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Investigation of Heat Transfer Associated with Deenbandhu Brick Built Anaerobic Digester Covered with Single-layer Soil Type

Vhutshilo Nekhubvi† and David Tinarwo
Department of Physics, University of Venda, Private Bag x5050, Thohoyandou, Limpopo 0950, South Africa
†Corresponding author: Vhutshilo Nekhubvi

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ABSTRACT

Energy in the form of heat is one of the important components of anaerobic digestion of cow manure, household waste, landfill waste, human waste and many others. This paper discusses the results of the investigation of heat transfer to a single layer soil type covering a 6 m^3 Deenbandhu 2000 biogas digester and the heat gained by bio-slurry undergoing anaerobic fermentation inside unstirred, unheated brick built digester. The thickness of the soil layer was measured to be 0.25m starting from the tangential top of the digester to the soil surface. Measurements of temperature were averaged in an hourly basis and the initial time (0700h a.m.) was chosen due to the observation that both soil and the slurry temperatures were found to be rising up until such time (1600h p.m.) where a drop is noticed. The Fourier law of diffusion was applied in order to facilitate the computation of the soil surface heat flux using soil surface temperature and soil volumetric heat capacity and soil volumetric heat conductivity as inputs. The variation of heat gained by the slurry was found to be in good agreement with the variation in soil surface heat flux. The slurry temperature and soil surface temperature were found to be closely related (R^2 = 0.949).

INTRODUCTION

In today's world, energy is regarded as a developmental key each society needs. Energy is found being used in industrial, residential areas, farms as well as in educational environment to light up building, run generators, power office appliances, etc. Research institutions and industries around the globe are researching on existing energy types in order to make them environmental friendly and efficient. Most of the energy types that are currently used in meeting our needs are non-renewable energy technologies (nuclear, coal and oil). Biogas as one of the renewable energy source (Kocak-Enturk et al. 2007, Zhang et al. 2016) yield a certain level (less compared to non-renewable energy) of input to support economic activities and is used in almost all countries in the world and is also under investigation. Biogas technology is a technology that convert organic degradable bio-waste through the anaerobic digestion (AD) process. Bio-wastes include but not limited to forestry residues, agricultural, municipal solid and liquid wastes, human food wastes, and considerable quantities of manure excreted by ruminant animals (Al-Rousan & Zyadin 2014). Anaerobic digestion primarily focuses on energy production known as biogas which is a mixture of gaseous compounds, principally methane (CH_4) and carbon dioxide (CO_2) (Zhang et al. 2016). Zhang et al. (2016) indicated that numerous studies were reported on all aspects of biogas production, processing and utilization. Production of biogas occurs inside a closed physical container called biogas unit or digester. Low cost biogas units like brick built, could be build using local construction materials and the size could be determined according to quantities of daily bio-waste produced from the nearest source. For anaerobic digestion process to start, organic materials are mixed with water at a desired ratio depending on the material type. Unlike in other countries like Germany cow dung is of focus in rural areas in South Africa and in India. Ratio of 1:1 of cow dung and water mixture is mainly used and this was tested in the laboratory under different temperature ranges. Research has shown that production of biogas depends on biological and chemical processes, physical dimension as well as social factors. Of all the factors mentioned, temperature as a physical quantity is regarded as the most influential parameter. The latter is also indicated in the study of Rennuit & Sommer (2013), and is given by the expression that represent biogas production, where the digester is not stirred:

$$\gamma(HRT, \mu m, T_d) = B_o \times [1 - \frac{k}{\mu m(T_d)} \times (HRT + \frac{1}{\mu m(T_d)}) - 1 + k] \quad ...(1)$$

Where k is the kinetic constant, T_d is the digester temperature, B_o is the biochemical methane potential determined by a batch fermenting test ($L_{CH4}\ kg^{-1}VS$), and HRT is the hydraulic retention time (days) and μm represent bacterial growth rate adapted to psychrophilic conditions and is given by;

$$mm(T_d) = 0.0019e^{0.1478\times T_d} \qquad ...(2)$$

Anaerobic digestion requires supply of heat that is neither at a low nor high temperature range. Anaerobic digestion temperature ranges (psychrophilic, mesophilic and thermophilic) have been studied (Alemayehu 2016, Mane et al. 2015, Khoiyangbam 2015, Khan & Martin 2016, Borjesson & Berglund 2006) and these studies show the highest temperature of 68°C and lowest temperature of 10°C. If the concentration of methane is plotted as a function of time for these three temperature ranges from the first day of fermentation, the concentration tends to increase from the start and then when a certain point of time is reached, the concentration peaks. After the peak, a drop in concentration occurs. An increase in concentration of methane from the start until the peak is reached in time is in the order of thermophilic, mesophilic and psychrophilic. The above order can also be used to show that hydraulic retention time (HRT) is less from thermophilic to psychrophilic. Thermophilic range is applied for artificial heated digester only, whereas psychrophilic and mesophilic are for unheated digesters although in some cases heat is supplied to obtain optimum temperature in both psychrophilic and mesophilic ranges when heat transferred to the soil, which is assumed to obey the Fourier law of diffusion, is unable to provide sufficient heat to the fermenting slurry inside the digester.

