Leadership in Sustainable Infrastructure

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Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

DESIGN AND OPERATION OF ACTIVELY-AERATED FIELD-SCALE METHANE BIOFILTERS

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ABSTRACT

Methane is the second most prevalent contributor to global warming after CO_2, with a global warming potential 34 times higher than CO_2. 60% of global methane emissions are a result of human activities such as the oil and gas industry, livestock farming, and landfilling. In the oil and gas industry, excess or unwanted flammable gases are often disposed by flaring or venting. Methane biofiltration is an economically feasible, low maintenance, biological method that can remediate low volume point source methane emissions from sources such as oil wells, and landfills. An active aeration closed methane biofilter (MBF), first of its kind, was designed, constructed and installed at a single well battery site in Hannah, AB. The MBF was packed with 100% compost into a $4m^3$ conical frustum shaped tank at a density of $800kg/m^3$. The source methane supply consists of 92% CH_4 and the inlet CH_4 flowrate varying between $10\text{-}25m^3/day$. Heated air was mixed with methane and injected into the bottom of the MBF to diffuse uniformly across the MBF. Inlet and outlet methane flowrate, air flowrate, inlet temperature and the temperature inside different locations of the MBF will be monitored throughout the lifetime of the MBF. The efficiency of the MBF will be calculated using this information, and will determine the carbon offsets achieved. This paper presents preliminary results during the operation of the MBF and the study of the temperature profiles.

Keywords – Methane, Biofiltration, Active-Aeration, Field-Scale, Design

1. INTRODUCTION

Methane (CH_4) is 34 times more effective at absorbing radiation than CO_2, even though it has a short lifetime (~10 years) in the atmosphere. Therefore, over a 100-year period CH_4 has a global warming potential 34 times higher than CO_2. The average global methane concentrations increased by a factor of 2.5 since pre-industrial times, from 722 parts per billion (ppb) to 1800 ppb by 2014, a concentration unprecedented within the last 800,000 years (IPCC, 2014). 60% of these emissions are a result of human activities such as natural gas and petroleum systems, enteric fermentation, solid waste landfills, and coalmines. Waste landfills produce biogas as a result of anaerobic degradation of waste, contributing towards 17% of the worldwide anthropogenic CH_4 emissions (Wuebbles and Hayhoe, 2002). When the CH_4 concentration in biogas is above 30% (v/v), the collected biogas can have economic value and practical use. In such instances, biogas is burnt in boilers for heating and other purposes. However, when the CH_4 concentration is lower than 30% (v/v), collected biogas is burned on site in order to reduce the risks of explosion associated with CH_4, or vented to the atmosphere (Streese et al., 2003).Methane biofiltration technology can be used remediate such low volume, point source, methane emissions.

Methane Biofiltration (MBF) Technology

Treatment of CH_4 through methane biofiltration technology aims at the aerobic conversion of CH_4 to CO_2 by methanotrophic bacteria. Methanotrophs are capable of converting CH_4 to CO_2 without producing unwanted by-products, making this a very attractive solution compared to any other method of handling CH_4. Methanotrophs are found in natural environments such as tropical forests, grasslands and meadows, landfill cover soils, deserts, and agricultural soils (Nikiema et al., 2007). The simplified biological degradation reaction of methane is given by eq.1

[1] $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + bacterial biomass (-890 KJ/mol)

A methane biofilter is a box like structure designed and constructed to achieve maximum methane oxidation by utilizing this phenomenon. Solid biofiltration medium, nutrients and water for growth of microorganisms and sufficient porous space for gas exchange, are the three essential constituents of a functional methane biofilter. MBFs can be classified into two main configurations, closed system and open system (Nikiema et al., 2005). Open systems are mostly found in landfill sites and utilizes a passive aeration system. Gas collected through a landfill gas collection system is directed to the bottom of the landfill, thus the flow proceeds upwards through the filter bed, while oxygen diffuses downwards from the ambient air into the bed. However, open systems are highly susceptible to environmental conditions, and pose problems in field scale MBFs as its filter media is constantly subjected to rainfall, snow and wind. Closed systems are more desirable as it is more controlled and allow for better estimation of the conditions inside the system. Since closed systems do not receive ambient oxygen from the top, they are aerated actively using an air distribution system. As can be seen from the equation above methane oxidation is an exothermic reaction producing heat energy (Reible, D. D., 1998). Therefore MBFs are capable of retaining its temperature above zero degrees even during cold winter months

Application of MBF technology in the oil and gas industry

In the oil and gas industry, excess or unwanted flammable gases are often disposed by flaring or venting. Flaring is the process of combusting the gases in an open atmosphere, to dispose flammable gases such as methane cost-effectively. However, if the emission flowrates are too low or too intermittent, or the heating value of gas is too low to sustain combustion, it is not economically feasible to burn surplus gases in a stable method. These low volume point source emissions could be directed into a methane biofilter instead of venting it directly to the atmosphere.

