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REMOVAL OF HYDROGEN SULFIDE FROM BIOGAS USING THE BIOFILTER INOCULATED WITH ACTIVATED SLUDGE CULTURES

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มณีรัตน์ วงษ์อุดม : การกำจัดไฮโดรเจนซัลไฟด์ออกจากก๊าซชีวภาพโดยถังกรองชีวภาพที่เพาะเชื้อจากกระบวนการแอคติเวเตดสลัดจ์. (REMOVAL OF HYDROGEN SULFIDE FROM BIOGAS USING THE BIOFILTER INOCULATED WITH ACTIVATED SLUDGE CULTURES) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: อ.ดร. ปฏิรูป ผลจันทร์, 154 หน้า.

ในการศึกษาการกำจัดไฮโดรเจนซัลไฟด์ (H_2S) ในระดับห้องปฏิบัติการครั้งนี้ ได้ ทำการคัดเลือกเชื้อจากกระบวนการแอคติเวเตดสลัดจ์ที่บำบัดน้ำเสียจากแหล่งต่างๆ และหาสภาวะที่เหมาะสมในการเลี้ยงเชื้อบนตัวกลางของถังกรองชีวภาพ 2 ชนิดคือ ฝาพลาสติกและเซรามิก ผลการทดลองพบว่ามีจำนวนของเชื้อที่โตในอาหารที่มีเฉพาะไธโอซัลเฟตเป็นแหล่งพลังงานจากน้ำเสียโรงงานเต้าหู้มากกว่าเชื้อจากน้ำเสียชุมชน โดยเชื้อสามารถเกาะอยู่บนตัวกลางเซรามิกได้ถึง 2.8×10^{11} cfu/L ของตัวกลาง ผลการศึกษาปัจจัยที่มีผลต่อการกำจัดไฮโดรเจนซัลไฟด์พบว่าค่า Space Velocity (SV) มีผลต่อการกำจัดไฮโดรเจนซัลไฟด์อย่างมีนัยสำคัญ โดยที่ค่า SV ต่ำ ($10\ h^{-1}$) การกำจัดไฮโดรเจนซัลไฟด์จะเกิดขึ้นได้เกือบสมบูรณ์ นอกจากนี้พบแนวโน้มของผลปัจจัยที่มีต่อกันของระหว่างชนิดของตัวกลางและอัตราการพ่นน้ำ ทั้งนี้จุลชีพในถังกรองชีวภาพที่มีประสิทธิภาพการกำจัดไฮโดรเจนซัลไฟด์ที่สูง มีอัตราการทำงาน (2.7×10^{-14} - 8.4×10^{-12} mg H_2S removed/ cfu.min) ที่มากกว่าจุลชีพในถังกรองชีวภาพที่มีประสิทธิภาพการกำจัดไฮโดรเจนซัลไฟด์ต่ำ ในการศึกษานี้พบว่า อัตราภาระการกำจัดสูงสุด มีค่าเท่ากับ 132 g H_2S /m^3.h สำหรับตัวกลางพลาสติกที่อัตราภาระบรรทุก H_2S เข้า 183 g /m^3.h และ 118 g H_2S /m^3.h สำหรับตัวกลางเซรามิกที่อัตราภาระบรรทุก H_2S เข้า 124 g /m^3.h ทั้งนี้ในการศึกษาพบการเปลี่ยนรูปของ H_2S เนื่องจากกระบวนการออกซิเดชันเป็นผลิตภัณฑ์หลัก คือ ซัลเฟต และ ซัลเฟอร์

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ปีการศึกษา 2551 ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ปฏิรูป ผลจันทร์

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MANEERAT WONGUDOM: REMOVAL OF HYDROGEN SULFIDE FROM BIOGAS USING THE BIOFILTER INOCULATED WITH ACTIVATED SLUDGE CULTURES. THESIS ADVISOR: PATIROOP PHOLCHAN, PH.D., 154 PP.

Removal of hydrogen sulfide (H_2S) was investigate in a laboratory-biofilter packed with selected activated sludge cultures immobilized on plastic cap and ceramic as packing materials. The results showed that relatively higher amounts of microorganisms from the activated sludge treating tofu wastewater were observed on the media having only thiosulfate as the energy source (TSA medium) compared to those from the activated sludge treating domestic wastewater. The cell numbers up to 2.8×10^{11} cfu/L of packing material were achieved on ceramic. Results from the study of effects of factors on H_2S removal found that space velocity (SV) significantly affected H_2S removal. Nearly complete H_2S removal was achieved at low SV (10 h^{-1}). Possible interaction effects were also observed, e.g. between type of packing materials and rate of sprayed water. Microorganisms growing in the high H_2S removing biofilter were shown to function at higher kinetic activity (2.7×10^{-14} - 8.4×10^{-12} mg H_2S removed/ cfu.min). The maximum removal capacity achieved in this study was 132 g H_2S /m^3.h for plastic cap at H_2S loading rate of 183 g /m^3.h and 118 g H_2S /m^3.h for ceramic at H_2S loading rate of 124 g /m^3.h. The main end products of H_2S oxidation were SO_4^{2-} and S^0.

Field of Study : Environmental Management Student's Signature : Maneerat Wongudom
Academic Year : 2008 Advisor's Signature : Patiroop Pholchan

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LIST OF ABBREVIATIONS

A_w	Water activity
Bal	Balance
°C	Degree Celsius
C	Carbon
CH_4	Methane
cm	Centimeter
cm^2/ cm^3	Square centimeter/Cubic meter
CO_2	Carbon dioxide
cfu/L	Colony forming units/Liter
cfu/m^3	Colony forming units/Meter
EBRT	Empty bed retention time
g/L	Gram/Liter
g/ m^3.h	Gram/Cubic meter. Hour
GRT	Gas retention time
H_2	Hydrogen gas
H_2S	Hydrogen sulfide
h^{-1}	Per hour
kPa	Kilopaskal
L	Liter
L/h	Liter/Hour
µm	Micrometer
m	Meter

mg/L	Milligram/Liter
m/s	Meter/second
min	Minute
m^2/ m^3	Square meter/ Cubic meter
N	Nitrogen
NH_3	Ammonia
O_2	Oxygen
ppm	Part per million
rpm	Round per minute
Rh	Relative humidity
S^0	Element sulfur
S^{2-}	Sulfide
SO_3^{2-}	Sulfite
SO_4^{2-}	Sulfate
SV	Space Velocity
VFAs	Volatile fatty acids

CHAPTER I

INTRODUCTION

1.1 Motivation

In the piggery farm, biogas produced from anaerobic digestion of wastewater is generally used as a fuel source for boiler and internal combustion engines. Hot water from heating boiler may be used for digester heating and/or farm heating. The combustion engines fueled by the biogas can be used for wastewater pumping, and have other miscellaneous used in the farm or in the vicinity (Polprasert, 1989). Biogas produced from piggery farm usually contains 60-65% methane, 34-39% carbon dioxide. In addition, hydrogen sulfide, ammonia and nitrogen gas may present in small amounts (Keattipakdee et. al, 1995). Hydrogen sulfide (H_2S) in biogas from piggery farm contains around 0.2-1% by volume or 2,000-10,000 ppmv (Pellerin et. al, 1987).

Apart from its unpleasant odor, hydrogen sulfide gas is highly toxic. Upon inhalation, hydrogen sulfide reacts with enzymes in the bloodstream and inhibits cellular respiration resulting in pulmonary paralysis, sudden collapse, and death. Continuous exposure to low concentrations (15-50 ppm) will generally cause irritation to mucous membranes and may also cause headaches, dizziness, and nausea. Higher concentrations (200-300 ppm) may result in respiratory arrest leading to coma and

unconsciousness. Exposures for more than 30 minutes at concentrations greater than 700 ppm have been fatal (MSDS, 1996).

One of the factors limiting the use of biogas is related to hydrogen sulfide, which is corrosive to internal combustion engines (Tchobanoglous et. al, 2003). Using biogas as a renewable energy source requires pre-treatment technologies to remove H_2S present in biogas. Due to the high cost of existing removal technologies, predominantly based on chemical and physical processes, biogas pre-treatment contributes significantly to the overall operation and maintenance costs of any energy recovery system (Monteith et. al, 2005). New research in biogas purification is focused on biological processes which are attractive from both economical and technological points of view.

In this research, H_2S removal by the biofilter inoculated with the screened activated sludge was investigated. Two kinds of inorganic materials, plastic cap and porous ceramic, were used as packing materials. Effects of operating factors on the biofilter performance were systematically studied based on the full factorial design of experiment. Operating parameters studied were space velocity, type of packing materials and rate of water spraying. These three parameters were selected to be studied because they all were main operating factor conditions for the biofilter. Knowing effects of these factors on the biofilter performance would lead to their optimum conditions being determined.

1.2 Objectives

The main objective of this study was to investigate effects of operating factors on the performance of biofilter inoculated with the screened activated sludge in removing H_2S from biogas. The specific objectives were:

1. To screen the activated sludge from the aeration tanks treating different kinds of wastewater which was capable of removing H_2S.
2. To determine the inoculating condition for the selected activated sludge on studied packing materials.
3. To investigate effects of operating factors on the performance of a biofilter in removing H_2S.
4. To determine the optimum condition for H_2S removal using a biofilter

1.3 Scopes of this Work

The study was divided into three phases as follows:

Phase 1: Selection of a source of the activated sludge

Microbial communities in a biological reactor were different, depending on wastewater characteristics and types of treatment process used. This phase of study was done to screen the suitable source of activated sludge to be inoculated on packing materials used in the biofilter. The activated sludge was selected from two sources; a domestic wastewater treatment plant (Maharaj Hospital, Chiang Mai) and wastewater treatment plant for a tofu production (Doisaket, Chiang Mai).

Phase 2: The optimum inoculating condition for the chosen activated sludge on each studied packing material

Inoculation condition for the selected activated sludge on studied packing materials was determined. The desired condition must provide microorganisms onto packing materials in the range of 10^7-10^9 cfu/L of packing material.

Phase 3: Effects of operating factors on H_2S removal efficiency by the biofilter

The chosen source of the activated sludge from the previous study had been immobilized on packing materials. Effects of space velocity, type of packing material, and rate of sprayed water on the performance of the biofilter were then investigated. All experiments were designed using the full factorial design to identify both main and interaction effects.

1.4 Benefits of this Work

1. Understand effects of operating factors on the performance of biofilter inoculated with the selected activated sludge in removing H_2S from biogas.
2. Capable of design and/or operate the biofilter system in treating H_2S generated from different kinds of wastewater, especially from piggery wastewater.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 Anaerobic Digestion

Anaerobic digestion is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen. It is widely used to treat wastewater sludges and organic waste because it provides volume and mass reduction of the input material. As part of an integrated waste management system, anaerobic digestion reduces the emission of landfill gas into the atmosphere. Anaerobic digestion is a renewable energy source because the process produces methane and carbon dioxide-rich biogas suitable for energy production as an alternative of fossil fuels. Also, the nutrient-rich solids left after digestion can be used as fertilizer (Polprasert, 1989).

There are four key biological and chemical stages of anaerobic digestion (Figure 2.1).

1. Hydrolysis
2. Acidogenesis (Fermentation)
3. Acetogenesis
4. Methanogenesis

In most cases biomass is made up of large organic polymers (protein, carbohydrates, fats, cellulose). In order for the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available by other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore hydrolysis of these high molecular weight polymeric components is the necessary first step in anaerobic digestion. Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids.

