Environmental Research Journal 8 (1): 21-29, 2014
ISSN: 1994-5396

Abatement of Odorous VOC Emissions in Biogas Power Plants by Biofiltration: A Review

Temitope A. Oshin
Chemostrides Process Company, P.O. Box 6733, Ikeja, Lagos, Nigeria

Abstract: Centralized Anaerobic Digestion (CAD) power plants are renewable energy solutions which generate electricity and heat from the combustion of biogas produced from animal manure and other organic wastes. Odour and Volatile Organic Compounds (VOC) emissions from these plants unless controlled are bound to constitute menace to the environment. In this review, biofiltration was established as the most suitable abatement technology for odorous VOC removal in the waste air stream of biogas plants. While other technologies often generate secondary wastes which require further treatment down stream there by incurring more costs, biofiltration does not and is often found less expensive. However, making a good design of a biofilter demands careful considerations of the bed material, microbes to be employed and a thorough characterisation of the polluted gas stream to be treated. This assessment report also examined the technical impacts of adopting this biological technology which has found application in publicly-owned treatment works, the pulp and study industry among others.

Key words: Biofiltration, biogas, anaerobic digestion, volatile organic compounds, odour control

INTRODUCTION

Biogas systems are increasingly being exploited as renewable energy sources. Other objectives such as bio-fertilizer, waste recycling, rural development, public health and hygiene have been identified as contributing drivers to the proliferation of these systems in many parts of the world (DaSilva, 1978). Decentralized farm-scale biogas plants are commonly employed to meet domestic or communal farm-site energy needs but few centralized industrial-scale biogas plants which address energy needs commercially exist as well. In a Denmark case study, Raven and Gregersen (2007) noted that the first ideas of these centralized plants emerged in the 1980s. A centralized anaerobic digestion strategy for the UK was proposed in 1995 owing to the observed poor performance of the on-farm plants (Dagnall, 1995). This review would focus on Centralized Anaerobic Digestion (CAD) plants producing biogas for Combined Heat and Power (CHP) generation from animal manure with possible blend from industrial organic wastes. At least, twenty such plants are running in Denmark (Al Seadi, 2000; Raven and Gregersen, 2007). The UK has the Holsworthy Biogas Plant in West Devon as her first large-scale plant. As at 2007, it was regarded as the only CAD power station in the UK (Monson *et al*., 2007). The concept of the centralized plants is captured in Fig. 1 (AEBIOM, 2009). It is the objective of this study to systematically identify the principal pollutant emanating from CAD biogas power plants (odorous volatile organic compounds) and arrive at a suitable abatement technology (biofiltration) and to further provide important information about the design and technical impact of the technology.

Centralized biogas power station: Process description, although, there are variations in the design and operation of these plants, the common process would be described under subheadings of feed collection and preparation, biological reaction process and product purification and utilization.

Feed collection and preparation: Cattle, pig and poultry manure in slurry form, collected from neighbouring farms is the usual feed to the plants. Supplementary organic wastes from industries and sewage treatment plants may be collected as well. These are collected by vacuum tankers or trailers and are discharged in reception tanks or pits where they are mixed. Further mixing may take place in buffer tanks to achieve desired concentrations. Some plants, like the Holsworthy Biogas Plant, employ a pasteurization pre-treatment step (Fig. 2) for a minimum residence time of 1 h at 70°C to kill pathogens and weed seeds. Heat-exchangers are used to bring the organic waste mixture to this pasteurizer temperature. After pasteurization, the waste is then taken through a heat recovery system for cooling to the digester temperature.

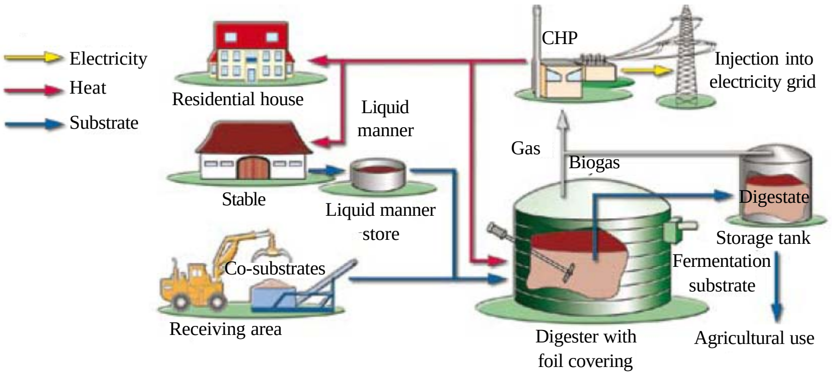

Fig. 1: The centralized biogas plant concept (AEBIOM, 2009)