An active aeration field scale methane biofilter was designed, constructed and installed at a single well battery site in Hanna, AB. A battery is a facility where production fluid from a well is separated into gas, oil and water. A storage tank is used as a treater which separates the fluid into these three layers; salt water at the bottom, crude oil emulsions in the middle and natural gas at the top. The gas layer at the top may also contain solution gas which gets released when the fluid pressure in the treater is reduced. The methane biofilter discussed in this paper is designed to receive a line of natural gas from the storage tank as the source of methane and would receive 92% CH4 with some impurities consisting of salt water and crude oil.

2. MATERIALS AND METHODS

Apparatus

Currently all field scale MBFs are open biofilters employing a passive aeration system. A closed MBF with active aeration was proposed for this site due to anticipated extreme weather conditions with high winds and high snowfall. Having the MBF closed, protects the media from rainfall, snowfall, and provides better control over the MBF.

As can be seen in figure 1, the system was designed to consist of a conical frustum shaped tank accompanied by a housing structure, built using 2”x4” wooden blocks on the wooden skid next to the tank.

The curved walls of the tank offer less wall resistance during gas migration as opposed to a box like structure with sharp corners. The housing structure stores all monitoring equipment and the air blower to pump air into the MBF. This provides a confined space to heat thus ensuring that the air sent into the tank is at a desired temperature.

The use of the wooden skid has two main advantages. It provides a stable structure to transport the setup and possible relocations at a later time. In addition, it ensures that the structure remains levelled over time. If some settling was to occur due to the weight of the tank**,** this would still be uniform.

