the ratio CS_{trench}/$CS_{tubular}$ is plotted with f_b, for different angles α in the case of f_{bell} = 1.3. In this way, the optimum f_b can be determined for each (α,f_{bell}).

Knowing the optimum f_b(α,f_{bell}), the rest of factors f_a, f_p and f_A can be determined. Finally, by assigning a circumference C, r can be obtained and the dimensions a, b, p, A, and L_{bell} can be calculated for the specific case.

6. Results and discussion

The optimum f_b for different (α,f_{bell}) is shown in Table 2, which includes the corresponding optimum f_a and f_p. The case where f_{bell} = 1 corresponds with the reference case of a digester without biogas bell, having total volume equal to the liquid volume contained in the trench.

In Fig. 3 the variation of CS_{trench}/$CS_{tubular}$, CS_{bell}/$CS_{tubular}$ and CS_{BDG}/$CS_{tubular}$ are plotted with the angle α of the walls, for the specific case of f_{bell} = 1.2. This behavior is similar for other values of f_{bell}. It is found that CS_{trench}/$CS_{tubular}$ decreases and CS_{bell}/$CS_{tubular}$ increases with the angle α of the walls.

Fig. 4 shows the variation of CS_{trench}/$CS_{tubular}$, CS_{bell}/$CS_{tubular}$ and CS_{BDG}/$CS_{tubular}$ with f_{bell}, for the specific case α = 7.5°. The behavior here is similar for other values of α. The relationship CS_{bell}/$CS_{tubular}$ decreases smoothly and CS_{bell}/$CS_{tubular}$ keep more or less constant for values f_{bell} > 1.3.

From Figs. 3 and 4, can be shown that, on the best cases of optimum trench dimensions, the lost of total volume respect the theoretical one given by the tubular form, used in the old methodology, is over 10%, and can reach 30% on the worst cases.

Once defined the optimum f_b for each pair (α,f_{bell}), the % of liquid and gas volume of the resultant digester can be estimated for each case (α,f_{bell}), by dividing Eq. 14 by Eq. 20. The results for % of gas volume are shown in Table 3, and the % of liquid volume can be derived.

The authors considered proposed 75–80% of liquid volume with respect to total volume. For f_{bell} = 1.2 the relation between the liquid and total volume is 80%, as can be found in Table 3. In this case, the distance D (see Fig. 1) between the top of the biogas bell (corresponding with the biogas outlet) and the liquid level is 0.46 times the radius r, enough to avoid the obstruction of the biogas outlet.

The mean angle α used by the considered authors is 7.6°.

So, if f_{bell} = 1.2 and α = 7.5° are selected, the optimum factors are obtained by Table 2, and a resume is showed in Table 4.

Using these factors for the typical circumferences of plastic used, and adding circumferences for HDPE (7 and 14 m) and PVC

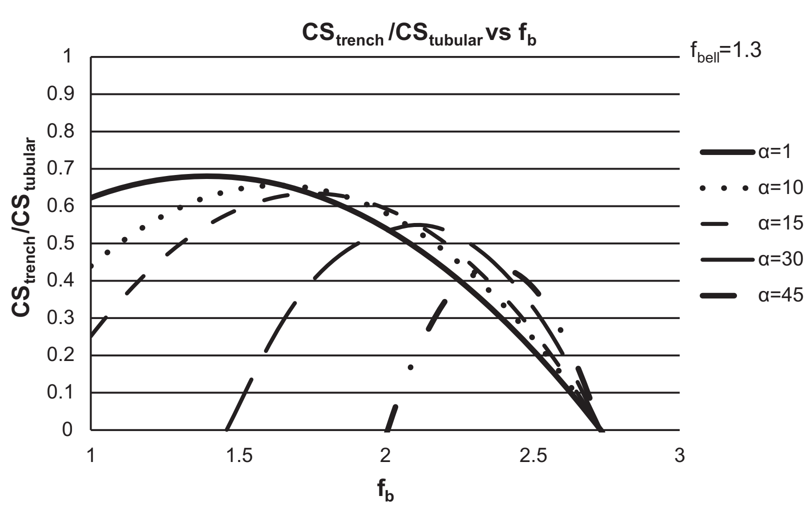

Fig. 2. CS_{trench}/$CS_{tubular}$ relation variation with f_b, for different angles α in the case of f_{bell} = 1.3.

Table 2
Optimum factors f_a, f_b and f_p, for different (α, f_{bell}).