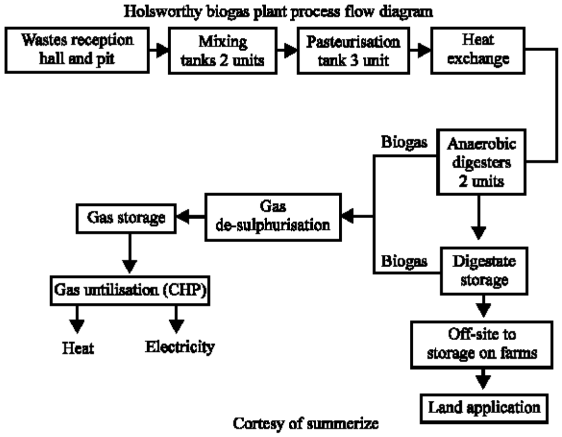

Fig. 2: Simplified flow sheet of the Holsworthy biogas plant. The plant processes 400 tonnes day^{-1} of animal manure and generates 4 million $\text{m}^3\ \text{year}^{-1}$ of biogas and 800-1000 MWh month^{-1} of electricity (Monson *et al*., 2007)

Biological reaction process: The pre-treated biomass is introduced into reactors known as anaerobic digesters in which certain bacteria degrade the organic waste. Digester size and number vary from plant to plant. Two 4000 m^3 continuous stirred tank bioreactors are used at Holsworthy (Monson *et al*., 2007). The operating temperature as well may differ.

Two ranges are possible: mesophilic (30-40°C) and thermophilic (50-60°C) (DaSilva, 1978). For example, Denmark's Ribe, Lintrup and Thorso plants employ the thermophilic temperature of 53°C (Al Seadi, 2000) while a mesophilic temperature of 37°C is used at UK's Holsworthy plant (Monson *et al*., 2007) as well as the Danish Fangel and Hashoj plants (Al Seadi, 2000). Typical residence time may take up to 10-30 days (Engler *et al*., 1998).

Product purification and utilization: Biogas produced in the digester is a mixture of gases containing mainly methane (50-70%), carbon dioxide (25-35%) and trace amounts of nitrogen, sulphur compounds, volatile organic compounds and ammonia (UNEP-BASE, 2005). Most plants adopt further purification treatment steps to increase the methane content of the gas before utilizing it for power generation. The toxic and corrosive hydrogen sulphide content, especially is removed in a desulphurization unit (usually a scrubber) before storing the gas. Scrubbing in water will help reduce the formation of sulphur dioxide in the combustion process as it also rids the gas of some of its carbon dioxide content and bring the gas' methane purity to 95% (Ilyas, 2006). The scrubbed gas is then withdrawn for use in CHP engines. In some Danish plants where excess gas is produced, it is also used to fire gas boilers to produce additional district heating (Al Seadi, 2000). A degraded substrate known as digestate is also produced which is stored and sold as bio-fertilizer for farm use.

Process effluent emissions and environmental impact: Biogas power stations inherently serve as solutions for environmental safety and sustainability. The conversion of biogas from animal and organic wastes to useful green energy has been lauded for a number of advantages which include the reduction of potential landfill emissions, offset of equivalent fossil fuel energy consumption and significant reduction of Greenhouse Gases' (GHG) emissions (Susta, 2007).

However, like every industrial activity, a biogas plant also produces effluent emissions with potential impact on the environment. It is the goal in this section to identify these emissions and their possible sources from the process operation.

Effluent emissions

Waste odorous air: The reception and storage of animal waste slurry is usually done in an enclosed area where the collecting lorries are emptied into the reception pit or tank. This is typical of the Holsworthy plant. The effluent air from this enclosure is very odorous. This is caused by

Volatile Organic Compounds (VOCs) released from the waste. Methane emissions are also expected from the storage of these wet organic feedstocks (UNEP-BASE, 2005). The larger scale of the storage facilities found in centralized plants gives indication of substantial methane and non-methane VOCs emissions. Pathogens and hydrogen sulphide are also likely to be contained in the odour-marred air.

Raw biogas leakages: In its environmental due diligence guidelines for biogas systems, the United Nations Environment Programme (UNEP-BASE, 2005) identified possible emissions of raw unscrubbed biogas from leaks in the gas collection system as a potential environmental risk common to all biogas production facilities.

Combustion gases: During the combustion process, carbon dioxide is released. It has been argued that the carbon dioxide emissions from biogas plants do not contribute excess additions of the gas into the environment as it is believed that it is the carbon which is already existent in the natural cycle that is being released. Other combustion gases like nitrogen oxides, sulphur oxide, particulates and trace amounts of toxic materials may be produced alongside carbon dioxide (UNEP-BASE, 2005).