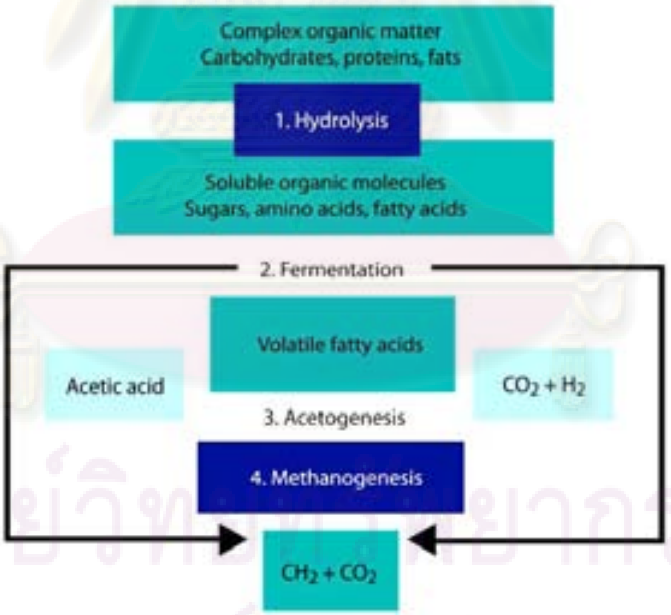


Figure 2.1 The anaerobic digestion process typically consists of four steps (*www.biomassmagazine.com*)

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFAs) with a chain length that is greater than acetate must first be catabolised into compounds that can be directly utilized by methanogens.

The biological process of acidogenesis is where there is further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here VFAs are created along with ammonia, carbon dioxide and hydrogen sulfide as well as other by-products. The process of acidogenesis is similar to the way that milk sours.

The third stage anaerobic digestion is acetogenesis. Here simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide, hydrogen and acetates.

The final stage of anaerobic digestion is the biological process of methanogenesis. Here methanogens utilize the intermediate products of the preceding stages and convert them into methane, carbon dioxide and water. It is these components that makes up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and pH 8. The remaining, non-digestible material which the microbes cannot feed upon, along with any dead bacterial remains constitutes the digestate.

A simplified generic chemical equation for the overall processes outlined above is as follows (Polprasert, 1989):

$$\text{Organic matter} \xrightarrow[\text{digestion}]{\text{anaerobic}} CH_4 + CO_2 + H_2 + NH_3 + H_2S \qquad (2.1)$$

2.2 Biogas Production

Biogas is the ultimate waste product of the bacteria feeding off the input biodegradable feedstock, and is mostly methane and carbon dioxide, with a small amount hydrogen and trace hydrogen sulfide. Most of the biogas is produced during the middle of the digestion, after the bacterial population has grown, and tapers off as the putrescible material is exhausted. The gas is normally stored on top of the digester in an inflatable gas bubble or extracted and stored next to the facility in a gas holder.

The methane in biogas can be burned to produce both heat and electricity, usually with a reciprocating engine or microturbine often in a cogeneration arrangement where the electricity and waste heat generated are used to warm the digesters or to heat buildings. Excess electricity can be sold to suppliers or put into the local grid. Electricity produced by anaerobic digesters is considered to be renewable energy and may attract subsidies. Biogas does not contribute to increasing atmospheric carbon dioxide concentrations because the gas is not released directly into the atmosphere and the carbon dioxide comes from an organic source with a short carbon cycle.

Biogas may require treatment or 'scrubbing' to refine it for use as a fuel. Hydrogen sulfide is a toxic product formed from sulfates in the feedstock and is released as a trace component of the biogas. National environmental enforcement agencies such as the U.S. Environmental Protection Agency or the English and Welsh Environment Agency put strict limits on the levels of gasses containing hydrogen sulfide, and if the levels of hydrogen sulfide in the gas are high, gas scrubbing and cleaning equipment (such as amine gas treating) will be needed to process the biogas to within regionally accepted levels. An alternative method to this is by the addition of ferric chloride $FeCl_3$ to the digestion tanks in order to inhibit hydrogen sulfide production (Zicari, 2003).

Biogas produced from piggery farm usually contains 60-65% methane, 34-39% carbon dioxide. In addition, hydrogen sulfide, ammonia and nitrogen gas may be present in small amounts (Keattipakdee et al., 1995). Hydrogen sulfide (H_2S) in biogas generated from the piggery farm contains around 0.2-1% by volume or 2,000-10,000 ppmv (Somboon, 2003).

In addition to its unpleasant odor, hydrogen sulfide gas is highly toxic (Roth, 1993). Upon inhalation, hydrogen sulfide reacts with enzymes in the bloodstream and inhibits cellular respiration resulting in pulmonary paralysis, sudden collapse, and death. Continuous exposure to low concentrations (15-50 ppm) will generally cause irritation to mucous membranes and may also cause headaches, dizziness, and nausea. Higher concentrations (200-300 ppm) may result in respiratory arrest leading to coma

and unconsciousness. Exposures for more than 30 minutes at concentrations greater than 700 ppm have been fatal (MSDS, 1996).

Hydrogen sulfide is poisonous, odorous, and highly corrosive. Some characteristics of H_2S are described in Table 2.1. Because of these characteristics, hydrogen sulfide removal is usually performed directly at the gas-production site.

Table 2.1 Physical, Chemical and Safety Characteristics of Hydrogen Sulfide

Molecular Weight	34.08
Specific Gravity (relative to air)	1.192
Auto Ignition Temperature	250° C
Explosive Range in Air	4.5 to 45.5 %
Odor Threshold	0.47 ppb
8-hour time weighted average (TWA) (OSHA)	10 ppm
15-minute short term exposure limit (STEL) (OSHA)	15 ppm
Immediately Dangerous to Life of Health (IDLH) (OSHA)	300 ppm

Source: OSHA (2002), Occupational Safety and Health Administration, www.OSHA.gov

The actual amount of water vapor entrained in the gas depends on the gas composition, pressure, and temperature. Approximately 25 kg of water is present in 1400 m^3 of saturated natural gas at 21° C and atmospheric pressure (Kohl, 1997).

2.3 Quality Requirements for Biogas

Biogas can be used for all applications designed for natural gas, assuming sufficient purification. On-site, stationary biogas applications generally have fewer gas processing requirements. A summary of potential biogas utilization technologies and their gas processing requirements are given in Table 2.2

Technologies such as boilers and stirling engines have the least stringent gas processing requirements because of their external combustion configurations. Internal combustion engines and microturbines are the next most tolerant to contaminants. Fuel cells are generally less tolerant to contaminants due to the potential for catalytic poisoning. Upgrading to natural-gas quality usually requires expensive and complex processing and must be done when injection into a natural-gas pipeline or production of vehicle fuel is desired (Zicari, 2003).

2.4. Traditional H_2S Gas-Phase Removal Methods

Since biogas is similar in composition to raw natural gas, purification techniques developed and used in the natural-gas industry can be evaluated for their suitability with biogas systems. The ultimate process chosen is dependent on the gas use, composition, physical characteristics, energy and resources available, byproducts generated, and the volume of gas to be treated.

Table 2.2 Biogas utilization technologies and gas processing requirements

Technology	**Recommended Gas Processing Requirements**
Heating (Boilers)[1]	H_2S < 1000 ppm, 0.8-2.5 kPa pressure, remove condensate (kitchen stoves: H_2S < 10 ppm)
Internal Combustion Engines[1]	H_2S < 100 ppm, 0.8-2.5 kPar pressure, remove condensate, remove siloxanes (Otto cycle engines more susceptible to H_2S than diesel engines)
Microturbines[2]	H_2S tolerant to 70,000 ppm, > 350 BTU/scf, 520 kPa pressure, remove condensate, remove siloxanes
Fuel Cells[3]	PEM: CO < 10 ppm, remove H_2S PAFC: H_2S < 20 ppm, CO < 10 ppm, Halogens < 4 ppm MCFC: H_2S < 10 ppm in fuel (H_2S < 0.5 ppm to stack), Halogens < 1 ppm SOFC: H_2S < 1 ppm, Halogens < 1 ppm
Stirling Engines[4]	Similar to boilers for H_2S, 1-14 kPa pressure
Natural Gas Upgrade[1,5]	H_2S < 4 ppm, CH_4 > 95%, CO_2 < 2 % volume, H_2O < (1×10^{-4}) kg/MMscf, remove siloxanes and particulates, > 3000 kPa pressure

Sources: [1] *Wellinger and Linberg (2000)*

[2] *Capstone Turbine Corp.(2002)*

[3] *XENERGY (2002)*

[4] *STM Power (2002)*

[5] *Kohl and Neilsen (1997)*

Gas purification processes generally fall into one of the following five categories: 1) Absorption into a liquid; 2) Adsorption on a solid; 3) Permeation through a membrane; 4) Chemical conversion to another compound; or 5) Condensation (Kohl, 1997).

Desirable attributes for a gas purification system include low capital and operating costs, ease of operation and media disposal, and minimal material and energy inputs. H_2S removal processes will be divided into dry-based, liquid-based, physical-solvent, membrane, alternative, and biological processes.

2.5 Removal Techniques of H_2S (Zicari, 2003; Lagrange, 1979)

2.5.1. Dry H_2S Removal Processes

2.5.1.1. Iron Oxides

As one of the oldest methods still in practice, iron oxides remove sulfur by forming insoluble iron sulfides. It is possible to extend bed life by admitting air, thereby forming elemental sulfur and regenerating the iron oxide, but eventually the media becomes clogged with elemental sulfur and must be replaced. The most well-known iron oxide product is called “iron sponge.”

2.5.1.2. Zinc Oxides

Zinc oxides are preferred for removal of trace amounts of hydrogen sulfide from gases at elevated temperatures due to their increased selectivity over iron oxide. Zinc oxides are used in dry-box or fluidized-bed configurations.

2.5.1.3. Alkaline Solids

Alkaline substances, such as hydrated lime, will react with acid gases like H_2S, SO_2, CO_2, carbonyl sulfides and mercaptans in neutralization reactions. Usually liquid-based scrubbers are used, but fixed-beds of alkaline granular solid can also be used in a standard dry box arrangement with up-flow of gas.

2.5.1.4. Adsorbents

Adsorbents rely on physical adsorption of a gas-phase particle onto a solid surface, rather than chemical transformation as discussed with the previous dry sorbents. High porosity and large surface areas are desirable characteristics, enabling more physical area for adsorption to occur. Media eventually becomes saturated and must be replaced or regenerated.

2.5.2. Liquid H_2S Removal Processes

Liquid-based H_2S removal processes have replaced many dry-based technologies for natural-gas purification due to reduced ground-space requirements, reduced labor costs, and increased potential for elemental-sulfur recovery. Gas-liquid contactors, or absorbers, are used which increase surface area and optimize gas contact time. Liquid-based H_2S removal processes can be grouped into liquid-phase oxidation processes, alkaline-salt solutions, and amine solutions.

2.5.3. Membrane Processes

Membranes operate based on differing rates of permeation through a thin membrane, as dictated by partial pressure. Because of this, 100% removal efficiency is not possible in one stage, and some product will inevitably be lost. Two types of membrane systems exist: high pressure with gas phase on both sides, and low pressure with a liquid adsorbent on one side. Membranes are generally not used for selective removal of H_2S from biogas but are becoming more attractive for upgrading of biogas to natural-gas standards because of attributes such as reduced capital investment, ease of operation, low environmental impact, gas dehydration capability, and high reliability.