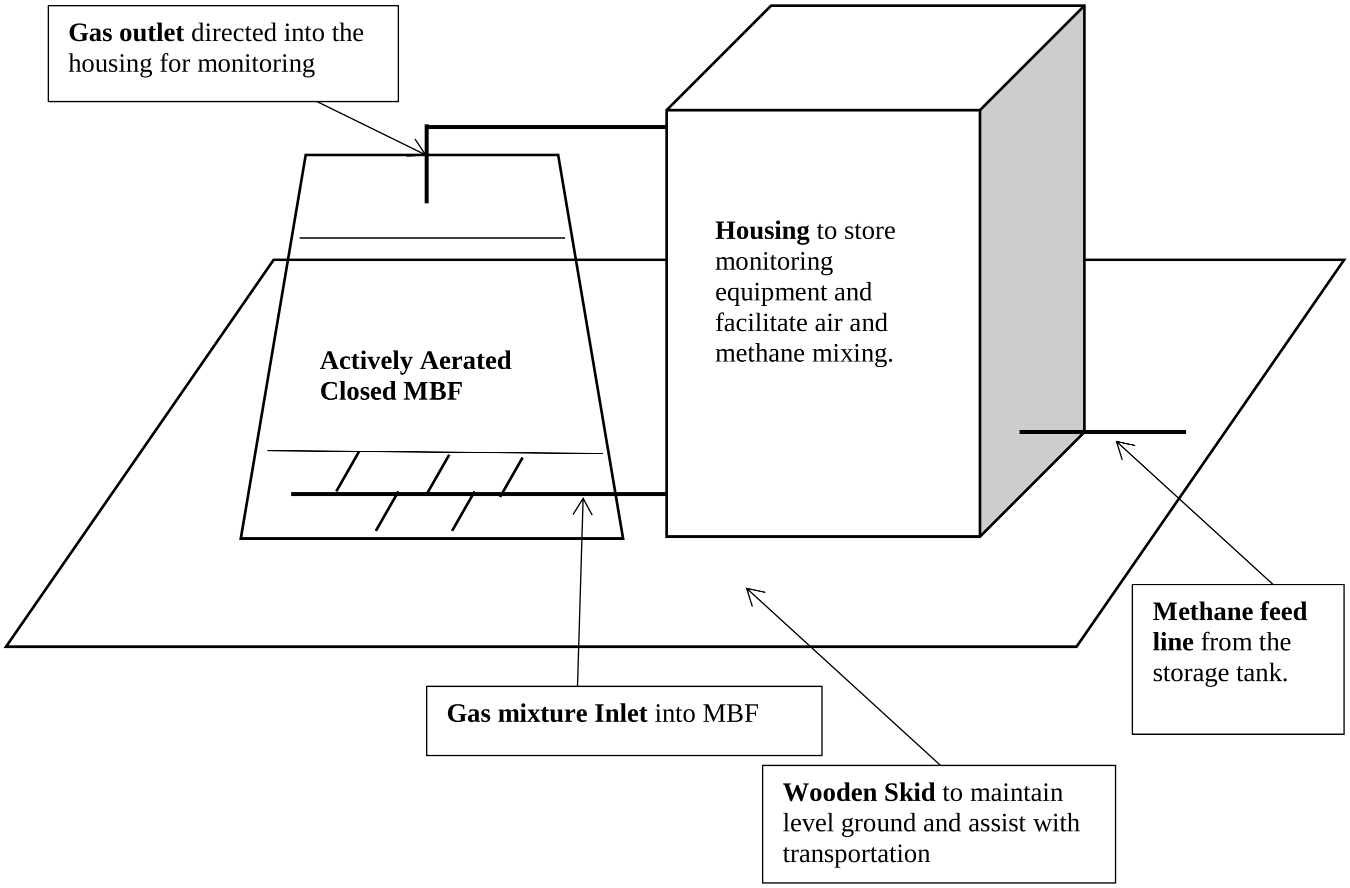

Figure 1: Schematic of MBF

An active MBF has an expected efficiency three times higher than a passive MBF. Therefore, a higher concentration of methane could be treated within a smaller volume. The current MBF has a volume of $4m^3$ and a maximum intake capacity of about $40m^3$/day of CH_4. This would provide an empty bed retention time of 2.4 hours. The actual retention time will be lower when the tank is packed with compacted media thus providing sufficient time for the microbes to act on the methane. A commercially available HDPE water tank was chosen to serve as the MBF which saves the additional cost of a custom made tank. Figure 2 shows the exact dimensions of the tank.

The internal walls of the housing and the external walls of the tank were insulated using 2” closed cell spray foam insulation providing an R value of 12.5. In order to protect the insulation foam from UV damages it was painted with a double coating. The lid of the tank was sealed by weather stripping the top perimeter of the tank and then wrapping coper pipe insulation around the edge. Silicone was passed inside the insulation to tighten the seal ensuring there were no leaks through the lid of the tank.

Gas Distribution System

At design capacity, the MBF would receive $40m^3$ of methane and $200m^3$ of air, adding up to a total of $240m^3$ of air-methane mixture per day. This gas should be well mixed and uniformly distributed across the cross section of the MBF. The gas distribution system consists of a piping network, gravel, and a geotextile to undertake this task. The distribution system was fabricated using 2” ABS pipes, with holes drilled into its surface to distribute the gas. The hole sizes were calculated to increase in diameter systematically, thus ensuring that the rear end of the MBF will receive equal amounts of gas as the front end. The distribution system was tested by connecting an air blower into the inlet to confirm that air was passing through all sides of the distribution system uniformly.

The holes were drilled at 45 degree angles facing the bottom to allow the gas to first reach the bottom of the tank, and seep up uniformly. 20mm crushed concrete gravel was filled up to about 10cm. Next, the gas distribution system was placed on top of the gravel and levelled using small wooden blocks. More gravel was filled on top of the distribution system to tightly secure it's positioning, and finally, the geotextile was placed on top of the gravel layer to prevent compost from settling down and clogging the gravel layer. A compressed CO_2 cylinder was used to send gas through the distribution system, and flux measurements were taken at the surface of the geotextile to confirm uniform distribution throughout the perimeter of the tank.