Pollutants involved: Some of the pollutants released through the earlier listed effluent sources are thus listed:

- Volatile organic compounds
- Methane
- Carbon dioxide
- Hydrogen sulphide
- Nitrogen oxides
- Sulphur oxides
- Pathogens

VOCS (The principal pollutant emission): Effective scrubbing could reduce hydrogen sulphide to the acceptable maximum exposure limit of 20 ppm from roughly 2000 ppm (UNEP-BASE, 2005) and hence significantly lower the sulphur oxides emission from the combustion to acceptable concentration. Again, carbon dioxide emission from a CAD biogas plant can be viewed as mere reconversion of existent natural cycle carbon and less harmful than methane from which it is generated in the process. Furthermore, biogas leakages are minimized by improving the design and operation of the gas collection systems.

However, the menace of odour emissions from organic feedstock storage facilities is poised to be the principal pollution problem from the biogas plant and thus raise major environmental concerns. This odour nuisance is owed to odorous VOCs emanating from the animal wastes thus making VOCs the key pollutant emission of a biogas plant.

Environmental impact of VOCs: Volatile organic compounds are noted to have a major impact on tropospheric chemistry (Atkinson, 2000; Badr, 2009a). In fact, biogenic Non-Methane VOCs (NMVOC) resulting from natural processes (such as the degradation of animal wastes) have higher atmospheric reactivity than anthropogenic ones and thus play a dominant role in the chemistry of the lower troposphere (Atkinson and Arey, 1998). In the presence of nitrogen monoxide (NO) emitted to the atmosphere, VOCs engage in reactions leading to the formation of ozone and likely formation of photochemical smog (Atkinson and Arey, 1998; Khan and Ghoshal, 2000). They also generate CO and other reactive VOCs and constitute a source of organic nitrogen compounds which act as temporary reservoirs for NOx (Badr, 2009a).

SELECTION OF SUITABLE VOC CONTROL TECHNOLOGY

A number of technologies and techniques are available to control VOC emissions. These have been classified as shown in Fig. 3 by Khan and Ghoshal (2000).

Possible VOC control technologies

Enclosing the source: Enclosing the source is one of the process modification techniques that can be adopted for this application. It is found in practice at the Holsworthy plant where organic waste is received and stored in an enclosed building. However, this is not sufficient in itself. It must be backed up by effective effluent collection and end-of-pipe treatment methods (Khan and Ghoshal, 2000). Some of these are outlined in this study.

Destruction by oxidation: When burned, most VOCs produce less harmful materials which can easily be controlled (Badr, 2009b). Two main methods can be used to destroy VOCs by combustion: thermal oxidation and catalytic oxidation.

Destruction by biofiltration: This method is the commonest for treating odorous waste air. Micro-organisms immobilised on a filter bed degrade the VOCs aerobically.

Control by absorption: In this technology, the waste gas stream is stripped of VOCs by contacting it with a liquid solvent.

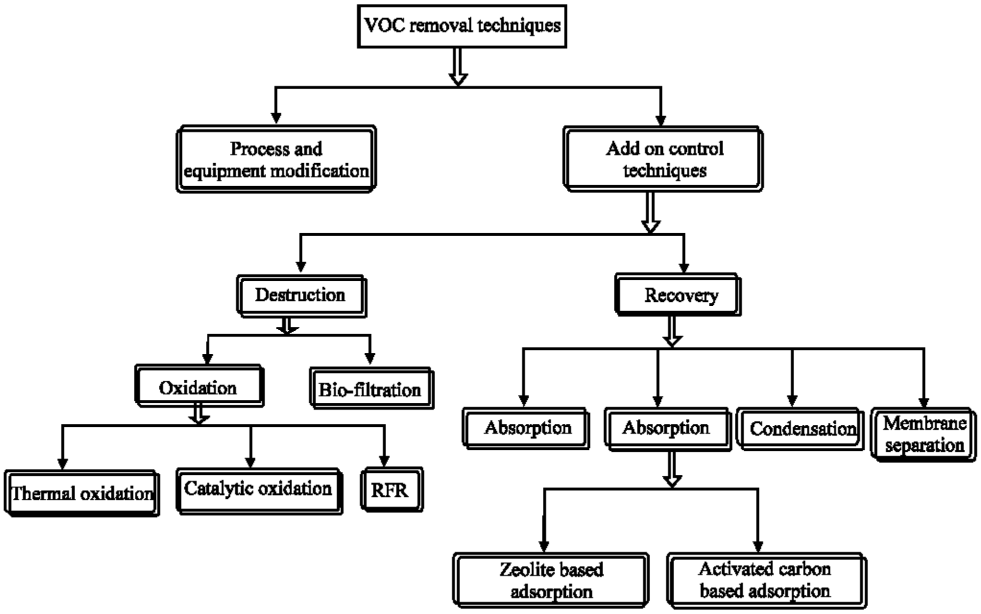

Fig. 3: Classification of VOC control techniques (Khan and Ghoshal, 2000).