2.5.4 Biological H_2S Removal Methods

Biological air treatment systems are based on the capability of microorganisms to transform certain organic and inorganic pollutants into less toxic and odorless compounds. As the pollutants are in air, the process of microbial degradation is generally oxidative in nature and the end products are carbon dioxide, water, sulfate and nitrate.

2.6 Type of Bioreactors

2.6.1 Bioscrubbers

In bioscrubbers, the pollutant in the gas phase is removed by absorption in the re-circulation liquid in a gas-liquid contactor (Figure 2.2). Subsequently, this pollutant-laden liquid is regenerated by the microorganisms

suspended in the liquid in a bioreactor with supplementary oxygen, to be returned to the contactor (van Groenestijn, 2001a). Nutrient addition and pH are continually controlled to maintain microbial growth and high activity. The excess biomass and byproducts are continually purged from the system.

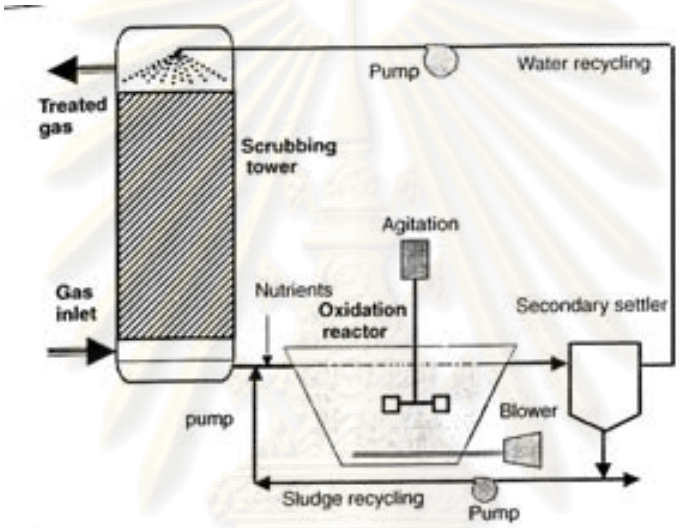


Figure 2.2 Schematic diagram of a bioscrubber system (Shareefdeen, 2005)

The gas-liquid contactors are designed to favor mass transfer from the air to the liquid phase, thus reducing equipment volume, while maintaining a low pressure drop (< 3 cm H_20 m^{-1}). The contactors can be packed towers, venture scrubbers, spray towers, etc. Typical gas velocities are 1 - 3 m/s in packed contactors. In the bioreactor, the liquid is regenerated by the suspended microorganisms, and CO_2, H_2O and other mineral products are produced. Most of the reactors are vessels where air is bubbled, and resemble activated sludge tanks. Water retention time in the

reactors is high, and biomass concentration is expected to be around 5 - 8 g/L (Ottengraff, 1986), which is reasonable for high volumetric rates, while reducing clogging problems in the packing. The low specific gas/liquid area restricts the use of bioscrubbers to pollutants with low Henry's coefficients (< 5). A large absorber or high water flow rates are to be avoided (van Groenestijn and Hesselink, 1993).

2.6.2 Biotrickling Filters

In the biotrickling filters, the polluted air is passed through a packed column where liquid is continuously recirculated through the packing (Fig. 2.3). The pollutant is first solubilized in the falling liquid film, and then transferred to the microorganisms growing on the surface of these supports. The liquid provides moisture, nutrients, pH control to the biofilm, and allows the removal of inhibiting products. Ideally, the excess biomass is sloughed off by the trickling liquid, and a stable operation can be achieved.

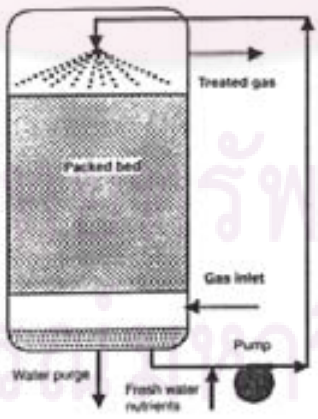


Figure 2.3 Schematic diagram of a biotrickling filter (Shareefdeen, 2005)

The supports are inert random or structured packings that are similar to those used in traditional scrubbers (plastic Raschig or Pall rings and saddles), although others such as lava rock or polyurethane foam have been tested. The air may be directed upflow or downflow, which is countercurrent or co-current with the liquid flow, respectively. It has been shown that generally there is no difference, except when there is stripping from the incoming liquid in the countercurrent configuration. To maintain low pressure drop and reduce clogging, the supports have low porosity and low specific surface (100-400 m^2/m^3). EBRTs are normally around 30 s but systems with EBRTs as low as 1.2 s have been reported for low H_2S concentration (Gabriel and Deshusses, 2003).

Overgrowth produces increased pressure drop, reduced real residence time, and a drop in performance. Several strategies (Diks and Ottengraff, 1994) have been studied to control overgrowth while maintaining appropriate microbial activity. These include choosing a specific size and structure for the packing, limiting organic load, limiting nutrients, and adding inhibitors. The possibility of using microbial predators, such as protozoa and nematodes (Cox and Deshusses, 1999), has been reported. In extreme cases the reactor has to be shut down and cleaned.

2.6.3 Rotating Biological Contactors

Rotating biological contactors were developed initially for water treatment. The polluted air passes through the headspace of the reactor, containing discs mounted on a rotating shaft that serve as support for a biofilm. The shaft is

rotated (~ 2 rpm), and the discs are partially wetted in water containing nutrients and other additives. The movement of the discs favors mass transfer and the control of the fixed biomass. Air can be fed tangentially to the disks or through perforations in a hollow shaft (von Rohr and Ruediger, 2001).

2.6.4 Membrane Bioreactors

In the membrane bioreactors, the pollutant in the gas phase is transferred through a membrane to the biofilm, attached to the other side and where nutrients and oxygen are provided. The basic configurations are hollow fibers and flat sheets. In hollow fibers, the gas is usually passed through the lumen of the tube, and the biomass is on the shell side. These reactors have been used for other waste treatment applications where the conditions of the stream exclude the possibility of direct contact with the biomass (van Groenestijn and Hesselink, 1993; Ergas, 2001).

Membranes can be constructed of very diverse materials, and have different chemical (solubility and selectivity) and physical properties (mechanical strength, pore size, thickness and porosity). In semi-permeable hydrophobic membranes, such as latex or silicon, the transfer rate is related to the solubility and diffusivity of the pollutant. In micro-porous membranes, the pollutant diffuses through the gaseous void volume and water, from the biofilm, is excluded by selecting hydrophobic materials. Micro-porous membranes are made of Teflon, polypropylene, polytetrafluorethylene (PTEE) and different composites. They have

pore sizes of 0.1-1.0 μm, small diameters (200-400 μm ID), and are usually packed in bundles in reactors containing between 30 and 100 cm^2/cm^3.

A distinct characteristic of the membrane bioreactors is the fact that the polluted gaseous stream and the biomass are physically segregated, which allows the biological waste gas treatment to be used in certain applications such as indoor air and, in an extreme case, for spaceship air treatment.

2.6.5 Suspended Cell Bioreactor

In the suspended cell bioreactors, the polluted air is bubbled in the bulk of the liquid containing suspended microorganisms (Figure 2.4). Several configurations have been proposed (Bielefeldt, 2001). In the activated sludge process, the biological activity from the treatment of municipal wastewater is used to simultaneously treat the sparged polluted air. The characteristics of the reactor, such as biomass concentration, aeration and sparger design, are generally imposed by the requirements of the wastewater treatment. A review of the characteristics of several facilities is given by Bowker (1998).

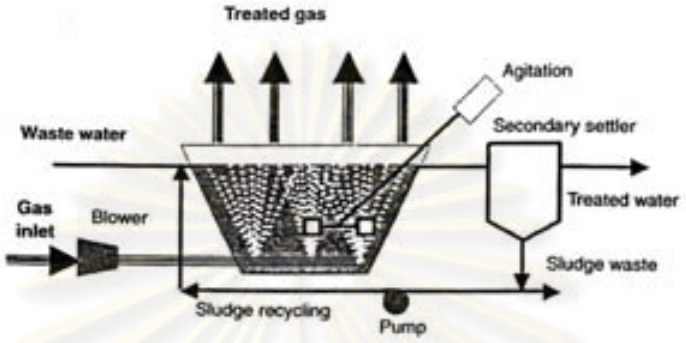


Figure 2.4 Schematic diagram of a suspended growth bioreactor (Shareefdeen, 2005)

In other cases, the reactor is conceived specifically for the treatment of the pollutant in air, and can be tanks or columns with different aeration configurations such as airlift, external loop, split cylinder, etc. (Shuler and kargi, 1992). These systems are designed to optimize mass transfer from the bubble to the bulk liquid where biodegradation occurs, and to allow the control of the conditions of the microbial population. An interesting example of the type of reactor is the cometabolic degradation of TCE with phenol and toluene (Ensley and Kurisko, 1994).

2.6.6 Biofilter

In biofilters the contaminated air passes through a moist, packed bed that contains the microorganisms. Microbes grow on the surface and crevices of the support, forming a biofilm. The biofilm activity is determined by its microbial density and the environmental conditions, such as temperature, nutrient availability, pH, and humidity. The humidity of the biofilm is one of the critical steps to maintain a proper

performance, as biological activity is highly dependent on water activity (A_w). The heat generated by the biological reaction and the humidity of the incoming air determines the rate of water loss and requirements for water restoration (Morales et al., 2003). Increased drying rates are attained with dry air and high elimination capacity. To maintain performance, air is generally pre-humidified, and biofilters have intermittent water spraying. To reduce ventilation costs, they generally have a high void fraction to limit pressure drop.

The supports can be either natural bioactive or inert (Figure 2.5). The natural bioactive supports are soil, peat, compost, bark, etc., which can retain water and generally contain enough mineral nutrients to support an initial active microbial population (Cardenas-Gonzalez et al., 1999). They are relatively inexpensive and easy to obtain, and have been used for many applications. To obtain suitable structural characteristics, a mixture of materials is generally used, including a coarser fraction to prevent high pressure drop in the packing. Sometimes inert synthetic materials, such as plastics or ceramic, are included. Other additives that can be used are pH regulators and slow released nutrients to increase biomass. The natural supports may degrade with time and loose the structure and water-retaining capacity, inducing channeling and the loss of performance (Morgan – Sagastume et al., 2003). In some cases, remixing the support with some fresh material and nutrients allows to recover the activity (Auria et al., 2000), but eventually it will need to be replaced. With proper maintenance, the support can be used for several years.

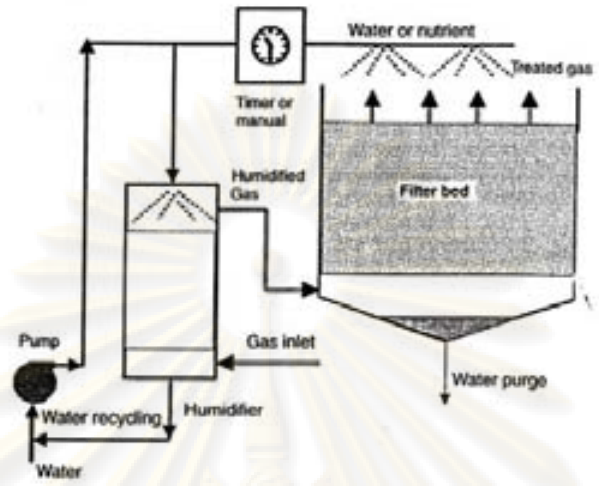


Figure 2.5 Schematic diagram of an open biofilter (Shareefdeen, 2005)

Inert natural or synthetic supports have been explored to be used in biofilters. These porous materials, such as activated carbon, ceramics, sintered glass, lava rock, polyurethane foam, vermiculite and perlite, do not contain the required nutrients to sustain microbial activity and, hence, it is necessary to provide them intermittently. On the other hand, they are not degraded and, in theory, could be engineered to have optimal properties such as controlled head loss, porosity, adsorptive capacity, etc. This remains an area of active research (Kennes and Veiga, 2002). The high surface and low water content of biofilters make them appropriate for the treatment of the less hydrophilic pollutants (H <10). The structural characteristics of the support determine the height of the packed bed, which is about 0.8-1.2 m for typical packings. This limitation necessitates having a large footprint for the biofilter, which may be a disadvantage for situations where space is limited.