Researchers have put their efforts in trying to increase heat to the digester by installing greenhouse tunnels and circulating pipes with warm water inside the digester. The motivation of this study is that household size digesters installed in the Limpopo Province are underground and the energy to heat them can only be associated with heat distribution into specific locations where the systems have been constructed. Thus, an incoming amount of heat flux striking the soil surface affect the internal temperature of the digester. Ayata et al. (2011) indicated that approximately 27% of total incoming solar radiation is reflected, plants and soil absorb only 60% of it and 13% is transmitted into the soil. The absorption and transmission of solar energy into the soil causes the soil to heat up to a certain temperature allowing the digestive system to change slurry temperature. In numerous heat transfer models such as Axaopoulos et al. (2001) and Wu et al. (2009), brick built fixed-dome digesters especially Deenbandhu model are not properly modelled.

Other studies can be cited on heat transfer associated with anaerobic digestion such as simulation and experimental performance of a solar heated anaerobic digester (Axaopoulos et al. 2001); heat transfer model for plug-flow anaerobic digesters (Gebremedhin et al. 2005); development of 3-D anaerobic digester heat transfer model for cold weather applications (Wu & Bibeau 2006); three-dimensional numerical simulation model of biogas production for anaerobic digesters (Wu et al. 2009); mathematical modelling, finite element simulation and experimental validation of biogas-digester slurry temperature (Baral et al. 2013); thermal simulation of biogas plants using matlab (Sain & Nene 2014); and thermic model to predict biogas production in unheated fixed-dome digesters buried in the ground (Terradas-III et al. 2014). Of all the reviewed papers, researchers used various types of digester systems for their heat transfer studies in order to develop a biogas digester that produces the required energy throughout the year. However, of these systems, report or study of a brick built fixed dome biogas digester system, more particularly unstirred, unheated, uninsulated and fully covered Deenbandhu model is not available. The lack of information type of the digester creates a set up to investigate the relationship of heat supplied through the top surface of the digester and heat gained by the fermenting slurry inside the digester during the day. The objectives of this study were to construct a brick built fixed dome Deenbandhu biogas digester with 6 m^3 in bulk volume to find the relationship between soil surface heat flux and heat absorbed by the fermenting slurry inside the digester during the day.

MATERIALS AND METHODS

Experimental arrangement: In Thulamela local municipality, the selected site for this study is Vele Secondary School of geographical coordinates 22°45’56.08”S, 30°20’34.44”E. The school is located in a rural village of Gogogo found in Vhembe district in Limpopo province. Three brick built biogas digesters were monitored for the period of eight months (May-December 2015). The digesters were constructed following the design of a fixed dome Deenbandhu 2000 model digester as in Cheng et al. (2013). The materials used to build digesters were cement bricks usually used for building houses in the area, each with thermal conductivity (λ), concrete slab at the bottom of each digester. The inner and outer walls of the digester were plastered and only painted with waterproof paint inside each digester to prevent gas and water leakage. The fermenting slurry temperature inside the digester and the soil surface temperature were measured using Multi Con CMC-141 data logger. The data logger was fitted with the K-type NiCr-Ni temperature sensors. The temperature sensors were located at the centre of the digester for slurry temperature measurements and at 0.5 mm for soil surface (skin) temperature. The data were logged every second and were automatically averaged on an hourly and daily basis by the logging device. The computation was based on the following major assumptions:

- The geometrical top surface or dome of the digester is spherical cap and is covered with a single layer type of soil of 0.25 m in thickness.
- Properties of the feeding slurry (specific heat, thermal conductivity and density) added to the system are assumed to be equivalent to the properties of the slurry inside the digester with the exception of temperature, which is assumed to be equal to ambient temperature.
- Feeding temperature does not significantly contribute to the variation of slurry temperature inside the digester.
- Slurry in the digester is not stirred, heated and the temperature is not constant.
- Radiative heat losses between the slurry surface and the biogas is neglected during the absorption of soil heat flux by the slurry.
- The temperature of the outer wall of the digester at a given depth is equal to the soil temperature at that depth.