Control by adsorption: By using adsorbents like activated carbon and zeolite, VOCs can be removed from polluted air streams.

Control by condensation: It is possible to remove VOCs from a gas stream by cooling the stream to a temperature low enough to achieve condensation of most of the VOCs (Badr, 2009b). This condensation may be achieved at chilling (Khan and Ghoshal, 2000) or even cryogenic (Gupta and Verma, 2002) temperatures.

Selection of suitable technology: To aid in evaluating the suitability of a VOC control technology for a particular application, a list of selection parameters to consider was provided by Khan and Ghoshal (2000), some of which are as listed:

- Source characteristics
- Recycle potential
- Variability of loading
- VOCs composition
- Maintenance
- Cost
- Removal efficiencies

Few strong parameters on this list would be discussed to arrive at a final choice of technology.

Recycle potential: Recycle potential represents the evaluation of the need to partially recover costs of the control equipment by recycling (Khan and Ghoshal, 2000). It is not desirable to recover the VOCs for reuse as would be necessary in certain chemical industries where they are important to the cost of the process (for example, use as solvent). Hence, the recovery techniques of VOC control (absorption, adsorption and condensation) would not prove suitable for this application.

Furthermore, some of these methods may create additional pollution control problems and would require another processing step (s) to finally combat the emissions. For instance in absorption, stripping of VOCs from the absorbing solvent would require further separation and incur additional costs. The same can also be said of adsorption.

Removal efficiency and waste generated: Removal efficiency puts the combustion (oxidation) technologies top among the destructive techniques now under consideration (Table 1). However, the possibility of generating toxic combustion products which would require further processing raises, again, the issue of costs. The catalytic oxidation technique was noted as a good option by Khan and Ghoshal (2000) when VOCs recovery is not important. That not with standing, biofiltration was also positively commended by the researchers as a bright option. It would be adjudged best for this application for its increasing use for similar waste treatment processes and a number of other reasons as would be discussed further.

Table 1: Analysis of various VOC control techniques (Khan and Ghoshal, 2000), VOC control techniques

Techniques	Annual operating cost ($/cfm)	Removal efficiency (%)	Secondary waste generated	Positive remarks	Negative remarks
Thermal oxidation	15-90 for recuperative 20-150 for regenerative	95-99	Combustion products	Energy recovery is possible (maximum up to 85%)	Hallogenated and other compounds may required additional control equipment downstream
Catalytic oxidation	15-90	90-98	Combustion products	Energy recovery is possible (maximum up to 70%)	Efficiency is sensitive to operating conditions. Certain compounds can poison the catalyst many require additional control equipment downstream
Bio-filtration	15-75	60-95	Biomass	Requires less initial investment less non-harmful secondary waste and non-hazardous	Slow and selective microbes decomposes selective organics thus require a mixed culture of microbes (which is difficult). No recovery of material
Condensation	20-120	70-85	Condensate	Products recovery can offset annual operating costs	Require rigorous maintenance. Not recommended for the materials having boiling points above 33°C
Absorption	25-120	90-98	Wastewater	Products recovery can offset annual operating costs	Require rigorous maintenance. May require pretreatment of the VOCs. Design could be different due to lack of equilibrium data
Adsorption activated carbon	10-35	80-90	Spent carbon and collected organics	Recovery of compounds which may offset annual operating cost	Susceptible to moisture and some compounds (ketones, aldehydes and esters) can clog the pores thus decreasing the efficiency
Zeolite	15-40	90-96	Collected organic spent zeolite after several cycles	Effective in >90% RH, recovery of compounds offset annual operating costs	High cost of zeolite, restricted availability
Membrane separation	15-30	90-99	Exhausted membranes	No further treatment recovery of solvent may offset the operating costs	Membranes are rare and costly

The secondary waste generated by biofiltration is biomass which is not harmful and hazardous. Therefore no additional treatment steps are required. The operating conditions are also mild. All these advantages are in addition to its cost benefits.

Cost: Biofiltration requires less initial investment (Khan and Ghoshal, 2000) although still viewed as comparable to those of alternative technologies (Badr, 2009b). Operating costs are minimal as well (Badr, 2009b). It should be noted that each of the VOC control techniques possesses some form of disadvantages and none can prove superiority as "one-fits-all" in industrial applications. Table 1 provides the analysis of the VOC control techniques and reviews each. Ultimately, a proper approach to the assessment and characterisation of the odorous air often holds the key to making the best judgement (Kleeberg *et al.*, 2005).