The technologies that can be applied to VOCs and odor control are relatively wide. The choice of a particular technology should include technical, health, legal and economic consideration. From a technical standpoint, variables such as stream (flow, temperature, presence of particles, humidity, etc.) and pollutant characteristics (composition, concentration, reactivity, solubility, and biodegradability) have to be evaluated.

Different reactor configurations respond differently to the various operating problems (Table 2.3). To improve the performance of the biological air treatment systems, there is a continuous innovation in reactor configurations. For example, two sequential reactors have been used to treat sulfides and VOCs from a wastewater treatment plant. In the first reactor, inorganic sulfides are degraded in a biotrickling filter operating under acidic conditions, and a compost-based biofilter reduces the organic compounds that are sparsely reduced in the first reactor (Kraakman et al., 1996; Chitwood et al., 1999; Schroeder, 2002). A combined system for the elimination of H_2S from waste gas has been described where, in the first step, H_2S is oxidized to elemental sulfur with ferric ion and, in the second step, the ferric ion is regenerated by *Thiobacillus ferroxidans* (Pagella et al., 1996). An advantage of the method is that the first reaction is very fast and that sulfur can be recovered from the medium.

The most important advantages of biological air treatment systems over physical and chemical technologies are the they are applicable for a wide range

of pollutants, are effective at low concentrations, can be used under normal conditions (pressure, temperature and pH), and are very little energy and material-intensive, simple to operate and economic. Although there are some disadvantage, research in this field has greatly expanded applicability and performance.

Table 2.3 Operating problem associated with different bioreactor configurations

Type	Moisture control[a]	Nutrient addition and pH control	Biomass control, clogging	Transient response	Airflow channeling	Startup
Biofilter	++	++	+	+	++	+
Biotrickling filter	-	-	++	++	+	++
Rotating contactors	-	-	-	++	-	++
Bioscrubber	-	-	-	++	-	+
Suspended growth	-	-	+	++	-	+
Membrane reactors	-	-	++	+	-	++

[a] -, Not sensitive; +, sensitive; ++, highly sensitive (Shareefdeen, 2005)

The operating conditions of the biofilter, supporting materials, and inoculated microbes are important parameters to consider (Duan et al., 2007). Recently, cell-immobilized biofiltrations has become one of the most important biological processes for treating H_2S gases. This process has low capital and operating

costs for its regeneration and recirculation. Moreover, it requires less energy and no additional chemicals or fuels. Above all, it was public acceptance as an environment-friendly process for reducing secondary pollution (Ma et al., 2006a).

2.7 Factors Affecting Biofilter Performance

2.7.1 Packing Media

To maximize the biodegradation of airborne contaminants, several factors can be optimized, many of which focus on the packing media. Many biofiltration companies have proprietary media that are designed to provide optimal performance through optimizing: high surface are for biofilm growth, long-term physical stability, low pressure drop, good moisture retention, pH buffering capacity, and nutrients. Traditional natural medium components that are frequently used for simple biofilters include compost, peat, wood chips, fertilizer, and soil. Some biofilters are also packed with adsorbents such as activated carbon, Although these adsorbents can be helpful in that they can reduce the quantity of contaminant that escapes during the microbiological acclimation period (Bishop and Govind, 1995), and have potential to damper peak loads if the adsorbent is not coated with a deep biofilm, they do not improve performance during steady-state operation (Mohseni et al., 1998).

2.7.2 Moisture Content

The moisture content of the filter bed is a critical factor for biofilter effectiveness, because microorganisms require water to carry out their normal

metabolic activities (Ottencgraf, 1986; Shimko et al., 1998; Marsh, 1994). Too little moisture content causes drying of the bed, along with the development of fissure the cause of channeling and short circuiting. This also deprives microorganisms of water, causing a significant reduction in the biodegradation rate. Too much water inhibits transfer of oxygen and hydrophobic pollutants to the biofilm, thereby promoting the development of anaerobic zones within the bed and limiting the reaction rate. Too much water can also result in foul smelling emissions due to the lack of oxygen, increasing backpressure due to the reduced void volume, and channeling of the gas within the bed.

Optimal water levels vary with different filter media, depending on medium surface area, porosity, and other factors (Hodge et al., 1991). Filter moisture content for optimal operation of the biological filter should be within 30-60% by weight, depending on the medium used (Ottengraf, 1986, 1987; van Lith et al., 1990). Moisture levels in a biofilter are often maintained through prehumidification of the inlet gas stream. Also, it is often necessary to provide direct application of water to the bed through a sprinkler system at the top of the bed. More advanced controls include the use of load cells that sense the weight of filter bed (van Lith et al., 1990; Rozich, 1995) and are connected to sprinkler controls. Supplemental moisture adjustments may be required because bio-oxidation is an exothermic reaction, and so drying can occur within the bed. Drying of the packing material can lead to localized dry spots, and can result in non-uniform gas distribution and reduction in the activity of microorganisms.

From the perspective of adding moisture, it is often advantageous to have the flow of waste gas downward (van Lith et al., 1990). Since most of the drying occurs at the entrance to the filter bed, drying at the top is easily handled through direct water addition and flow from the top to the bottom. Downward flow also helps when too much water is added (either directly or due to humid gas cooling), since the water will flow by gravity co-currently with the gas out the bottom of the filter.

2.7.3 Temperature

Temperature control is also very important in biofiltration to avoid thermal shocks. There are three general temperature classes of aerobics microorganisms: psychrophilic microorganisms, which grow best below a temperature of 20 °C; mesophilic microorganisms, which achieve highest growth rates at 20-40 °C; and thermophilic organisms, which grow best above 45 °C. Biological activity roughly doubles for each 10 °C (Leson and winter, 1991; Vohn, 1992). This means that if the pollutant gas temperature is above 40 °C, then the gas should be cooled before it enters the biofilter, similarly, for cold air below 10 °C, the heating of the gas stream to a desirable temperature is needed because microorganisms are relatively inactive at low temperatures.

The cost of controlling temperature to within the mesophilic range often means that it is not economical to treat emissions that are relatively cold or hot. However, some recent studies suggest that we may be able to expand the temperature range of biofilters, and treat emissions at the temperature at which they are emitted.

For example, Giggery et al. (1994) reported on the biofiltration of odor below 0 °C with snowfall. Also, a recent study by Kong et al. (2001) has shown that treatment of methanol and ∝-pinene can be conducted at temperatures up to 70 °C, and Datta et al. (2004) have shown that hydrogen sulfide can also be effectively treated at 70 °C. Future work at the laboratory, pilot and full scale in expanding the temperature range can open the economic application of biofilters to a range of emission sources.

2.7.4 Oxygen Content

Oxygen is vital to the operation of biofilters because the predominant microorganisms used in biofiltration are aerobic, and require oxygen for metabolism. Aerobic heterotrophic bacteria present in filter beds require at least 5 - 15% oxygen at the inlet gas stream to survive (Dharmavaram, 1991). Yang et al. (2002) showed that biofiltration can be oxygen-limited in highly loaded systems, by showing that biofiltration with 63 % oxygen in the inlet stream increased the maximum removal rate of methanol from 120 to 145 $g/m^3.h$ over regular air (21 % oxygen); a further increase in oxygen content up to 80 % did not lead to a further improvement in biofilter performance. Generally, for most air pollution control systems, oxygen supply is not an issue because it is abundant in the incoming airstream and the biofilm is relatively thin. In overloaded filters, however, it may be a limitation resulting in the formation of acidic and other intermediaries.

2.7.5 pH

Microorganisms have a specific, optimum pH range for their activities. The pH within the biofilters can be maintained by the addition of solid buffer agents to the packing material at the beginning of the operation, and once this buffering capacity is exhausted, the filter bed is removed and replaced with fresh material.

Compost beds generally have a pH between 7 and 8, a range preferred by most microorganisms. Carbon dioxide or SO_4^{2-} evolved in the metabolic activities of aerobic microorganisms tends to depress the system pH. So, if the waste gases of its intermediate by products do not provide sufficient buffering capacity, additional pH control has to be accomplished by addition of a base such as sodium or magnesium hydroxides.

Although hydrogen sulfide gas can be biofiltered effectively at low pH (Yang and Allen, 1994), other odorous gases like methyl sulfide may not be removed effectively (Pomery, 1982; Tanji et al., 1989).

2.7.6 Nutrients

Carbon and energy required for microorganisms may be derived from the contaminant gas, while other nutrients such as nitrogen, phosphorus, minerals, and trace elements should be supplied to microorganisms in the biofilter for good performance (Auria et al., 1996). Natural packing materials (e.g., peat, compost) contain nutrients to support biomass growth but, in the case of artificial packing

material, nutrients should be provided for better performance (Weckhuysen et al., 1993; Morgenroth et al., 1996). Yang et al. (2002) studied nitrogen requirements for biofiltration of methanol and found that, at low nitrogen levels, removal rate increased with increasing N:C ratio for both NH_3 and NO_3. At high concentrations, however, NH_3 had an inhibitory effect on the removal rate while the removal rate simply reached a plateau at high NO_3 concentrations.

2.7.7 Pressure Drop

In a biofilter, the synthesis of biomass leads to accumulated growth of microbial mass over time, which has been related to an increase in airflow resistance in the bed (Kinney et al., 1996; Mohseni et al., 1998). Biomass accumulation is greater at the inlet sections of the biofilters (Corsi and Seed, 1995; Swanson and Loehr, 1997), and leads to a change in bed characteristics e.g., reduction in interparticle void space, and the compaction of natural packing material like wood chips; these changes cause channeling and increased pressure drop.

In general, there is an approximately linear increase in pressure drop with increasing gas flow rate (Yang and Allen, 1994), which begins to become exponential at higher flow rates (Morgan-Sagastume et al., 2001). In addition, at a given gas flow rate, the pressure drop increase exponentially with increased biomass (Morgan-Sagastume et al., 2001) and with decreasing particle size, especially for particles less than 1 mm. The exponential increase with biomass means that a lower overall pressure drop will be obtained if biomass growth is distributed along the entire

filter, as opposed to being localized in specific regions (Morgan-sagatume et al., 2001). Compaction of the filter bed over extended periods of usage and due to overwatering will also give rise to high pressure drops (Pinnette et al., 1994).

Several researchers have developed predictive equations to describe pressure drops across biofilters for various particles, but there is no universal correlation that can accurately predict pressure drop for packed beds of varying particle sizes as well as the impact of biomass, Higgins et al. (1982) have developed equations for predicting pressure losses through compost piles, However, Williams (1988) found that the equation did not accurately predict headlosses through a compost biofilter that utilized screened sludge compost, Morgan-Sagastume et al. (2001) developed an equation to take into account biomass growth that fits their experimental data. While these predictive tools can provide guides for media development, the variability in the physical characteristics of the media (Particle size distribution, available pore space, moisture content, bulk density, etc.) biomass growth, and the characteristics of the gas (loading, particulates) are so variable from one medium to another that onsite measurements are required over a long term to thoroughly assess the pressure drop associated with a particular application.