	Angle of walls (α)							
	1	5	7.5	10	15	30	45	60
f_b optimum								
Relation L_{bell} and $b\cdot(f_{bell})$								
1	1.6	1.71	1.78	1.84	1.98	2.36	2.68	2.93
1.1	1.52	1.63	1.7	1.77	1.9	2.26	2.57	2.8
1.2	1.46	1.56	1.63	1.7	1.82	2.18	2.47	2.68
1.3	1.39	1.50	1.57	1.63	1.76	2.1	2.37	2.57
1.4	1.34	1.44	1.51	1.57	1.7	2.02	2.28	**2.47**
1.5	1.28	1.39	1.46	1.52	1.64	1.95	2.2	**2.37**
1.6	1.24	1.34	1.41	1.47	1.59	1.89	2.12	2.29
1.7	1.19	1.30	1.36	1.42	1.54	1.83	2.05	2.21
1.8	1.15	1.25	1.32	1.38	1.49	1.78	1.99	2.13
1.9	1.11	1.22	1.28	1.34	1.45	1.72	1.93	2.06
2	1.07	1.18	1.24	1.3	1.41	1.68	1.87	2
f_a optimum								
Relation L_{bell} and $b\cdot(f_{bell})$								
1	1.55	1.44	1.37	1.29	1.17	0.80	0.45	0.19
1.1	1.47	1.36	1.29	1.23	1.10	0.72	0.43	0.19
1.2	1.41	1.29	1.23	1.17	1.02	0.69	0.42	0.18
1.3	1.34	1.23	1.17	1.10	0.98	0.65	0.36	0.16
1.4	1.29	1.17	1.11	1.04	0.93	0.58	0.32	0.17
1.5	1.23	1.12	1.06	1.00	0.88	0.54	0.31	0.05
1.6	1.19	1.07	1.02	0.95	0.84	0.52	0.26	0.16
1.7	1.14	1.04	0.97	0.91	0.80	0.49	0.24	0.17
1.8	1.10	0.98	0.93	0.87	0.75	0.48	0.27	0.07
1.9	1.06	0.96	0.89	0.84	0.72	0.42	0.27	0.06
2	1.02	0.92	0.86	0.80	0.69	0.44	0.24	0.17
f_p optimum								
Relation L_{bell} and $b\cdot(f_{bell})$								
1	1.57	1.56	1.55	1.55	1.51	1.35	1.11	0.79
1.1	1.57	1.56	1.55	1.53	1.49	1.33	1.07	0.75
1.2	1.56	1.56	1.54	1.52	1.49	1.29	1.03	0.72
1.3	1.57	1.55	1.52	1.51	1.46	1.26	1.00	0.69
1.4	1.56	1.54	1.52	1.50	1.44	1.24	0.98	0.66
1.5	1.57	1.53	1.50	1.48	1.42	1.22	0.95	0.67
1.6	1.56	1.53	1.49	1.47	1.40	1.19	0.93	0.61
1.7	1.56	1.51	1.49	1.46	1.38	1.16	0.90	0.59
1.8	1.56	1.52	1.48	1.44	1.38	1.13	0.86	0.60
1.9	1.56	1.50	1.47	1.43	1.35	1.12	0.83	0.58
2	1.56	1.50	1.46	1.42	1.34	1.08	0.81	0.53

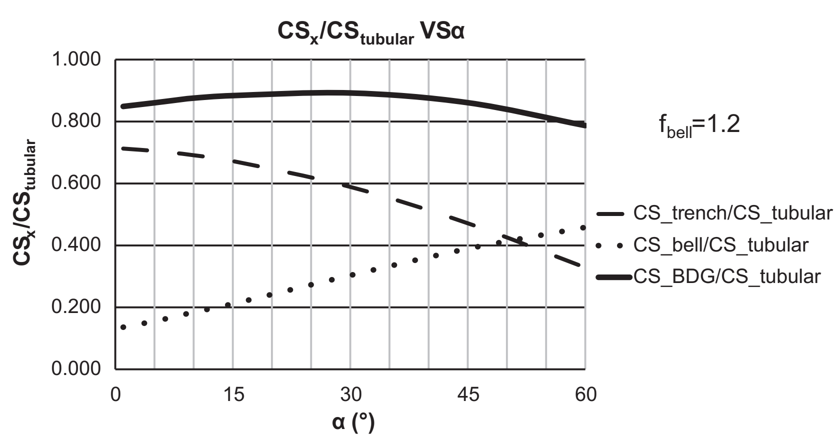

Fig. 3. Variation of $CS_{trench}/CS_{tubular}$, $CS_{bell}/CS_{tubular}$ and $CS_{BDG}/CS_{tubular}$ with α for a fixed f_{bell} = 1.2.

(multiples of 1.4 m), the optimum dimensions for the trenches are found, as shown in Table 5.