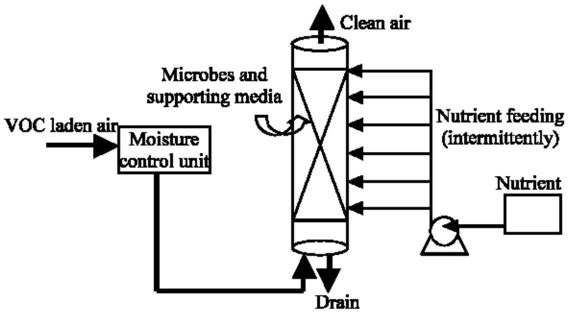

Fig. 4: A simple schematic sketch of a biofiltration system (Badr, 2009b)

Odorous VOC control by biofiltration

Description of technology: Biofiltration is a process in which polluted air stream is contacted with a porous packed bed on which micro-organisms are immobilised to degrade the pollutants in the stream (Khan and Ghoshal, 2000; Badr, 2009b). There is an initial process of adsorption of the pollutants from the polluted air stream to the water-biofilm phase of the supporting medium (Khan and Ghoshal, 2000). Then, the micro-organisms degrade these pollutants producing carbon dioxide, water and biomass in the process (Andres *et al.*, 2006; Khan and Ghoshal, 2000). A schematic representation of a biofiltration system is shown in Fig. 4.

Biofiltration is regarded effective for the removal of VOCs, hydrogen sulphide and some other toxic emissions (Khan and Ghoshal, 2000). The success of the biofilter is dependent on the favourable condition created to support microbial activity. Humidity of the air-stream is controlled; likewise pH in order to meet the microbes' operating requirements (Badr, 2009b). Nutritional requirements are also supplemented. The filter bed size is also important and is often sized to provide residence time of 30-120 sec or more (Badr, 2009b) depending on application.

There are two types of biofilters: open-bed and closed-bed biofilters. The open-bed filters are in-ground or on-ground and are open. They are usually employed in treating exhaust from livestock facilities (Zhang *et al*., 2002). The closed-bed biofilters are closed packed-bed designs which are more suited for VOC and odour removal in industrial applications (Zhang *et al*., 2002).

Design considerations: For effective application of this technology, a number of important questions must be raised and answers attempted:

- What mix and concentration of VOCs is expected in the odorous waste air
- What kind or blend of microbes would be needed?
- What type of filter-bed material would be appropriate?
- What size of biofilter would be required?

Although, the crux of the design of a biofilter is the specification of the size of biofilter bed required for the duty however, the other considerations also have great impact on the performance of a biofilter. These other questions would therefore be briefly examined as well. It is important to state here that due to failures of poorly designed biofilters, some plant operators had been forced to prefer other treatment options (Streese *et al*., 2005). The new owners of the Holsworthy plant had to seek alternative control scheme because the initial biofilter design was not performing to expectation (Monson *et al*., 2007). Proper design is therefore paramount.

Biofilter sizing: One key design parameter for sizing a biofilter is the filter-bed volume required for a specific load. Two kinds of models are employed to estimate this: microkinetic and macrokinetic models (Streese *et al*., 2005). Microkinetic models are usually complex differential equations which attempt to capture all the mass transfer and bioconversion processes of the biofilter and in doing these often involve many empirical parameters to be determined. There has been observed limitations with these models (Streese *et al*., 2005). Macrokinetic models on the other hand do not explore such process details but use empirical means to model the biofilter behaviour with the aid of simpler kinetic design equations.

Streese *et al*. (2005) formulated a macrokinetic design equation which could be used empirically to estimate the volume of a biofilter. From elemental mass balances (Fig. 5) the following equation was obtained:

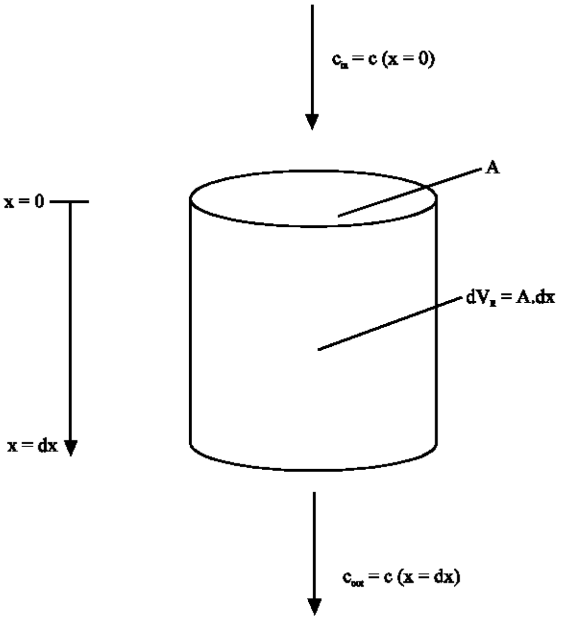

Fig. 5: Mass balance on a differential element of a biofilter (Streese *et al*., 2005)

$$V_R = \frac{\ln\left(\frac{C_{in}}{C_{out}}\right) + k_2 (C_{in} - C_{out})}{k_1} \times \dot{V}_g \tag{1}$$

