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Research Note

Location of the inlets and outlets of Chinese dome digesters to mitigate biogas emission

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A model based on three equations was developed and validated for the design of the inlet and outlet of the Chinese dome digester (CDD) to prevent biogas emission or leakage. The model was implemented in MATLAB software and validated with results from a pilot study. Biogas and temperature data from the pilot experiment were used to validate the model and the results fitted well with the experimental data at low gas volume (<20 mols) but with some slight deviation at high gas volume. The model predicted the reactor pressure (P_G) and the slurry displacement in the expansion chamber, inlet pipe head (h) and head inside the digester (h_G). The relationship between the gas and h was not linear at high gas volume (>20 mols). The model can be used to predict the optimal size of the CDD for daily biogas storage based on different reactor and expansion chamber sizes, in order to mitigate the emission of surplus biogas from the inlet and outlet pipes.

1. Introduction

Household digesters can serve as a sustainable energy solution to meet the cooking needs of rural households in developing countries. These digesters make use of the anaerobic digestion process to break down organic matter for the production of biogas and nutrient rich effluent or bio-fertiliser. However, the application of household digester technology in rural areas has had many challenges such as poor performance of the digester, limited application of feedstock to mono-substrate and high costs of installation (Asam et al., 2011; Yu, Yaoqiu, Ningsheng, Zhifeng, & Lianzhong, 2008). About 45 million domestic biogas or household digesters have been installed in developing countries, mostly in China (Mungwe & Mapelli, 2014; Bond & Templeton, 2011). The Chinese dome digester (CCD) is the most widely applied household digester design used in developing countries. It is usually constructed using bricks, concrete or prefabricated plastic (Jegede, Bruning, & Zeeman, 2018a; Perez, Garfí, Cadena, & Ferrer, 2014). The CCD operates based on the wet anaerobic digestion concept (influent total solid (TS) concentrations around 7%) at ambient temperature - mesophilic 20–45 °C (Mungwe, Colombo, Adani, & Schievano, 2016).

When monitoring and evaluating the performance of household digesters it is important to evaluate the impact and the overall benefits of the system as a cooking source. The performance the digester could be evaluated using economic, social and environmental indicators. The economic indicators are investment cost, net present value and payback time.

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Nomenclature

Abbreviations

BMP	Biochemical methane potential
CCD	Chinese dome digester
TS	Total solids
GHG	Greenhouse Gas
PVC	Polyvinylchloride
STP	Standard temperature pressure

Symbols

ρ	Density, kg m^{-3}
g	Acceleration due to gravity, m s^{-2}
R	Universal gas constant, J mol^{-1} K^{-1}
T	Temperature, K
n	Number of moles, mol
P_a	Atmospheric pressure, N m^{-2}
P_G	Pressure inside the digester, kPa
h	Slurry displacement in inlet pipe and expansion chamber, m
h_G	Slurry displacement in the digester, m
V	Gas volume, m^{-3}
A_G	Surface area of slurry in the digester, m^{-2}
A_1	Surface area of slurry in the inlet pipe, m^{-2}
A_2	Surface area of slurry in the expansion chamber, m^{-2}

Social indicators include clean cooking environment, elimination of time to collect firewood, and local job creation while the indicators for the environment are reduction of indoor emission and greenhouse gases, and elimination of the use of firewood (Mungwe et al., 2016), which can help in the mitigation of deforestation. Because of these benefits, household digesters have been strongly supported and promoted by governments and international organisations in Asia and Africa (Feng, Guo, Yang, Qin, & Song, 2012).

A major reason why various governments and international donors support this system, if managed well, is that it a cost-effective way of mitigating methane (CH_4) emissions from animal dung or manure (Sommer, Petersen, & Møller, 2004). Although the combustion of biogas does release a CO_2, a greenhouse gas (GHG), it does reduce the amount of CH_4 (a much more potent GHG) that would be released if the manure were not subject to anaerobic digestion. Studies have calculated these savings in India (Bhattacharya, Thomas, & Abdul Salam, 1997), South America (Garfí, Gelman, Comas, Carrasco, & Ferrer, 2012), and China (Yu et al., 2008). However, the benefits that household digesters present may not be as positive as they portray because domestic biogas plants often release methane via leaks from their inlets and outlets (Khoiyangbam, Kumar, & Jain, 2004; Nazir, 1991). In addition, surplus biogas can be intentionally released into the atmosphere and this could be very significant (Thien Thu et al., 2012). Biogas production in household digesters depends on the type of feedstock, ambient temperature and residence time. The Chinese fixed dome digester, operated in China for example, makes use of cow and pig manure and the volume usually ranges between 6 and 10 m^3 (Chen, Yang, Sweeney, & Feng, 2010; Jiang, Sommer, & Christensen, 2011). These digesters produce between 0.1 and 0.3 m^3 [biogas] m^{-3} [reactor volume] d^{-1} (Jiang et al., 2011).

Since methane, a strong GHG, is the main component of biogas, emissions from household reactors via leaks and the deliberate release of surplus gas threaten to outweigh the benefits of household biogas plants in mitigating the release of GHG. The known sources of methane loss in the digester are the inlet and outlet pipes, cracks in the tubing and walls of digesters, and intentional release of biogas into the atmosphere whenever gas production is greater than demand. The latter is the greatest source of the emission of biogas into the atmosphere (Prapaspongsa, Christensen, Schmidt, & Thrane, 2010; Thien Thu et al., 2012). For instance, about 15% of biogas produced yearly in Thailand is released and flared-off (Prapaspongsa, Pholchan, Hansen, Poulsen, & Christensen, 2009). In Vietnam, data from Vu and Dinh (2012), showed 65% of household digesters had surplus biogas which was released into the atmosphere because it could not be used. The total losses of biogas from all these sources have been estimated to be as high as 40% of that generated. However, emissions vary depending on location, weather and materials of construction (Bruun, Jasen, Vu, & Sommer, 2014).

The gas storage capacity of a CDD is directly related to the positions of its inlet and outlet pipes, and to displacement in the expansion chamber because biogas is stored above the slurry. Biogas release occurs because little effort has been put into optimising and improving the CDD. To the best of our knowledge, there is no specific literature or study on the prevention of gas leakage from the inlet and outlets of the CDDs as a result of excess or unused biogas. A recent study of (Rupf, Arabzadeh, De Boer, & McHenry, 2017) described a model for the estimation of the daily methane potential and the gasholder volume in a fixed dome digester, but the model was not validated and it failed to include the pressure component which is an important parameter. The objective of this study was therefore to develop a mathematical model that can be used to design the location of the inlet and outlet, height and volume of the extension chamber, thereby indirectly estimating gas storage in the dome and helping designers and operators of CDD to plan biogas demand and storage in to avoid leakage through the inlets and outlets and prevent the intentional release of biogas into the atmosphere.

2. Methods

2.1. Model development

The model focuses on the displacement level of slurry in the inlet pipe and the extension chamber as a result of the pressure build-up in the dome caused by biogas production.

Feeding of the digester occurs through the inlet pipe and the slurry level in the extension chamber is usually in equilibrium as shown in Fig. 1. The gas produced is accumulated in the upper part of the dome. The slurry level difference in the expansion chamber and the inlet is the result of the pressure build-up, as shown in Fig. 2. The stored gas expands and forces some of the slurry into the effluent chamber and inlet