7. Final considerations for biogas pressure influence on HRT

The liquid volume and so the HRT calculated with this methodology is for biogas pressure equal to atmospheric pressure. As the pressure inside the digester increases, the volume of biogas increases and the level of the liquid inside the digester decreases, resulting in a reduced volume of volume (Martí-Herrero, 2011).

To estimate this loss of liquid volume, it is necessary to calculate the new p and b, due the drop in liquid level, while a keeps invariable. h_p is the mean pressure inside the digester expressed in meters of water column. The new depth is $p' = p - h_p$, and $b' = b - 2\cdot h_p\cdot\tan\alpha$. Introducing a, b' and p' in Eq. 3 the new final CS'_{trench} is obtained.

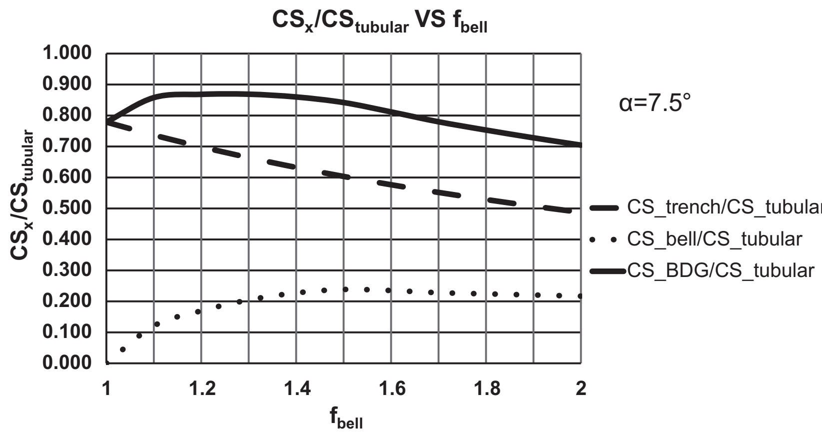

Fig. 4. Variation of $CS_{trench}/CS_{tubular}$, $CS_{bell}/CS_{tubular}$ and $CS_{BDG}/CS_{tubular}$ with α for a fixed α = 7.5°.

Table 3
Percentage of gas volume for the optimum tubular digester for different (α,f_{bell}).

% Gas volume		Angle of walls (α)							
		1	5	7.5	10	15	30	45	60
Relation L_{bell} and $b\cdot(f_{bell})$	1	0	0	0	0	0	0	0	0
	1.1	11%	13%	14%	15%	17%	25%	35%	48%
	1.2	16%	18%	20%	21%	24%	34%	45%	58%
	1.3	19%	22%	24%	25%	29%	40%	52%	64%
	1.4	22%	24%	26%	28%	32%	44%	56%	69%
	1.5	23%	26%	28%	30%	35%	47%	59%	71%
	1.6	23%	27%	29%	31%	36%	48%	60%	72%
	1.7	23%	27%	29%	32%	36%	49%	61%	73%
	1.8	23%	27%	30%	32%	37%	50%	62%	74%
	1.9	24%	28%	30%	33%	38%	51%	63%	75%
	2	24%	28%	31%	33%	39%	52%	64%	76%

Table 4
Factors and characteristics for the typical trench with f_{bell} = 1.2 and α = 7.5°.

f_{bell}	α (°)	f_a	f_b	f_p	D/r	$\%V_{liq}$	$\%V_{gas}$
1.2	7.5	1.23	1.63	1.54	0.46	80	20

In order to conserve the proper HRT and liquid volume by the biogas pressure influence, the length of the digester L should be multiplied by the factor CS_{trench}/CS'_{trench}, obtaining the final length L'.

8. Validation of the design tool

In order to validate this new design methodology it is necessary to show how the theoretical HRT is maintained once the digester is installed and the biogas pressure influences the level of the liquid inside. These issues are not considered when old common methodology is used (Martí-Herrero, 2011).

In the valleys of the Andes has been implemented several household low cost tubular digesters designed by the old methodology (Martí-Herrero, 2008). The digester design requirements were based on the production of fertilizer and the use of the biogas for cooking for a farmer family. The main substrate available is cow manure, with 13% VS and 0.27 $m^3{}_{biogas}\,kg_{SV}{}^{-1}$ for biogas production as general reference for the region (Martí-Herrero, 2008). So 20 kg of fresh manure were supposed to produce 700 l of biogas with a proper HRT, assigned in 45 days. As the tubular digester works as plug-flow system, the slurry must be fluent enough to avoid obstruction, and after some field trials, a 1:3 manure–water relation were chosen, giving 80 l of daily load of a mixture of water and manure in a 45 days HRT low cost tubular digester. The old common methodology proposes to use tubular plastic with C = 3 m and 6.3 m length in order to reach a cylinder total volume

Table 5
Optimum dimensions for trenches for typical tubular low cost digesters for different circumferences of plastic (LDPE, HDPE and PVC) available in the market.