The biofilter is predicted to follow first-order kinetics at low concentrations (with degradation rate linearly proportional to substrate concentration) then a later shift to zero-order at higher concentrations giving rise to a constant degradation rate. Often, it is sufficient to approximate the biofilter with first-order kinetics. Then, $k_2 = 0$ in Eq. 1 and the design equation simplifies to Eq. 2 (Streese *et al*., 2005):

$$V_R = \frac{\dot{V}_g}{k_1} \times \ln\left(\frac{C_{in}}{C_{out}}\right) \tag{2}$$

In using these equations to size a biofilter, the researchers outlined the following five-step procedure:

- Biofiltration experiments should be conducted at different concentrations covering the whole concentration range C_{in} to C_{out} expected for the application at the intended operating temperature
- The degradation rate r should be calculated from Eq. 3 and plotted against logarithmic mean concentration C_m (Eq. 4) for each experiment set:

$$r = \frac{(C_{in} - C_{out}) \times \dot{V}_g}{V_R} \tag{3}$$

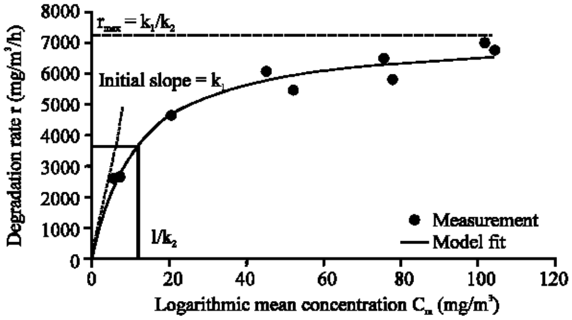

Fig. 6: Example of first to zero order kinetics for a biofilter (Streese *et al*., 2005)

$$C_m = \frac{(C_{in} - C_{out})}{\ln\left(\frac{C_{in}}{C_{out}}\right)} \quad (4)$$

- The reaction order can then be assessed from the plot. First-order kinetics can be assumed for a data plot which can be satisfactorily fitted by linear regression. But most data may follow the multiple orders of 1 and 0 as shown in Fig. 6
- The first and zero-order rate constants (k_1 and k_2, respectively) should then be determined either graphically or by non-linear regression according to Eq. 5. Linear regression for k_1 using Eq. 6 would be needed for a solely first-order approximation

$$r = \frac{k_1 c}{1 + k_2 c} \quad (5)$$

$$r = k_1 c \quad (6)$$

- Finally, the required biofilter volume to bring the intended VOC-polluted gas, supplied at flow rate $\dot{V}_g$, from concentration C_{in} to C_{out} can be calculated using Eq. 1 or 2

Waste gas' VOC mix, concentration and flow rate: It has been observed that in odour control, several hundreds of different compounds may be involved (Streese *et al*., 2005). In a recent study to degrade VOCs found in a landfill soil and gas recovery wells, Tassi *et al*. (2009) analysed 48-63 VOCs including many aromatics and alkanes. Knowing the kind and concentration level of VOCs contained in the odorous air in a biogas plant would help in the proper design of a biofilter.

Kleeberg *et al*. (2005) suggested odour assessment and characterization using olfactometry and physico-chemical analysis. The loading or flow rate of the waste gas is equally important.

Microbe type: Biodegradation is often achieved in a biofilter by mixed cultures of microbes with different substrate affinities (Streese *et al*., 2005). Hence, it is important to know what blend of microbes is needed to degrade the kind of VOCs found in the waste air stream to be treated. Bacterial cultures and other non-defined mixed cultures are being used. The use of fungi has also been reported (Kennes and Veiga, 2004).

Filter-bed material: The filter-bed is an important part of the biofilter providing more than just a growing surface for the microbes. The characteristics of the filter-bed packing are crucial. Certain mechanical, physical and biological properties which would strongly influence the efficiency and cost of a biofiltration system have been identified (Khan and Ghoshal, 2000; Andres *et al*., 2006):

- Void fraction usually 0.5-0.9
- Specific surface area between 300-1000 m^2/m^3
- Nutritive capacities to supplement microbes nutrient requirement not available in waste gas stream
- Strong mechanical resistance and low bulk density
- Significant water retention capacities with bed humidity of 40-60%
- High buffer capacities to avoid pH fluctuations

Various types of materials are employed in practice: compost, soil, wood chips, peat, wood bark and mixed materials (Khan and Ghoshal, 2000; Andres *et al*., 2006).