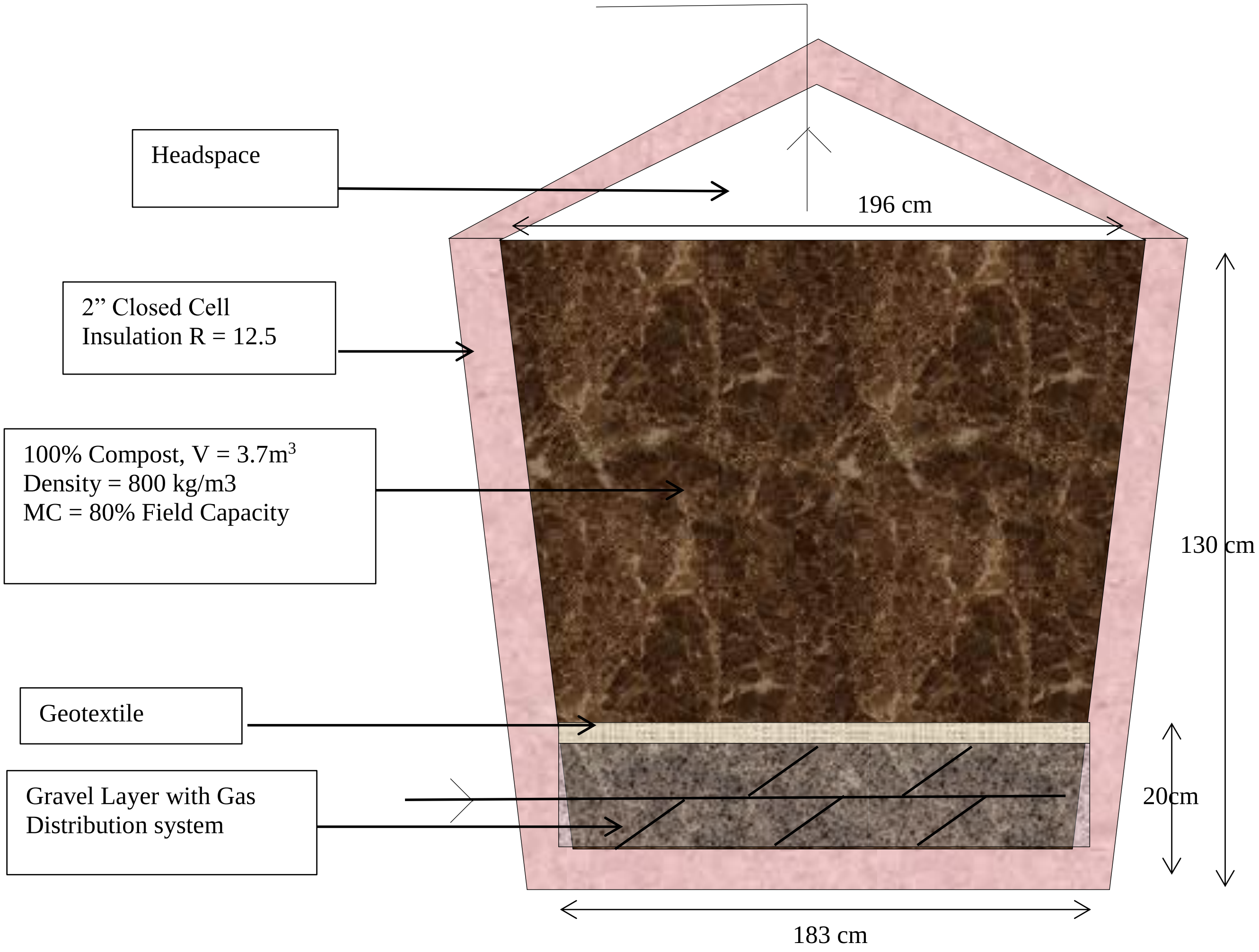

Figure 2: Detailed Schematic of MBF

Active Aeration System

According to stoichiometry (eq. 1), an air to methane ratio of 10:1 (v/v) is optimum for methane oxidation. However, increasing the air flow would result in higher flowrates resulting in a reduced retention time. If the time of contact between methane and the MBF media is limited, the methantrophs would not have sufficient time to oxidise the methane. Therefore an air to methane ratio of 5:1 was chosen. Thus, the system is designed to receive 200m3/day of air, with the option to increase if need be.

A 24 V DC, air blower which could send in up to 650m3/day (16 CFM) is used to pump air. This blower is powered by two adjacent 100W, 12V solar panels, connected to two 12V,100Ah AGM Batteries. A 12V catedyne heater, which uses natural gas as its power source, will be installed to heat the housing structure, was installed and set to heat the housing structure to about 15°C thereby heating the air that will be pumped into the MBF. Figure 3 shows the details of the air supply system.