Theoretical consideration: According to Wang & Bras (1999), the heat transferred to the soil where the digester is buried is assumed to obey the Fourier law of diffusion given by the following expression;

$$\frac{\partial T}{\partial t} = D_0 \frac{\partial^2 T}{\partial z^2} \qquad ...(3)$$

Where, T represents soil temperature, z is the soil depth and D_0 is a constant thermal diffusivity. Hence, soil heat flux equation obtained from the diffusion equation was then used to facilitate the computation of the soil surface heat flux instead of solar radiation flux equation. The principal heat supplied to the slurry through the digester is taken as equal the soil surface heat flux since solar influx calculations does not take soil properties into account. The expression developed by Wang & Bras (1999) to compute soil surface heat flux is applied and is given by.

$$Q_{\text{sup}} = G(t) = \sqrt{\frac{k_s C_s}{p}} \int_0^t \frac{dT_s(s)}{\sqrt{t-s}} \qquad ...(4)$$

Where, $G(t)$ is the soil surface or soil surface heat flux (Wm^{-2}), k_s represents the volumetric heat conductivity ($Jm^{-1}s^{-1}K^{-1}$), C_S is the volumetric heat capacity of the soil material ($Jm^{-3}K^{-1}$) and T_s is the soil surface temperature over the period of time t and s is the variable of integration. The expression above is a time-series of soil surface temperature. Heat gained (Q_{gained}) by the slurry inside the digester is given by the equation:

$$Q_{gained} = \frac{m_{slurry} C_{slurry} dT}{dt} = \frac{m_{slurry} C_{slurry} \sum_{i=0}^{N} T_{i+1} - T_i}{(t_{i+1} - t_i)} \qquad ...(5)$$

Where, m_{slurry} is the mass of the slurry inside the digester, C_{slurry} is the specific heat capacity of the slurry inside the digester, $DT = T_{i+1} - T_i$ is the temperature of the slurry, t represents the period when the temperature starts to rise from minimum until the maximum value of temperature is reached. Calculations of both soil surface heat flux and heat gained by the slurry were carried out using hourly average temperature data from 0700h a.m. to 1600h p.m. for each month.

RESULTS AND DISCUSSION

Fig. 1 shows the total amount of monthly energy accumulated by the slurry inside the digester. It can be seen from the bar graph that the slurry acquired more heat compared to the other months during the month of May followed by June, August, July, October, September, November and December.

Whilst still focusing on the information presented in Fig. 1, the increment of the heat gained values by the fermenting slurry were found to be in the order of 52.46 kW, 54.76 kW, 57.53 kW, 60.75 kW, 75.37 kW, 75.56 kW and 76.85 kW during December, November, September, October, July, August and June then 78.09 kW during the month of May. But looking at the averages of the slurry temperature over the period of nine hours of each month, it is found that the increment is in the order of 20.90°C, 21.26°C, 23.01°C, 23.08°C, 24.38°C, 26.56°C, 27.20°C and 29.25°C during the month of June, July, August, September, May, October, November and December. From this observation, it can be emphasised that warmest months (e.g. December and November) simply warrant the possibility of low heat requirement of the digester. In this study we attempted to investigate why the warmer month (December) yield lowest heat requirement compared to the colder month (June). It was found that during the colder month, the minimum temperatures is 5.0°C and the maximum temperature is 30.65°C. During December month the least temperature is 19.95°C and the maximum temperature is 38.75°C. Hence, the temperature difference in an hourly basis was found to be greater during colder months than in warmer months. Another point to note is that as the difference between the low and high temperature in a given period of time increases, the total heat gained also increases. This is understandable because of Eq. (5).

Fig. 2 shows estimated results of soil heat flux. The horizontal axis presents the days and the vertical axis shows

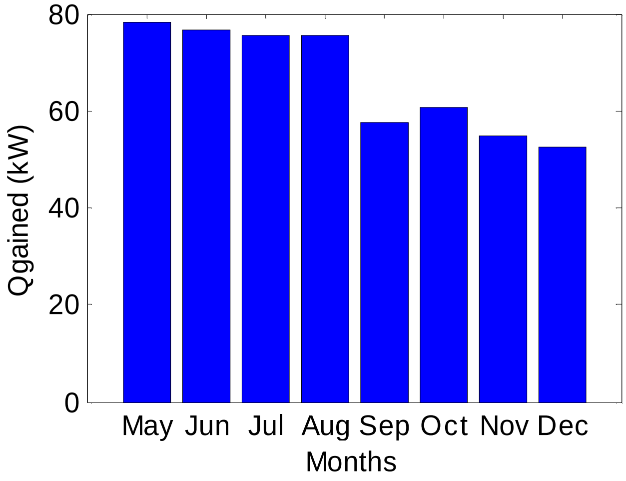

Fig. 1: Total heat gained by the fermenting slurry.