BIOFILTRATION FOR SIMILAR PROCESS APPLICATIONS

Biofiltration is a technology which has found application in many industrial air-treatment and waste water treatment processes. Examples of these processes would be examined, especially where biofilters are being employed to remove VOCs from waste air streams. This is to give breadth of application and lend credence to its suitability for containing odour in CAD biogas power plants.

Biofiltration in municipal waste treatment

Application in sludge and solid waste composting: During composting of wastewater sludges and solid wastes, odorous VOC gases are released. Gases like hydrogen sulphide, dimethyl sulphide, alongside ketones, alcohols and organic acids are some of the identified VOCs in composting exhausts (Pagans *et al*., 2006). The use of biofiltration to treat waste air contaminated by these gases during composting operations is considered one of the classical applications of the technology (Streese *et al*., 2005).

Application in aerosol can puncturing: In some Household Hazardous Waste (HHW) treatment facilities in the United States, biofilters are used to capture off-gases from puncturing several thousands of aerosol cans. These disposed aerosol cans are treated as hazardous wastes because many had been used for paint products, lubricants, polishes and cleaners and thus contain volatile organic solvents (Stewart and Barton, 1999). Therefore, in order to prevent the release of hazardous VOCs to the atmosphere during puncturing and recycling, there is need to capture and destroy the VOCs emitted during the process. Some special brands of biofilters have recorded success in this operation resulting in huge disposal savings in a particular HHW facility (Stewart and Barton, 1999; Garner and Barton, 2002).

Biofiltration for petroleum industry applications: Industrial researchers at the Bio-Reaction Industries, United States (Stewart and Barton, 1999) have demonstrated the suitability of their biofilter designs to control high loads of VOC emissions in the petroleum industry. VOC emissions originate in the petroleum industry from process vents and storage tanks' leakages. Their research detailed point-source mitigation applications to gasoline-derived VOCs from gasoline storage tanks and BTEX (Benzene, Toluene, Ethylbenzene and Xylenes) and non-BTEX VOC emissions from glycol dehydrators used in gas production fields for removing water and other contaminants from natural gas.

Biofiltration in the pulp and paper industry: During the kraft pulping process, certain odorous compounds are emitted. Hydrogen sulphide and organo-sulphur compounds like methyl mercaptan, dimethyl sulphide and dimethyl disulphide have been identified as principal odorous emissions (Wani *et al*., 1999). Biofiltration is a viable technology employed to combat these emissions.

TECHNICAL IMPACT OF BIOFILTRATION

The incorporation of pollution abatement technologies has undeniable impact on the operation and economics of a process. The use of a biofilter as odour and VOC control technique in a CAD biogas power station would likewise have technical impact on the process. Operational and maintenance issues would arise and constitute technical impacts.

Operational impact: The first obvious operational change to the process would be the additional energy requirement needed for the collection of the waste air from the emission source (s) and for its flow into the biofilter. Furthermore, the stringent moisture requirement of the microbes would require humidity and temperature control of the gas stream (Badr, 2009b) and this would bring additional control unit to the central plant control structure.

Maintenance impact: Certain long-term effects arise with biofilters that impinge on their operation thereby necessitating maintenance. Clogging would occur due to accumulation of biomass leading to reduced removal efficiency, hence, the need to remove excess biomass (Zhang *et al*., 2002). Depending on the packing material, filter-bed medium replacement is a practice which may be required every 3-5 years (Badr, 2009b). However, few novel packing materials like Biosorbens™ may have longer durability of 10-15 years (Prado *et al*., 2009).

CONCLUSION

Principal among the emissions of CAD power stations is odour caused by VOC releases from feedstock storage facilities. A number of control technologies exist for its mitigation but biofiltration offers the best characteristic advantages: conversion of pollutants to harmless biomass and lower costs. Its efficient operation however, is dependent on accurate design stemming from careful study of relevant process facts (waste gas' flow rate and VOC characterisation), informed choice of the equipment internals (microbial culture and filter-bed material) as well as knowledge of the macrokinetics of the system. Moisture control and filter-bed media replacement are bound to be the key operational and maintenance issues of technical significance.

REFERENCES

AEBIOM, 2009. A Biogas Road Map for Europe. European Biomass Association, Brussels.

Al Seadi, T.A., 2000. Danish centralised biogas plants-plant descriptions. http://www.ub.edu/bioamb/PROBIOGAS/centralcodig_descrip2000.pdf.

Andres, Y., E. Dumont, P. Le Cloirec and E. Ramirez-Lopez, 2006. Wood bark as packing material in a biofilter used for air treatment. Environ. Technol., 27: 1297-1301.