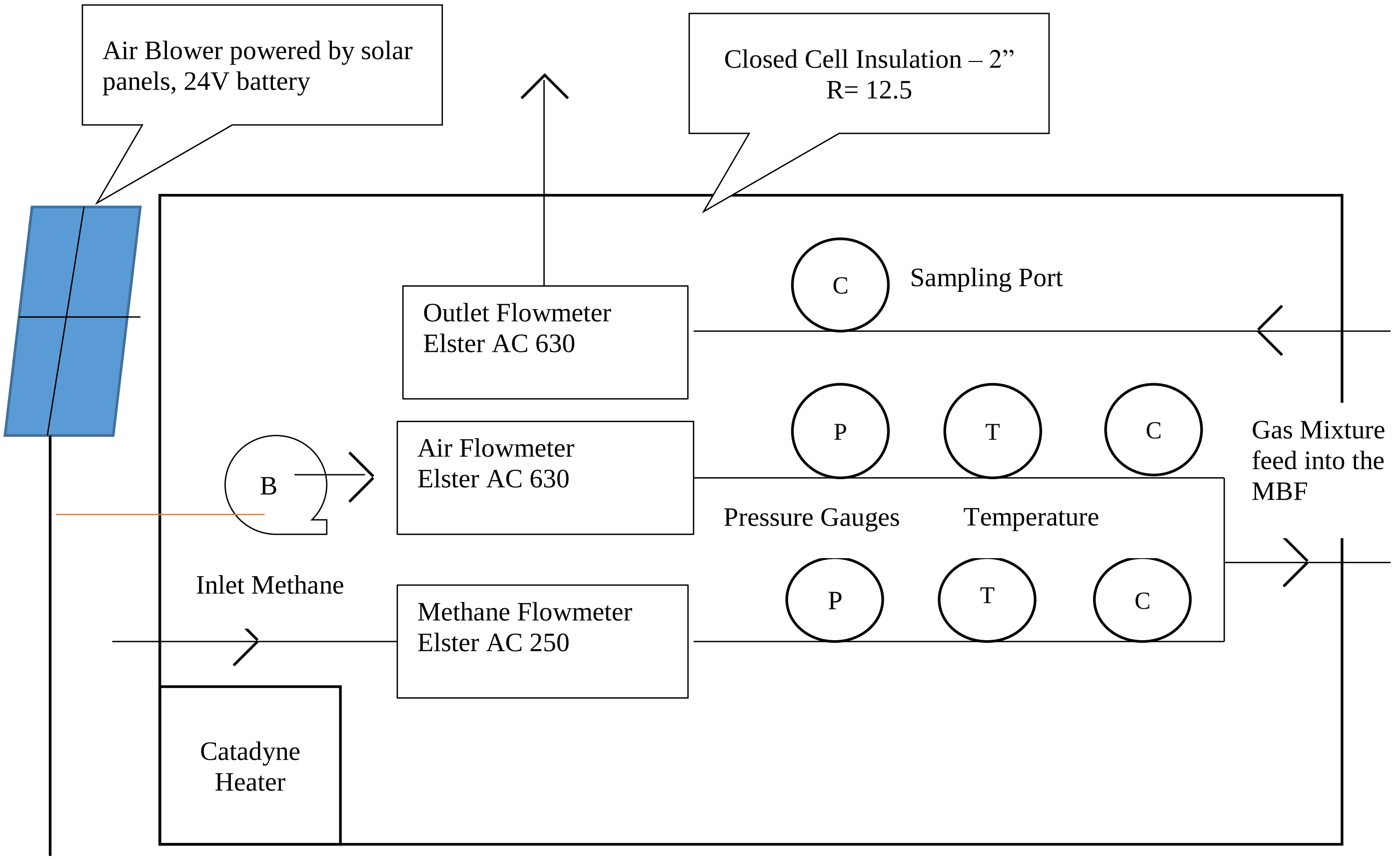

Figure 3: Detailed Schematic of Housing

Materials

Compost has a high organic content, nutrients and water holding capacity, providing an ideal environment for methanatrophs and yields the best oxidation efficiencies during laboratory experiments (Hettiaratchi, J. P. and O. Hurtado, 2010). It also has known parameters such as the thermal conductivity and specific heat capacity rather than when using a mixture of media. Compost was collected from the East Calgary Landfill, and tested to measure the moisture content, field capacity and dry solids content. Table 1 shows the media properties of the compost.

Moisture content (MC), dry solids (DS)

The Moisture contents (MC) of compost samples were determined by drying 10 g of in an oven (model 1510 E, Sheldon Manufacturing Inc.) at 105 ◦C for ~12 h until a constant weight was obtained. The weight of the sample before and after drying was measured (scale model: METTLER AT 250, Fisher Scientific). The weight lost during drying was the MC and the weight remained was the DS content.

Field capacity (FC)

Funnel experiments were conducted to determine the field capacity (FC) of the compost. First, the material was oven-dried at 105 ^{o}C for 2 h. A filter paper was wetted, drained and fitted into a 500 mL funnel. The funnel was filled with the compost samples and the bottom tip of the funnel was closed. Known volume of water was added slowly to the compost until it was saturated. A beaker was placed at the bottom of the funnel, the bottom tip was opened, and the drained water was collected. The water was allowed to drain for ~1 h, until no water drained into the beaker. The field capacity was calculated using the difference between the added water and the collected water volume.

Table 1: Media properties

Media	Field Capacity (FC)	Moisture Content (MC)	Dry Solids (DS)
100% Compost	50%	40%	60%

The compost was packed into the tank systematically to achieve the desired density i.e. 800kg/m^3. CO_2 was passed through the MBF using a compressed cylinder after every 20cm of packing, to ensure equal distribution of gas until it was confirmed that the gas reached the top of the filter in all sides of the tank.

Methods

Methane Removal Capacity/Efficiency

During operation, the performance of the MBF is measured by its methane removal capacity. Inlet and outlet methane flowrates and air flowrates are measured using flowmeters as can be seen in Figure 3. Inlet gas concentration and outlet gas concentrations are also measured through sampling ports as seen in Figure 3. If there are no leakages in the system, the efficiency of the MBF can be calculated using the flowrates and concentration measurements.