2.7.8 Medium Depth

Biofilter medium depth has ranged from less than 0.5 to 2.5 m. a depth of approximately 1 m appears to be most common, to allow sufficient residence time while minimizing filter land area requirements. Some manufacturers recommend the

use of multiple layers of biofilter media, since these will need less land area for high loading rates (Leson and Winter, 1991). Greater filter depth could be used too, but the system headloss will increase in that case, and there is also the potential for compaction of the bed at the bottom, with subsequent increased pressure drop and channeling.

2.7.9 Waste Gas Pretreatment

The microbial communities in biofilters can be poisoned by the presence of toxic contaminants, excessive concentration of the contaminant, or excursion in environmental conditions like pH, temperature, and moisture content. In order to meet the basic requirements for optimal operation of the biofilter, waste gas conditioning is often required. A sufficient supply of oxygen and humidity, and an acceptable range of temperature and pH levels in the filter bed, are indispensable for the survival of the microbial community present in the bed (Werner et al., 1986; Beerli and Rotman, 1989; van Lith et al., 1990). High particulate loads in the waste gas can adversely affect the operation of a biofilter by clogging the air distribution system and the filter material itself (Willam and Miller, 1992; Bohm, 1993). Pretreatments options can include humidification for temperature and humidity control and/or the use of devices for particulate control, such as a wet scrubber or a wet electrostatic precipitator.

2.7.10 Maintenance

The timing and frequency of routine or periodic maintenance of a biofilter depend upon a number of factors including waste gas temperature and relative humidity, filter bed moisture content, medium stability, temperature, pH, and backpressure (Leson and Winter, 1991; Yang and Allen, 1994). Fully engineered, enclosed systems with optimized packing generally reduce maintenance requirements. However, no matter how carefully a biofilter is designed, aging due to the bio-oxidation of organic substrates of the medium and buildup of minerals occur in most systems, which often require medium replacement.

Biofilters can fail to achieve their designed removal efficiencies for various reasons, such as inadequate assessment of the waste gas stream for its contaminants, particulates and the concentration levels, variations in temperature, pH, moisture, and oxygen content within the filter bed (Goldstein, 1996; Standerfer and Willingham, 1996; van Lith et al., 1996). Channeling in the filter bed, bed drying, generation of acid metabolites, and system upsets due to improper gas conditioning are the probable problems encountered during operation (Ottengraf, 1986, 1987; Leson and Winter, 1991: Leson et al., 1995; Allen and van Til, 1996).

2.8 Microbiology of Biofilters

Bohn (1992) estimates microbiological populations in biofilters to be in order of 1 billion microorganisms per gram of organic material. Several groups of microorganisms are known to be involved in the degradation of air pollutants in

biofilters, including bacteria, actinomycetes and fungi (Ottengraf, 1987). There is one report on utilizing a co-culture of fungi and mites for the biofiltration of hydrophobic pollutants (Van Groenestijin et al., 2001). The composition of the microbial community and their survival in a biofilter depend on physical and chemical conditions in the packing material. The diversity of the active microorganisms is a function of the inlet gas stream composition and media.

Natural packing material like compost contains a sufficient number of different microorganisms to initiate biodegradation of contaminants. Initially, it takes time for the microorganisms to adapt, this time interval being known as the acclimatization period. The efficiency of the process is generally enhanced following the growth of active organisms during the adaptation phase. For easily biodegradable organic compounds, acclimatization can typically take less than 10 days, and for less biodegradable compounds and those contaminants for which the microorganisms are less likely to be initially present in the biofilter material, the period can be longer (Ottengraf, 1986; Leson and Winter, 1991). If the filter bed is inoculated with a specific culture that is known to degrade that particular pollutant, the adaptation time can be reduced to only a couple of days. Microorganisms can survive for fairly long periods when the biofilter is not loaded (Ottengraf and van der Oever, 1983) – up to 2 months, if sufficient nutrients are available from the filter material (Leson and Winter, 1991).

2.9 Factorial Design

Factorial design is an important method to determine the effects of multiple variables on a response. Traditionally, experiments are designed to determine the effect of one variable upon one response. Factorial design can reduce the number of experiments one has to perform by studying multiple factors simultaneously. Additionally, it can be used to find both main effects (from each independent factor) and interaction effects (when both factors must be used to explain the outcome). However, factorial design can only give relative values, and to achieve actual numerical values the math becomes difficult, as regressions (which require minimizing a sum of values) need to be performed. Regardless, factorial design is a useful method to design experiments in both laboratory and industrial settings.

Factorial design tests all possible conditions. Because factorial design can lead to a large number of trials, which can become expensive and time-consuming, factorial design is best used for a small number of variables with few states (1 to 3). Factorial design works well when interactions between variables are strong and important and where every variable contributes significantly.

2.10 Advantage of Factorial Design

The advantage of factorial designs can be easily illustrated. Suppose we have two factors A and B, each at two levels. We denote the levels of the factors by A^-, A^+, B^- and B^+. Information on both factors could be obtained by varying the factors one at

a time, as shown in Figure 2.6. The effect of changing factor A is given by $A^{+}B^{-} - A^{-}B^{+}$, and the effect of changing factor B is given by $A^{-}B^{+} - A^{-}B^{-}$. Because experimental error is resent, it is desirable to take two observations, say, at each treatment combination and estimate the effects of the factors using average responses. Thus, a total of six observations are required (Montgomery, 2005).

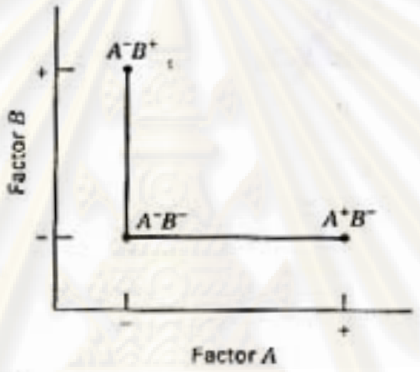


Figure 2.6 A one factor at a time experiment (Montgomery, 2005)

If a factorial experiment had been performed, and additional treatment combination, A+B+, would have been taken. Now, using just four observations, two estimates of the A effect can be made : $A^{+}B^{-} - A^{-}B^{-}$ and $A^{+}B^{+} - A^{-}B^{-}$. Similarly, two estimates of the B effect can be made. These two estimates of each main effect could be averaged to produce average main effects that are just as precise as those from the single-factor experiment, but only four total observations are required and we would say that the relative efficiency of the factorial design to the one –factor-at-a-time

experiment is (6/4) = 1.5. Generally, this relative efficiency will increase as the number of factors increases, as shown in Figure 2.7.

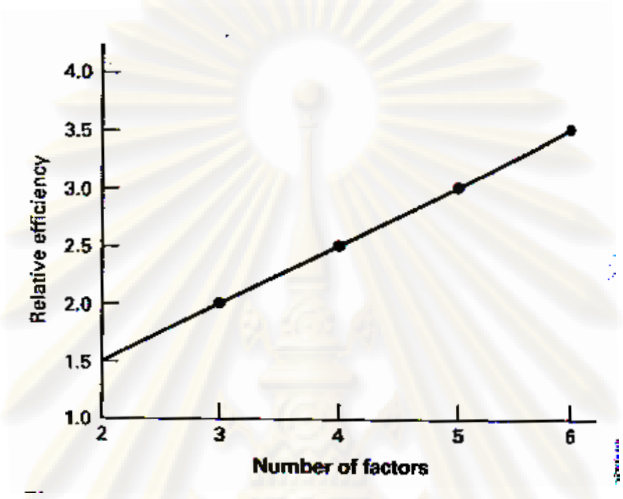


Figure 2.7 Relative efficiency of a factorial design to a one factor at a time experiment (two factor levels) (Montgomery, 2005)

Now suppose interaction is present. If the one-factor-at-a-time design indicated that A^-B^+ and A^+B^- gave better responses than A^-B^-, a logical conclusion would be that A^+B^+ would be even better. However, if interaction is present, this conclusion may be seriously in error.

In summary, note that factorial designs have several advantages, they are more efficient than on-factor-at-a-time experiments. Furthermore, a factorial design is necessary when interactions, may be present to avoid misleading conclusions. Finally, factorial designs allow the effects of a factor to be estimated at several levels of the

other factors, yielding conclusions that are valid over a range of experimental conditions (Montgomery, 2005).

2.11 Literature Review

Biofilter is a three phase bioreactor (gas, liquid, solid) made with a filter bed that has a high porosity, high buffer capacity, high nutrient availability, and high moisture retention capacity to ensure that the target microorganisms can grow on it. The contaminated gas is continuously fed in the biofilter, while a nutrient solution is discontinuously added. Various types of biofilter media have been used by researchers (Syed et al., 2006).

Chung et al. (1996) immobilized *Thiobacillus thioparus* CH11 with Ca-alginate producing pellet packing material for the biofilter. At 28 second optimal retention time, the H_2S removal efficiency was more than 98%. Elemental sulfur or sulfate was produced depending on the inlet H_2S concentration. Chung et al. (1997) used *Thiobacillus novellus* in a biofilter for H_2S oxidation under mixotrophic conditions. A removal efficiency of 99.6% was achieved and the products were sulfate (83.6%) and sulfite (12.6%). Little conversion of sulfide to elemental sulfur was achieved. Later, Chung et al. (2001) used biofilters packed with co-immobilized cells *Pseudomonas putida* CH11 and *Arthobacter oxydans* CH8 for removal of H_2S and NH_3, respectively, which are often present in off-gases of a livestock farm. In the 5-65 ppm range, H_2S and NH_3 removal efficiencies were greater than 96%. However, at higher concentrations, H_2S and NH_3 showed inhibitory effects on H_2S removal.

They also assessed the environmental risk associated with the release of bacteria when treating large volumes of waste gases. The exhaust gas contained small amounts of bacteria (< 19 CFU/m^3 in all cases) and was considered safe.

Elias et al. (2002) used packing material made up of pig manure and sawdust for biofiltration purposes. More than 90% H_2S removal efficiency was attained at a loading rate of 45 g/m^3.h. No nutrient was added to the system and the porosity of the packing material decreased from 23.1 to 12.9%. However, this change in porosity did not affect the removal efficiency significantly and it was claimed that the biofilter could be easily cleaned by flushing water through the inlet. The main by-product of the biodegradation process was sulfur (82% of total sulfur accumulation), accompanied by sulfates and thiosulfates (<18%).

Kim et al. (2002) investigated the simultaneous removal of H_2S and NH_3 using two biofilters, one packed with wood chips and the other with granular activated carbon (GAC). A mixture of activated sludge (as a source of nitrifying bacteria) and *Thiobacillus thioparus* (for sulfur oxidation) was sprayed on the packing materials and the drain solution of the biofilter was recirculated to increase the inoculation of microorganisms. Initially both of the filters showed high (99.9%) removal efficiency. However, due to the accumulation of elemental sulfur and ammonium sulfate on the packing materials removal efficiency decreased over time to 75 and 30% for H_2S and NH_3, respectively.