Atkinson, R. and J. Arey, 1998. Atmospheric chemistry of biogenic organic compounds. Acc. Chem. Res., 31: 574-583.

Atkinson, R., 2000. Atmospheric chemistry of VOCs and NO_x. Atmos. Environ., 34: 2063-2101.

Badr, O., 2009a. Atmospheric pollution. PSE 04: Environmental Management Lecture Notes, Cranfield University, UK.

Badr, O., 2009b. Control of atmospheric pollution. PSE 04: Environmental Management Lecture Notes, Cranfield University, UK.

DaSilva, E.J., 1978. Biogas generation: Developments, problems and tasks-an overview. Proceedings of the Conference on the State of the Art of Bioconversion of Organic Residues for Rural Communities, November 13-15, 1978, Guatemala, pp: 72-83.

Dagnall, S., 1995. UK strategy for centralised anaerobic digestion. Bioresour. Technol., 52: 275-280.

Engler, C.R., E.R. Jordan, M.J. McFarland and R.D. Lacewell, 1998. Economics and environmental impact of biogas production as a manure management strategy. Southern Economics Association, Corpus Christi, Texas. http://tammi.tamu.edu/Engler2.pdf.

Garner, L.G. and T.A. Barton, 2002. Biofiltration for abatement of VOC and HAP emissions. Metal Finish., 100: 12-18.

Gupta, V.K. and N. Verma, 2002. Removal of volatile organic compounds by cryogenic condensation followed by adsorption. Chem. Eng. Sci., 57: 2679-2696.

Ilyas, S.Z., 2006. A case study to bottle the biogas in cylinders as source of power for rural industries development in Pakistan. World Applied Sci. J., 1: 127-130.

Kennes, C. and M.C. Veiga, 2004. Fungal biocatalysts in the biofiltration of VOC-polluted air. J. Biotechnol., 113: 305-319.

Khan, F.I. and A.K. Ghoshal, 2000. Removal of volatile organic compounds from polluted air. J. Loss Prev. Process Ind., 13: 527-545.

Kleeberg, K.K. M. Schlegelmilch, J. Streese, H. Steinhart and R. Stegmann, 2005. Odour abatement strategy for a sustainable odour management. Proceedings of the 10th International Waste Management and Landfill Symposium, October 3-7, 2005, Cagliari, Italy.

Monson, K.D., S.R. Esteves, A.J. Guwy and R.M. Dinsdale, 2007. Case sudy-other AD waste treatment systems: Holsworthy (Summerleaze) biogas plant. University of Glamorgan, UK.

Pagans, E., X. Font and A. Sanchez, 2006. Emission of volatile organic compounds from composting of different solid wastes: Abatement by biofiltration. J. Hazard. Mater., 131: 179-186.

Prado, O.J., D. Gabriel and J. Lafuente, 2009. Economical assessment of the design, construction and operation of open-bed biofilters for waste gas treatment. J. Environ. Manage., 90: 2515-2523.

Raven, R.P.J.M. and K.H. Gregersen, 2007. Biogas plants in Denmark: Successes and setbacks. Renewable Sustainable Energy Rev., 11: 116-132.

Stewart, W.C. and T.A. Barton, 1999. High VOC loadings in biofilters-petroleum and industrial applications. Proceedings of the Gas Institute-Gas Industry Air Toxics Conference, May 24-26, 1999, San Antonio, Texas.

Streese, J., M. Schlegelmilch, K. Heining and R. Stegmann, 2005. A macrokinetic model for dimensioning of biofilters for VOC and odour treatment. Waste Manage., 25: 965-974.

Susta, M.R., 2007. Biogas production from MSW. Powergen Asia 2007, Bangkok-Thailand.

Tassi, F., G. Montegrossi, O. Vaselli, C. Liccioli, S. Moretti and B. Nisi, 2009. Degradation of C_2-C_{15} volatile organic compounds in a landfill cover soil. Sci. Total Environ., 407: 4513-4525.

UNEP-BASE, 2005. Environmental Due Diligence (EDD) of renewable energy projects: Guidelines for biogas systems. Release 1.0. United Nations Environment Programme and Basel Agency for Sustainable Energy.

Wani, A.H., A.K. Lau and R.M.R. Branion, 1999. Biofiltration control of pulping odours-hydrogen sulphide: Performance, macrokinetics and coexistence effects of organo-sulfur species. J. Chem. Technol. Biotechnol., 74: 9-16.

Zhang, Q., J. Feddes, I. Edeogu, M. Nyachoti and J. House *et al.*, 2002. Odour production, evaluation and control. Project MLMMI 02-HERS-03. Final Report Submitted to Manitoba Livestock Manure Management Initiative Inc., October, 2002.