Operation and Maintenance

Controlling the back pressure is a major concern during operation of the MBF. Since the tank is closed, the pressure inside the tank could build up. This MBF, when packed to design criteria will have a pressure of 8.6KPa (P = 1.1m*800kg/m3*9.81m/s2). Therefore, the methane and air entering the MBF should have a pressure greater than this value in order to reach the top of the MBF. Furthermore, methane and air together is flammable, and its contact with electricity could be very dangerous. Therefore it is important to have control over the air to methane ratios at all times, as well as the pressures within the gas lines. Three way valves are installed to divert the flow and take pressure, temperature and concentration measurements from the corresponding gas lines as seen in figure 3.

Temperature modelling

Methane oxidation is an exothermic reaction and generates heat. Therefore, there is a direct correlation between the temperature rise inside an MBF and the methane oxidation that took place during a given period time. 15 Temperature sensors were installed in three levels as shown in figure 4 to monitor the temperature profiles inside an MBF.

One sensor will be kept outside to record the ambient temperature data, and the temperature inside the housing structure is recorded. The 15 sensors are connected to two data loggers, and stored inside the housing structure.

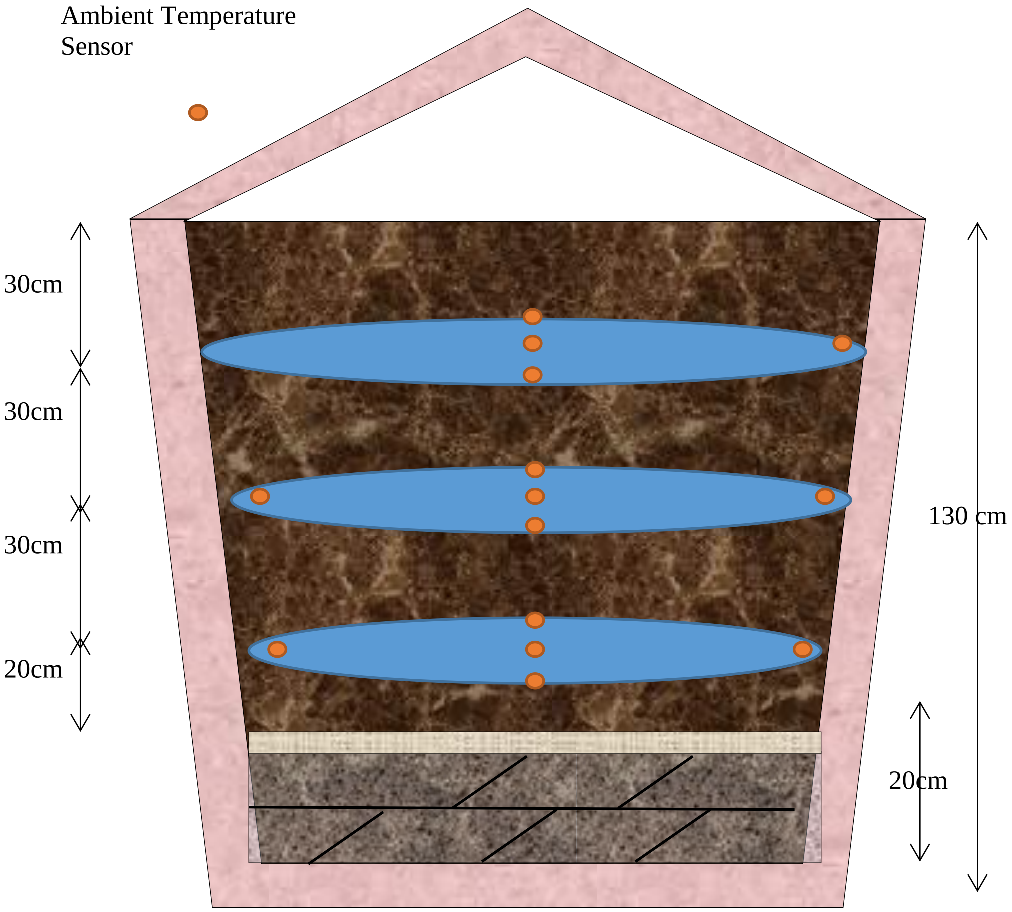

Figure 4: Temperature Sensor Locations

3. PRELIMINERY RESULTS

Baseline data of the temperature variation inside the MBF was obtained before the methane supply was connected to the MBF. This would show how to the solar radiation, wind and soil insulation affects the temperature inside the MBF, before methanatrophic activity takes place. It is also a good indicator of whether there are other bacterial activities acting as a heat source inside the MBF.

Figure 5 shows how the average temperature inside the MBF changes with the change in ambient temperature during the month of September. As can be seen, the temperature inside the MBF is consistently lower than the outside temperature. This difference in temperature is due to the thermal resistance caused by the HDPE walls, insulation and compost of the MBF. Therefore, these preliminary results can quantify to which degree the atmospheric temperature influences the temperature inside the MBF.