C (m)	r (m)	a (m)	b (m)	p (m)	CS_{trench} (m^2)	CS_{bell} (m^2)	α (°)	L_{bell}/b
2	0.32	0.39	0.52	0.49	0.223	0.0538	7.5	1.2
2.5	0.40	0.49	0.65	0.61	0.348	0.0841	7.5	1.2
3	0.48	0.58	0.78	0.73	0.496	0.1211	7.5	1.2
3.5	0.56	0.68	0.91	0.86	0.684	0.1649	7.5	1.2
4	0.64	0.78	1.04	0.98	0.892	0.2154	7.5	1.2
5	0.80	0.97	1.3	1.22	1.385	0.3365	7.5	1.2
8	1.27	1.56	2.08	1.96	3.567	0.8615	7.5	1.2
7	1.11	1.36	1.82	1.71	2.719	0.6596	7.5	1.2
14	2.23	2.73	3.63	3.43	10.907	2.6384	7.5	1.2
1.4	0.22	0.27	0.36	0.34	0.107	0.0264	7.5	1.2
2.8	0.45	0.55	0.73	0.69	0.442	0.1055	7.5	1.2
4.2	0.67	0.82	1.09	1.03	0.984	0.2375	7.5	1.2
5.6	0.89	1.09	1.45	1.37	1.740	0.4221	7.5	1.2

of 4.51 m^3. Twenty percent of the total volume will be fulfilled with biogas and 80% by the liquid. So 3.6 m^3 of liquid volume tubular digester is obtained (45 day·0.08 m^3/day = 3.6 m^3). This methodology could be acceptable if the ditch where the digester would be placed, maintain the tubular shape, but trapezoidal ditches were used. For C = 3 m the dimensions of the trench proposed in the old methodology are a = 0.5 m, b = 0.7 m and p = 0.8 m (Martí-Herrero, 2011). The resultant liquid volume, once the digester is placed in the trench and loses the tubular shape as it adapts to the trapezoidal trench, is 3 m^3, corresponding in this case to 37.5 days of HRT. This is 17% lower than the HRT considered for design. If the influence of the biogas pressure is considered, the final HRT is 32.3 days, 28% lower than the desired HRT.

With the methodology proposed in this paper, the same design case, is solved using Table 3, and selecting f_{bell} = 1.2 and α = 7.5°, corresponding to 80% of liquid volume. So the optimum dimensions of the trench, using the factors of Table 2 and for a C = 3 m, are a = 0.59 m, b = 0.78 m and p = 0.74 m. With these dimensions, a 7.1 m length trench is needed to reach a 3.6 m^3 of liquid volume. The next step is to consider the biogas pressure estimating CS_{trench}/CS'_{trench}. For a typical case of 980.64 Pa biogas pressure (equivalent to 0.1 m of water column) $CS_{trench}/CS'_{trench} = 1.18$. So the final length of the digester is L' = 7.1 m·1.18 = 8.37 m in order to keep the 45 days of HRT once the digester is installed in the trench and in used with a mean biogas pressure of 980.64 Pa.

If the biogas pressure effect is considered with the trench dimensions recommended by the old common methodology (Martí-Herrero, 2011), it results in a length for the digester of 8.75 m, involving 0.38 m more for the trench, and needing more plastic (considering that double layer is used), thus making the digester more expensive.

The digesters installed with old methodology had 17% less HRT (or 28% if the biogas pressure is considered) than the digesters installed with the methodology developed in this paper. The complaints of the new users about biogas production has been reduced, but not removed, perhaps due other social factors as digester feeding behavior, and also other operational issues. Future research must be carried out in field research to confirm the improve of the biogas production of the digesters designed with the proposed methodology, that avoid the loss of 17–28% of HRT.

So, the methodology proposed is validated in order the design low cost tubular digesters with the optimum dimensions (cost effective) in order to keep the designed HRT once the digester is installed and working affected by the biogas pressure.

9. Conclusions

The methodology proposed in this paper to obtain the optimum dimensions is based on two determinate parameters: the angle of the walls, and the relation between the length of the arc of the biogas bell, and the upper width of the trench. From these two parameters, and the introduction of the circumference of the plastic that is used to build the tubular digester, one can determine the optimum dimensions of the trench. The influence of the biogas pressure is considered, too.

Finally, the discrepancy showed by different authors in trench dimensions for typical circumferences is solved using this methodology.

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