Rattanapan et al. (2009) used sulfur oxidizing bacteria which were stimulated from concentrated latex wastewater and immobilized on granular activated carbon (GAC) as a packing material for biofiltration. The comparison between the performance of sulfide oxidizing bacterium immobilized on GAC and GAC without cell immobilized systems was done. It was found that the efficiency of the H_2S removal was more than 98% even at high concentrations (200 - 4000 ppm) and the maximum elimination capacity was 125 g H_2S/m^3 of GAC/h in the biofilter with cultures.

To investigate different inorganic materials used as the packing material for the biological H_2S removal, Hirai et al. (2001) compared four inorganic packing materials in terms of hydrogen sulfide removal. The efficient and complete H_2S removal capacity of some packing materials, i.e. porous ceramics and calcinated and formed obsidian, were correlated to their physical and chemical properties such as the maximum water content, high porosity, and mean pore diameter. The selection of packing materials is an important factor and many different types of packing materials suitable for microbial growth have been actively researched. Some requirements for a good packing material are as follow: (i) high water-holding capacity, (ii) high porosity and large specific surface area, (iii) less compacting nature, (iv) low-pressure drop over a wide range of water content, (v) small change in form in long periods of use, (vi) lightness, (vii) low cost, (viii) appropriate adsorbing ability for malodorous gases and (ix) large buffering capacity for acidic end products. Inorganic packing materials,

such as perlite, porous ceramics, activated carbon filter and porous lava are used, because they meet requirements (iii), (iv) and (v).

Cho et al. (2000) investigated inorganic media supports for durability during low pH H_2S biofiltration. *Thiobacillus thioxidans* was immobilized on porous lava rock. The rock showed favorable moisture retention and resisted excessive pressure drops. Increase removal capacities up to 428 g $S/m^3.h$ was reported with space velocity of 300 h^{-1}.

Table2.4 Summarizing of relevant studies of hydrogen sulfide removal in biofilter

Reference	Chung et al. (1996)	Hirai et al. (2001)	Elias et al. (2002)	Barona et al. (2004)
Bacteria	*Thiobacillus thioparus*	mixed microbial culture	nature	sulfide oxidizing
Packing material	Ca-alginate	Four type of inorganic	pig manure & saw dust	Four type of organic
Influent H_2S concentration (ppmv)	5 - 100	0 - 2000	-	-
H_2S removal efficiency (%)	> 98%	80 – 90	> 90%	83 – 97
H_2S removal capacity ($g/m^3.h$)	25	-	10.0 - 45.0	0.03 – 0.32
Gas flow rate (m^3/h)	0.018 - 0.185	-	0.785 – 1.57	0.084
Space velocity (h^{-1})	25.7 – 264.3	50 – 140	133 – 266	2.5
Retention time (s)	0.23 – 2.3	-	13.5 - 27	24
pH (the growth of bacteria)	7	4,7	6.8 - 8.4	4.3 – 7.2
Temperature (^oC)	28 ± 2	-	20 - 22	23
Surface area packing material (m^2)	-	-	_	-
Reactor	Up-flow	Down-flow	Down-flow	Up-flow
Reactor size	di = 6 cm, H = 25 cm	di = 5 cm, H = 50 cm	di = 10 cm, H = 1 m	di = 5 cm, H = 29 cm
Relative humidity (%)	95 – 100	70 - 80	-	-
Pressure drop	-	6.1 – 31.1 mm H_2O. m^{-1}	15 - 460 $Pa.m^{-1}$	-
final product	SO^{2-}_4, SO^{2-}_3, S^{2-}, S^o	-	SO^{2-}_4, SO^{2-}_3, S^o	-

Table2.4 (cont.) Summarizing of relevant studies of hydrogen sulfide removal in biofilter

Reference	Duan et al. (2006)	Lee et al. (2006)	Kim et al. (2008)	Rattanapan et al. (2009)
Bacteria	sulfide oxidizing	*Acidithiobacillus thiooxidans* AZ11	mixed microbial culture	sulfide oxidizing
Packing material	activated carbon	Porous ceramic	Na-alginate and polyvinyl alcohol (PVA)	granular activated carbon (GAC)
Influent H_2S concentration (ppmv)	5 - 100	200 – 2000	10 – 130	200
H_2S removal efficiency (%)	94 - 99	99.99	> 99%	> 98%
H_2S removal capacity ($g/m^3.h$)	110 - 181	47 – 670	8	125
Gas flow rate (m^3/h)	0.034 - 0.24	-	7.65- 12.19	0.035
Space velocity	170 - 200	200 h^{-1}	70.6 – 112.5	52.24
Retention time (s)	2 - 21	9	32 – 51	60 days
pH (the growth of bacteria)	1.0 - 7.0	1.5	7	2.10-8.35
Temperature (^oC)	25	-	30	27-32
Surface area packing material (m^2)	807 m^2/g	-	_	-
Reactor	Up-flow	Down-flow	Down-flow	Down-flow
Reactor size	di = 3.6 cm, H = 30 cm	di = 4.6 cm, H = 30 cm	di = 14 cm	di = 5.5 cm, H = 60 cm
Relative humidity (%)	-	80 - 90%	-	-
Pressure drop	-	-	0.2 - 1.4 cm H_2O m^{-1}	-
final product	TS, SO^{2-}_4	-	SO^{2-}_4, SO^{2-}_3, S^{2-}, S^o	SO^{2-}_4, S^o

CHAPTER III

METHODOLOGY

The study of operating factors effect on the performance of the lab-scale biofilter in removing H_2S was carried out at the Energy Research and Development Institute (ERDI), Chiang Mai University, Chiang Mai, Thailand. The biogas generated from piggery farm treatment at Mae-Hea, Chiang Mai was utilized over the entire period of study between August 2008 and March 2009. The microbial cell counting was undertaken at the Microbiology Department, Faculty of Science, Chiang Mai University. All water characteristic analysis was done at Environmental Engineering Department, CMU. Details of sources of activated sludge, procedure for screening of activated sludge, determination of optimum condition for immobilizing activated sludge on packing materials, experimental set-up and operation and analytical method are presented separately as follows;

3.1 Sources of Activated Sludge

Activated sludge had been taken from two sources. The first source (Source A) was from an aeration tank at a domestic wastewater treatment plant (Maharaj Hospital, Chiang Mai, Figure 3.1). This treatment plant receives 8,000 m^3/day of wastewater from Maharaj hospital and Chiang Mai University. The second source (Source B) was from an aeration tank at tofu production factory (Doisaket, Chiang

Mai, Figure 3.2). This aeration tank receives the effluent from an anaerobic reactor treating 20 m^3/day of wastewater generated during the tofu production process.

Rational of screening the activated sludge from both sources was that, due to its size, the microbial diversity supposed to be high in the aeration tank from Source A. Diverse microbial community should be advantageous, as there are several species which might be able to function at different difficult conditions, e.g. high load, lack of nutrients, etc. On the other hand, activated sludge from Source B supposed to have microbial species which had been familiar to sulfide. This assumption was supported by the fact that the aeration tank at Source B receives the sulfide-containing effluent from an anaerobic reactor. At Source A, activated sludge was taken from a return sludge line (Figure 3.3) to get the concentrated sludge. At Source B, the activated sludge was taken directly from the aeration tank (Figure 3.4).

Figure 3.1 Domestic wastewater treatment plant at Maharaj Hospital, Chiang Mai.

Figure 3.2 Treatment reactors at tofu factory, Doisaket,Chiang Mai.

Figure 3.3 Return sludge line of a domestic wastewater treatment plant at Maharaj Hospital, Chiang Mai.

Figure 3.4 Aeration tank at tofu factory, Doisaket, Chiang Mai.

3.2 Screening of Activated Sludge

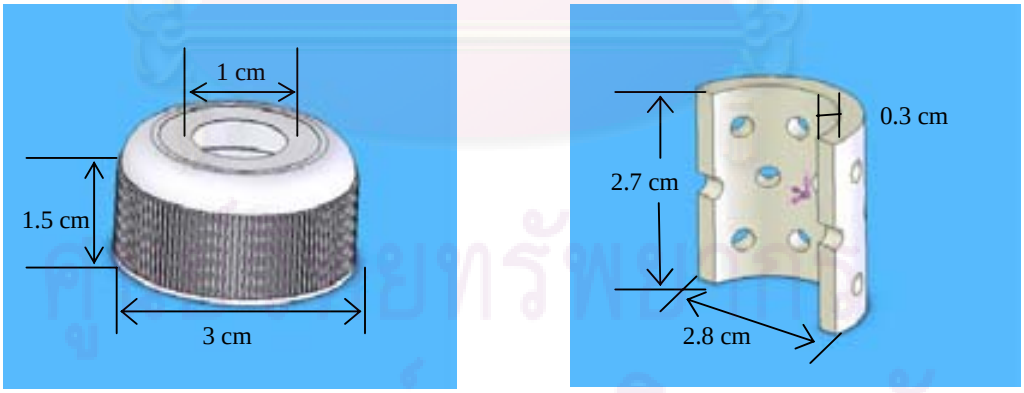
Several different packing materials have been used in biofiltration for the removal of H_2S. In this current study, two inorganic materials, e.g. plastic cap and ceramic (Figure 3.5), were evaluated. The plastic cap used in this study was the off-specification product from the drinking water bottle making factory, therefore could be considered as solid waste. On the other hand, ceramic was chosen to be used in this study because it is the local product in the northern part of Thailand. Both materials occupy different characteristics, some of which relating to these required for the biofilter packing material. While plastic cap surface is obviously smoother, its water holding capacity is inferior to that of the rougher surface ceramic. Moreover, calculated by the Solid Work program, both materials (Figure 3.6) have different surface area (541 m^2/m^3 and 182 m^2/m^3 for plastic cap and ceramic, respectively).

Apart from those differences; however, both plastic cap and ceramic can resist some undesirable conditions, e.g. acid condition, which is expected to occur inside the operated biofilter.

Plastic cap Ceramic

Figure 3.5 Studied packing materials

(The bored plastic cap was used to prevent water from accumulating inside)



Plastic cap Ceramic

Figure 3.6 Studied packing materials from Solid Work program

To screen the activated sludge, each kind of packing materials, e.g. plastic cap and ceramic, was separately submerged in the activated sludge taken from each source in an aerated plastic container (Figure 3.7). Cell numbers of microorganisms growing on the surface of each packing material were determined everyday for the period of 7 days. To determine the cell number, a piece of packing material was sampling and votex for 5 min, the microorganisms were then harvested by centrifugation (6000 rpm for 10 min) and counted by the traditional plate-counting method using three different mediums. Screening of activated sludge was done on three mediums; nutrient agar containing yeast extract (NYA) for heterotrophic bacteria, thiosulfate agar (TSA) for less acidophilic sulfur-oxidizing bacteria and modified wasksman gellan gum (MWG) for acidophilic sulfur-oxidizing bacteria (Hirai et al., 2001). Components of these mediums were summarized in Table 3.1. Figure 3.8 shows all steps of cell number determination. The activated sludge capable of increasing the cell number on the TSA to the desired range ($> 10^9$ cfu/L of packing material) was selected to be utilized in the biofilter study. This criteria was set from the assumption that groups of the less acidophilic sulfur-oxidizing bacteria growing on TSA, a medium containing high concentration of thiosulfate, should play a big role in removing H_2S in the biofilter.

After a source of activated sludge had been selected according to the criteria explained above, the optimum immobilization condition was determined.