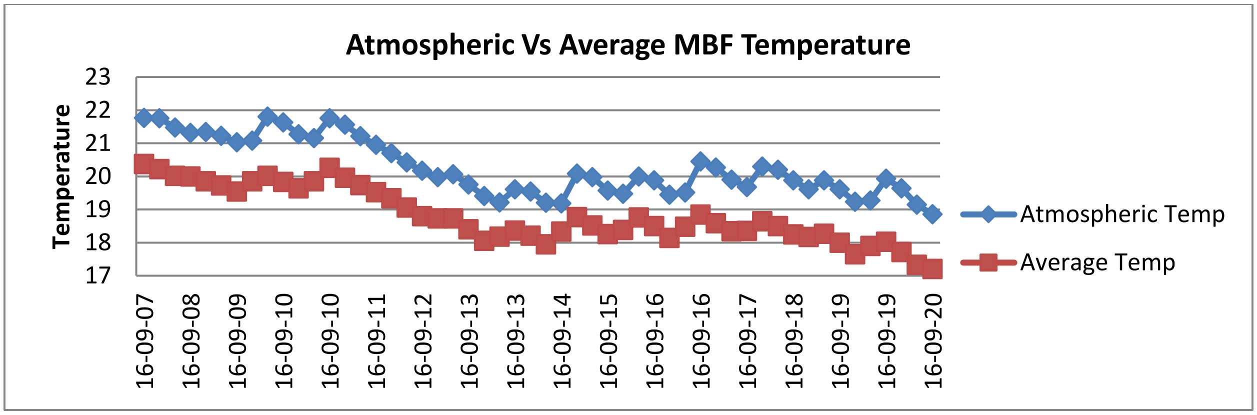

Figure 5:Change in MBF temperature with ambient temperature

The CH_4 supply from the storage tank was connected to the MBF on 20th of September 2016. Table 2 tabulates the source CH_4 composition.

Table 2: Source Methane Composition

Source Methane Composition (%)	
CH_4	91.7
CO_2	0.15
O_2	1.85
N_2	7.63

During the seeding period of an MBF, methanatrophic activity will be low. Therefore the MBF will not be able to perform at a high efficiency. The temperature fluctuations inside the MBF give a good indication of the amount of CH_4 converted to CO_2 by methanotrophs. Figure 6 shows the average temperature change inside the MBF from November 2016 to March 2017. The temperature inside the MBF reduces to about 10°C between December to January (the coldest months) indicating the seeding period, but gradually increases to about 40°C by the beginning of March.

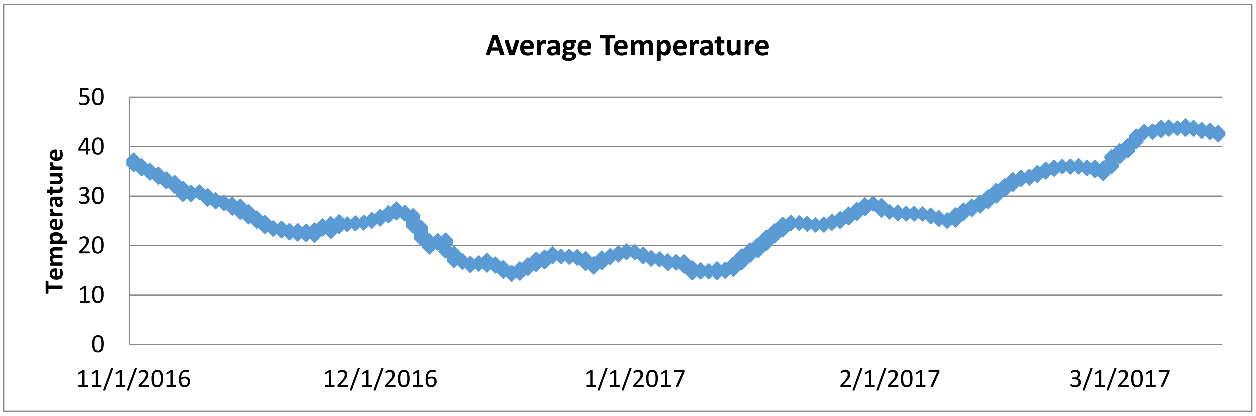

Figure 6: Change in average MBF temperature over time

The contour plots in Figure 7 and 8 show the distribution of heat across the cross section of the MBF at 60cm and 90cm on 1st of December.