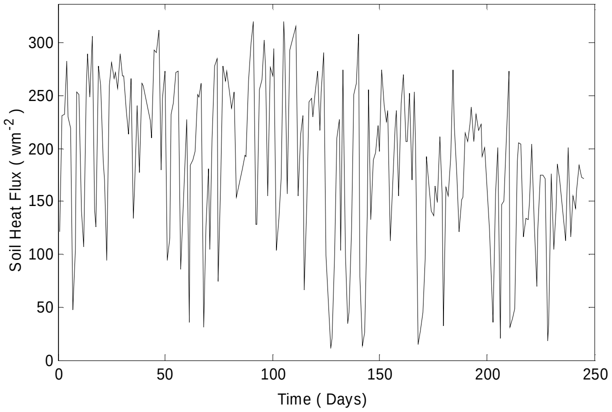

Fig. 2: Results of soil surface heat flux over a period of 245 days.

soil heat flux. The starting time of the integration was set to 0700h a.m. and end at 1600h p.m. of each day in order to enable soil heat flux estimates. As shown in Fig. 2, daily sums of the soil heat flux estimated by Eq. (4) depend on the temperature difference of the soil at its surface since it is assumed that the soil properties remain constant in order to simplify the calculations.

Fig. 3(a) shows the relationship between the total heat gained computed over the period of 245 days and soil surface heat flux. As shown in the figure, horizontal axis presents the heat gained and the vertical axis shows soil heat flux. The variation of heat gained by the slurry was found to be in good agreement with the variation in soil surface heat flux. The RMSE of 5.33×10^{-6} and linear slope nearly to 1 were obtained from the linear polynomial curve. The relation obtained from the linear fit in Fig. 3(a) suggests that the heat gained by the slurry may be obtained from the soil surface heat flux since the two comprise a set of connected variable as shown by the regression equation:

$$Q_{gained} = 0.358G(t) + 3.44e^{-13} \qquad ...(6)$$

Fig. 3(b) shows the relationship between the average slurry over the period of 245 days and average soil surface temperature. Horizontal axis presents the soil surface temperature and the vertical axis shows slurry temperature. It shows that slurry temperature and soil surface temperature are closely related (R^2=0.949), leading to a linear regression Equation:

$$T_{slurry} = 1.13T_s + 0.18 \qquad ...(7)$$

Using the equation derived by Katterer and Andren (2009) to express T_{slurry} in Eq. (7), leads to the extended regression equation.

$$T_{slurry} = 1.13[T_{air} \times (s_1 + (1 - s_1)e^{(-s_2(LAI - LAI_{ref}))})] + 0.18 \qquad ...(8)$$

Eq. (8) simply suggests that ambient air temperature could be a substitute to predict slurry temperature provided Eq. (8) satisfy the conditions stipulated by Katterer & Andren (2009).

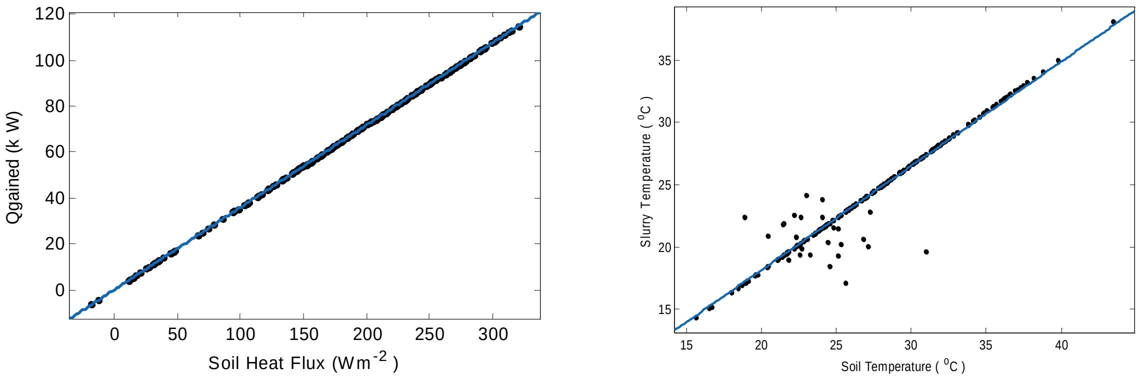

Fig. 3(a): Relationship of heat gained and soil surface heat flux, (b) Relationship of slurry temperature and and soil surface temperature.

CONCLUSIONS

The results of the calculations of the heat absorbed by the digester over a given period of time must be interpreted in a manner that is understandable. The choice of using soil layer as insulator of the cover was to avoid implications on digester economics. The objective of this study was to construct a brick built fixed dome biogas digester in order to investigate the relationship of soil surface heat flux and heat absorbed by the fermenting slurry of cow manure and water inside the digester during the day. The objective has been achieved and if extended, the relationship could turn to be a useful tool to forecast slurry temperature depending on the daily ambient temperature variation.

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