Table 3.1 Media used for activated sludge screening (all in g/L)

NYA		MWG		TSA	
Meat extract	3	KH_2PO_4	8	KH_2PO_4	2
Polypepton	15	NH_4Cl	0.1	K_2HPO_4	2
Yeast extract	3	$CaCl_2.2H_2O$	0.5	NH_4Cl	0.4
$Na_2HPO_4.12H_2O$	2	$FeSO_4.7H_2O$	0.3	$MgCl_2.6H_2O$	0.2
NaCl	3	$Na_2S_2O_3.5H_2O$	0.01	$Na_2S_2O_3.5H_2O$	8
				$FeSO_4.7H_2O$	0.01
Agar	15	Gellan gum	5	Agar	15
pH	7	pH	4	pH	7

Figure 3.7 Aerated plastic container used for inoculating the packing materials

a) A sampled piece of packing material

b) Votexed for 5 min

c) Centrifuged at 6000 rpm for 10 min

d) Dilution spread plate

Figure 3.8 Determination of the cell number on packing material

3.3 Determination of Optimum Condition for Immobilizing Activated Sludge on Packing Materials

Each packing material was soaked into the mixture of selected activated sludge and wastewater from an anaerobic reactor at Source B (1:1 by volume) using a 10-liter plastic container under aerobic condition. Three different inoculating

conditions were investigated; (1) no sludge or wastewater addition, (2) addition of mixture of wastewater and sludge (1:1 by volume) after settling once per day and (3) addition of mixture of wastewater and sludge (3:1 by volume) after settling once per day. The cell number of microorganisms on each packing material was counted by dilution plate count method using those three mediums everyday to a period of 5 days.

Table 3.2 Inoculating Conditions

Conditions	Addition of mixture of wastewater : sludge (by volume)
1	No addition
2	Addition 1:1 once per day
3	Addition 3:1 once per day

3.4 Lab-scale Biofilter Set-up and Experiment

The schematic diagram of the lab-scale biofilter is shown in Figure 3.9. The lab-scale biofilter (Figure 3.10) was constructed from a PVC column having inside diameter of 10 cm and 60 cm in height. The effective volume of a biofilter was 4.7 L. The height of packing material in the biofilter was 50 cm, corresponding to the bed volume 3.93 L. The packing materials, i.e. plastic cap and ceramics, inoculated with the screened activated sludge were randomly filled in the biofilter. The biogas, produced from the digester treating piggery waste, was fed to the biofilters in the up-flow mode at the pre-determined rate controlled by a flow meter. Air was supplied by an air compressor at the flow rate of 10% by volume of biogas for every experiment.

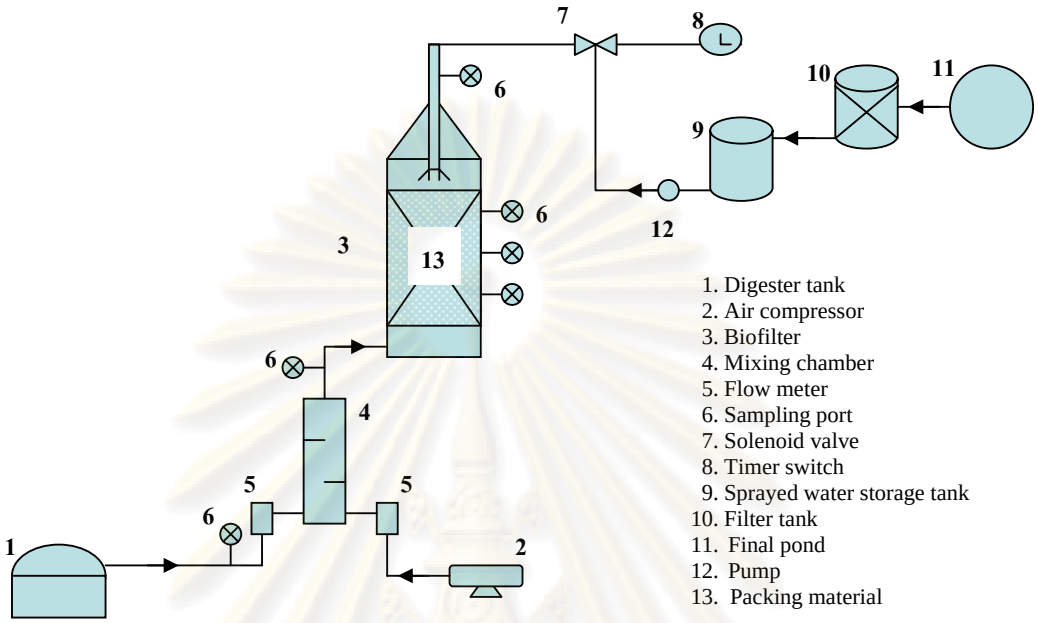


Figure 3.9 Schematic diagram of the experimental lab-scale biofilter

The sampling ports were located at the gas inlet point, along the column at the levels of 12.5, 25, 37.5 cm from the bottom of the bed of packing material and at the outlet point. At the end of each experiment, the packing material was taken from the biofilter at different levels to determine the cell number. Apart from pH measurement, mass balance of sulfur was done at the end of each experiment to determine sulfate and sulfite concentrations in sprayed water during the period of 20 min. The biofiltration system was operated at room temperature for all experiments. Each experiment was done until the pseudo-steady state was achieved within the period of at least approximately 200 hours. The pseudo-steady state can be defined as the conditions that changes in the biofilter performance are small during a steady operating condition, especially the inlet H_2S concentration. This performance,

Figure 3.10 The Lab-scale Biofilter

therefore, can be differed and reached other levels at different inlet H_2S concentrations. The water sprayed was analyzed once a month during the experiment.

The experiments (Table 3.3) were designed according to the full factorial design method using MINITAB 14 (Minitab Inc.). The program randomly generated test conditions, in which all possible combinations of studied factors were created. Each combination was conducted in duplicate, therefore there were in total 16 experiments. Effects of three factors were investigated in this study; which were packing materials (plastic cap and ceramic), space velocity (10 and 50 h^{-1}) and rate of water spraying (low = spray 30 min; stop 30 min and high = spray 60 min; stop 10 min).

The space velocity (SV) can be calculated using Equation 3.1;

$$SV = \frac{Q}{V} \tag{3.1}$$

where; SV = space velocity (h^{-1})

Q = the gas flow rate (L/h)

V = the volume of packing bed (L)

From the total working volume of a biofilter of 0.0047 m^3, total surface areas calculated for plastic cap and ceramic were 2.13 m^2 and 0.72 m^2, respectively. Percent removal of H_2S calculated for each experiment was entered in the program worksheet

to be statistically analyzed using the Two-way ANOVA to reveal the effects of studied factors.

The removal efficiency (RE) is the fraction of the contaminant removed by the biofilter, expressed as a percentage;

$$\text{Removal efficiency} = \frac{(C_I - C_O)}{C_I} \times 100 \qquad (3.2)$$

where; C_I = the inlet concentration

C_O = the outlet concentration

The level of significance (α) used in the current study was 0.05. Moreover, the equation used in predicting biofilter performance was generated using coefficients obtained from the multiple linear regression analysis.

3.5 Determination of Optimum Condition for H_2S Removal

Using the results from factorial analysis, some additional experiments were conducted to determine the optimum condition for H_2S removal by a biofilter. As described in Section 4.3.5, only SV was found to significantly affect H_2S removal by the biofilter. The optimum SV was, therefore, determined by comparing the biofilter performance when operated at three different SV values, i.e. at 20, 30, and 40 h^{-1}, respectively.

Table 3.3 Experiments obtained using the full factorial design

Run Order	Packing material	Space Velocity (h^{-1})	Sprayed water
1	Ceramic	50	High
2	Plastic cap	10	High
3	Plastic cap	50	Low
4	Ceramic	50	Low
5	Plastic cap	10	Low
6	Ceramic	10	Low
7	Plastic cap	50	High
8	Ceramic	10	High
9	Ceramic	10	Low
10	Plastic cap	10	High
11	Plastic cap	50	High
12	Ceramic	50	High
13	Plastic cap	50	Low
14	Plastic cap	10	Low
15	Ceramic	50	Low
16	Ceramic	10	High

*Low = water spray 30 min; stop 30 min, High = water spray 60 min; stop 10 min

3.6 Analytical Method

H_2S, CH_4, CO_2, and O_2 were measured everyday at very sampling port by the gas detector (Biogas check, Geotechnical Instrument, UK). Coupled with ATEX Gas Pod the detector was capable of measuring H_2S in the range of 0-5000 ppm. CH_4 and CO_2 were measured by dual wavelength infra-red cell. O_2 and H_2S were measured by internal electrochemical cell. The pH was determined using a pH meter (SevenEasy, USA). A relative humidity/temperature meter (Di-LOG DL7102) was used to determine the relative humidity and temperature of gases. Sulfate concentrations were measured by ion chromatography (Dionex 4500i). Sulfite was determined by titration using a standard potassium iodide-iodate titrant and a starch indicator (APHA, 1998).

For the determination of microbial cell numbers, a piece of packing material was sampled and measured at the start and at the end of the experiment by the traditional plate-counting method. Dilution plate count was performed to quantify the microorganism during the test. NYA, MWG and TSA mediums were used (Table 3.1). Bacterial growth could be observed by an increase of bacterial colonies after inoculation. The plates having colonies between 30 to 300 colonies were selected to be counted. The cell number was expressed in colony forming units (cfu) per liter of packing material. The analytical parameters performed during the experiments are presented in Table 3.4 and some experimental instruments are shown in Figure 3.11.

(a) Gas detector (Biogas check)

(b) A relative humidity/ temperature meter (Di-LOG DL7102)

Figure 3.11 the experimental instruments

(a) Gas detector, (b) A relative humidity/ temperature meter

Table 3.4 Analytical parameter

Parameter	Analytical method
1. H_2S (ppm)	Gas Detector
2. biogas composition(%)	Gas Detector
- CH_4	
- CO_2	
- O_2	
3. A relative humidity and temperature	Humidity&temperature meter
- Outer of biofilter	
- Inner of biofilter	
4. pH	pH meter
5. SO_3^{2-}(mg/l)	Titration (Iodometric method)
6. SO_4^{2-} (mg/l)	Ion Chromatography
7. The cell number	Dilution spread plate
8. Quality of sprayed water	Standard method (APHA,
- COD, BOD, TKN, VFA, Alk, TS,	1998)
VS, SS, VSS, TP, pH	

CHAPTER IV

RESULTS AND DISCUSSION

As stated in Chapter 1, the objectives of this work were to; (1) screen the source of activated sludge capable of oxidizing H_2S, (2) determine the condition for inoculating selected activated sludge onto the studied packing materials, and (3) investigate effects of operating factors, i.e. SV, type of packing material, rate of water spraying, on biofilter performance. Results and the corresponding discussion of each experiment done to fulfill each objective are orderly presented in this chapter.

4.1 Screening of Activated Sludge Source

Two sources of activated sludge were utilized in this part of study. Activated sludge in an aeration tank treating Chiang Mai University wastewater (Source A) was chosen due to its putatively high microbial diversity, while the activated sludge from an aeration tank treating tofu production wastewater (Source B) was selected as it had been expected to contain some amounts of sulfide-acclimatized microorganisms.

Characteristics of the studied activated sludge are presented in Table 4.1. MLVSS values of sludge from Source A and B were 1620-1640 mg/L and 553-695 mg/L, respectively. Amounts of microorganisms, determined as MLVSS concentration, were considerably higher for activated sludge from Source A compared to those from Source B as samples were collected from the returned sludge line.

Moreover, considering that as much as approximately 8,000 m^3/day of wastewater from different university activities has been treated at Source A, greater microbial diversity should be found from this source. This assumption is supported by the fact that activated sludge from Source B has been used in purifying only around 20 m^3/day of anaerobically treated wastewater generated during the tofu producing process.