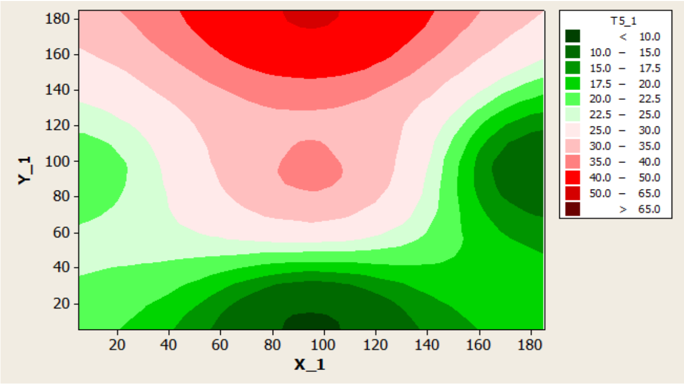

Figure 7: 60cm below surface level

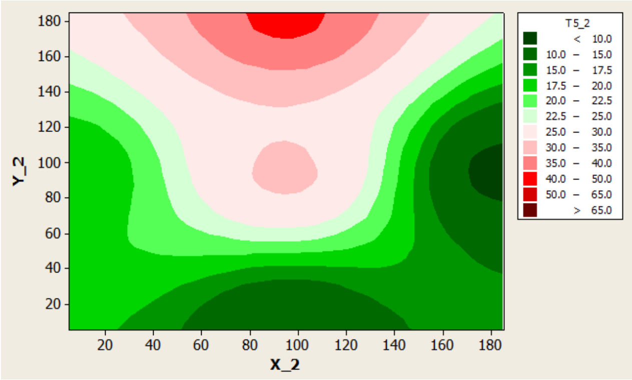

Figure 8: 90cm below surface level

As can be seen the temperature inside the MBF was higher than 10°C, which was much greater than the recorded average atmospheric temperature (-5°C) on 1st of December confirming bacterial activity. It is also evident that the temperature follows the exact pattern at both the surface levels although there is a slightly higher average temperature at 60cm. Since the two opposite sides of the tank have the highest and lowest temperatures, this could be due to the wind direction and solar radiation falling directly onto one side. Compost sample from various locations of the MBF should be analysed for its nutrient content and bacterial population to confirm findings.

The methane and air flow-rates were manipulated based on the temperature indications of the MBF performance. Composition of the inlet and outlet gas mixtures were measured using a Gas Chromatograph (GC) and the efficiency of the MBF was calculated based on equation [2]. Equation [2] includes a N_2 component, which accounts for dilution that takes place through the addition of air. Table 3 shows how the efficiency of the MBF improved over time.

[2] $Efficiency = (CH_{4,in} - CH_{4,out} * (N_{2,in}/N_{2,out}))/CH_{4,in} * 100$

Table 3: MBF performance

Date	Gas	Flowrate (m3/day)	Inlet Conc. (%)	Outlet Conc. (%)	Efficiency (%)
27/02/2017	CH_4	23	11.52	7.38	38.73
	O_2	121	19.32	19.34	
	N_2		72.98	76.31	
	CO_2		0	0	
13/03/2017	CH_4	23	11.11	6.5	42.75
	O_2	171	18.89	20.9	
	N_2		70.85	72.4	
	CO_2		0.2	0.2	
10/4/2017	CH_4	21	64.2	2.5	98.45
	O_2	5	8.18	20.92	
	N_2		30.74	77.47	
	CO_2		0.11	0	
10/4/2017	CH_4	8.15	26.88	0.49	98.65
	O_2	15	15.82	21.41	
	N_2		58.68	79.15	
	CO_2		0.03	0	

4. CONCLUSION

Methane biofiltration is an economically feasible, low maintenance, biological method that can remediate point source methane emissions from sources such as oil wells, and landfills. An active aeration closed methane biofilter (MBF) was constructed and installed at a single well battery site in Hannah, AB during the summer of 2016. The MBF will receive source methane consisting of 92% CH_4 with a design capacity of oxidizing $40m^3$/day of methane. 100% compost, with moisture content at 80% field capacity is used to pack the MBF to a density of $800kg/m^3$. It is insulated to achieve a 12.5 R-value, and minimize heat loss during cold months. Flow rates of inlet and outlet methane, flowrate of the air, inlet temperature and the temperature inside different locations of the MBF are monitored throughout the lifetime of the MBF. Initially the methane supply was connected to the system at a flow rate of $20m^3$/day, and will be increased gradually as the MBF starts to oxidize methane at its full capacity Preliminary temperature profiles inside the MBF show that there is bacterial activity inside the MBF and is rapidly increasing. This inference is also confirmed by the increasing efficiency calculated using inlet and outlet methane concentrations. A 98% efficiency was obtained at the lower flow rate of $21m^3$/day with minimal air supply, suggesting that the MBF is now ready to accept a higher load of CH_4. However, temperature inside the MBF is not uniform across its cross section, suggesting presence of hot spots with higher bacterial activities, or a non-uniform effect of ambient conditions on the MBF. Further analysis on compost at different locations of the MBF is required to confirm the bacterial population at different areas of the MBF.

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