Table 4.1 The characteristics of the activated sludge

Sources	MLVSS*	pH
Domestic wastewater (Source A)	1620 - 1640 mg/L	6.55 - 6.73
Tofu production wastewater (Source B)	553 - 695 mg/L	7.12 - 8.02

* measured from 2 samples collected at different times.

To screen the activated sludge, microorganisms from both sources were inoculated on the plastic cap and ceramic, used as the studied packing materials. During the inoculation process, both packing materials were submerged into the mixture of wastewater and sludge in the ratio of 1:1 under aerobic conditions. Cell numbers obtained on both packing materials using three different mediums are shown in Table 4.2. Surprisingly, cell numbers observed on the mediums when packing materials were inoculated with cultures from Source B were significantly higher than those observed when packing materials were inoculated with cultures from Source A. The difference was obvious, particularly on TSA, the medium used for screening sulfide-oxidizing cultures functioning at medium pH range. Apart from having lower amounts, cell numbers obtained from activated sludge of Source A were also found to

be highly variable (from 1.2×10^3 to 1.7×10^7 cfu/L of packing material). This finding implies that to screen cultures having specific activity, sulfide oxidizing-in this study, higher microbial diversity may be not as important as using microbial community tending to contain the required groups of microorganisms. As found in this work, though activated sludge from Source B supposed to have less diverse microorganisms, it was found to contain higher amounts of cultures capable of oxidizing sulfide (in form of thiosulfate in TSA medium). The reasons of highly variable amounts of cultures found when using activated sludge from Source A were not clear. However, it is possible that toxic substances occasionally released from some laboratories within Chiang Mai University, e.g. from hospital, might be a cause of this variety.

Table 4.2 Cell number on packing materials (cfu/L of packing materials)

Activated sludge from	Plastic			Ceramic		
	NYA	TSA	MWG	NYA	TSA	MWG
Source A	2.3×10^7 to 1.2×10^9	1.5×10^3 to 1.7×10^7	0 to 9.3×10^4	3.8×10^7 to 1.9×10^{10}	1.2×10^3 to 1.2×10^7	4.4×10^4 to 2.3×10^8
Source B	6.8×10^7 to 6.8×10^8	1.2×10^7 to 2.3×10^9	5.2×10^4 to 5.4×10^4	1.7×10^7 to 1.9×10^7	7.7×10^5 to 2.8×10^7	2.3×10^4 to 3.4×10^4

Results from this part indicated that activated sludge from Source B was superior to that from Source A in terms of both amounts and consistency of culture numbers. Therefore, activated sludge from Source B was selected to be used in the next parts of study.

4.2 Optimum Inoculating Condition for the Selected Activated Sludge

To obtain the highest possible amount of cultures on the studied packing materials, three inoculating conditions (Table 3.2) were investigated and compared. Three different mediums were used to determine the cell number on both packing materials; NYA, TSA and MWG which were specific for growing heterotrophic bacteria, less acidophilic sulfur-oxidizing bacteria and acidophilic sulfur-oxidizing bacteria, respectively (Hirai et al.,2001). Condition for inoculating screened activated sludge on studied packing material should be capable of growing microorganisms onto packing materials in the range of 10^7-10^9 cfu/L of packing materials on the TSA medium. The initial mixture of wastewater and sludge was at 1:1 (by volume) for every studied condition. Packing materials were kept submerged in this initial mixture under aerobic condition (using an air pump) without any liquid addition for Condition 1. A mixture of 1:1 (wastewater:sludge) was added after some amounts of container content were removed once per day for Condition 2, while for Condition 3 a mixture of 3:1 was added in the same manner as that for Condition 2. Cell numbers counted on each medium for each studied inoculating condition are presented in Table 4.3.

Table 4.3 Cell numbers on packing materials (cfu/L of packing materials)

Conditions	Plastic cap			Ceramic		
	NYA	TSA	MWG	NYA	TSA	MWG
1	6.8×10^8	1.2×10^7	5.2×10^4	1.7×10^7	7.7×10^5	2.3×10^4
2	3.1×10^9	2.3×10^9	7.7×10^5	2.2×10^8	2.8×10^7	3.6×10^4
3	6.8×10^9	1.2×10^{11}	5.4×10^4	1.9×10^{12}	2.8×10^{11}	7.7×10^5

From Table 4.3, it was found that Condition 1 provided the lowest number of microorganisms on the TSA medium. Moreover, cell numbers obtained were lower than the desired range (10^7-10^9 cfu/L of packing materials). For condition 2, the cell numbers achieved on plastic cap were higher than 10^9 cfu/L packing materials. However, using the same period of time amounts of microorganisms capable of growing on ceramic were less than the required range. Unlike those found for Condition 1 and 2, more than 10^9 cfu/L packing material of microorganisms were observed on both packing materials using inoculating Condition 3. The highest cell numbers determined on plastic cap (1.2×10^{11} cfu/L) and on ceramic (2.8×10^{11} cfu/L) using TSA medium were achieved after 3 and 5 days, respectively.

Results of this study show that addition of wastewater and sludge during the inoculation process improved the cell numbers obtained. Cell numbers were found to be significantly increased when the addition of wastewater and sludge was done in Condition 2 and 3. Ratio of wastewater and sludge added was also important. When ratio of wastewater:sludge equal to 3:1 was used in Condition 3, cell numbers

obtained, particularly on TSA, could be increased. Provided with adequate amount of substrate and nutrient, microorganisms will be able to have high rate of growth, i.e. growing in the log phase. This may explain the increase of cell numbers found on TSA medium when more substrate (in form of wastewater) was added for the inoculating Condition 3. Hirai et al. (2001) evaluated four inorganic packing materials for removing H_2S; porous ceramics (A), calcinated cristobalite (B), calcianted and formed obsidian (C), granulated and calcinated soil (D). Each packing material was soaked in the sludge taken from a reservoir tank for UF film separation of a nondilution and high-load night soil treatment plant. Cell numbers achieved in this current study on both packing materials using TSA medium were slightly higher than those reported by Hirai et al. (2001) on all packing materials (Table 4.4).

Table 4.4 The comparison of cell number on different packing materials (cfu/L of packing materials)

References	Packing materials	Mediums		
		NYA	TSA	MWG
Hirai et al. (2001)	A	1.3×10^{11}	2.6×10^{10}	2.1×10^{9}
	B	5.4×10^{10}	1.8×10^{10}	3.2×10^{9}
	C	1.2×10^{11}	3.8×10^{10}	6.7×10^{9}
	D	7.8×10^{10}	2.4×10^{10}	4.3×10^{9}
This work	Plastic cap	6.8×10^{9}	1.2×10^{11}	5.4×10^{4}
	Ceramic	1.9×10^{12}	2.8×10^{11}	7.7×10^{5}

However, the acidophilic sulfur-oxidizing bacteria obtained (using MWG medium) were obviously lower. This is reasonable as the activated sludge from a tofu production factory used in this current study had pH in the rage of 7.12 - 8.02, which is not the optimum range for the bacteria preferring acid conditions. As the majority of bacteria functioning in the bioreactor prefer condition of pH in the middle range, cultures growing on the TSA medium should be more vital in terms of long term reactor performance. Therefore, in this current study, importance was given to the number of microorganisms growing on the TSA medium. The suitable inoculating condition capable of increasing cell numbers to the required range was Condition 3. This condition had been used to inoculate cultures onto both studied packing materials to be used in lab-scale biofilters.

4.3 Lab-Scale Biofilter Experiment

Inoculated packing materials were used in this part of study to investigate effects of SV value, type of packing material and rate of water spraying on the lab-scale biofilter performance in removing H_2S. To reveal both the interaction and main effects, the experiments were designed based on the full factorial theory. Amounts and types of end products produced from H_2S oxidation and numbers of microorganisms on packing materials at the end of each experiment were also evaluated.

4.3.1 Characteristics of Sprayed Water

The sprayed water was taken from a pond used as the post-treatment unit for piggery wastewater (Figure 4.1). This water was utilized as it was expected to contain some required organic substances and nutrients for sulfide-removing microorganisms. Moreover, its alkalinity was also important in maintaining the pH level at the optimum range. Utilizing this water was therefore advantages in the economical points of view. Characteristics of this water are presented in Table 4.5.

Figure 4.1 The pond used as a source of water sprayed

Some amounts of microorganisms were detected in the pretreated pond water, but cell numbers found ($1.6 \times 10^4 - 4.3 \times 10^5$ cfu/ml on TSA medium) were significantly lower than those inoculated on the packing materials. However, it is possible that these cultures might have some roles in H_2S removal at long term biofilter operation.

Table 4.5 Characteristics of sprayed water before and after filtration

Parameters	Characteristics of sprayed water* (all in mg/L except pH)	
	Before filtration	After filtration
pH	6.83 - 7.64	6.64 - 7.79
BOD_5	6.4 - 14	4.9 - 5.2
COD_t	61 - 70	46
TKN	9.4 - 10.8	7.5 - 8.3
VFA	16.7 - 100	14.4 - 150
Alk	125 - 152	138 - 180
TS	250 - 282	245 - 256
VS	74 - 88	55 - 82
SS	15 - 21	4
VSS	9 - 14	2 - 4
TP	6.08 - 6.86	5.13 - 6.3

* Measured from 2 samples collected at different times.

As seen in Table 4.5, raw water from the pond contained some amounts of suspended solids (15-21 mg/L). In order to avoid clogging of a sprinkler used in spraying water in the biofilter, this raw water had been pretreated using the sand filter unit. As the result, concentration of suspended solids was reduced to 4 mg/L after filtration.

Not only did the raw water contain suspended solids, some amounts of organic compounds (measured as BOD, COD and VFA), nutrients (in forms of TKN and TP) were also presented. Although concentrations of these compounds were decreased after filtration (Table 4.5), amounts remained should be adequate for the microbial activities. Considering that dominant species of microbial communities were the sulfide-oxidizing autotrophic bacteria requiring relatively low amounts of macro–nutrients, i.e. nitrogen and phosphorus, and some trace elements, the assumption of this adequacy seemed to be appropriate.

4.3.2 H_2S Removal Efficiency During the Experimental Period

Using the optimum inoculating condition attained, cell numbers on each studied packing material were counted. The inoculated packing material was then randomly filled into the biofilter before its performance was tested according to the condition designed using the full factorial theory. Cell numbers obtained on each medium used in this study in order of the test order are shown in Table 4.6**.**

Numbers of cultures growing on TSA before implementation of the biofilter were in the range required (10^7 – 10^9 cfu/L packing material). This guaranteed that the microbial communities present on the packing materials before the commence of each test were dominated or, at least, contained considerable amount of the sulfide-oxidizing cultures. In contrast to cultures on TSA, those growing on TSA (pH = 4) were highly inconsistent. Numbers of cultures found on this medium ranged from non-detectable to 2.3×10^8 cfu/L. Thus, performance of the biofilter in removing H_2S should be governed by cultures growing on TSA. From 4.0×10^7 to 1.8×10^{12}

Table 4.6 Cell numbers and conditions in order of each test

Test Order	Packing material	Space Velocity (h^{-1})	Rate of water spraying*	Cell numbers achieved after inoculation (cfu/L packing materials)		
				NYA	TSA	TSA (pH=4)**
1	Ceramic	50	High	2.7×10^{9}	1.8×10^{8}	1.1×10^{8}
2	Plastic cap	10	High	2.3×10^{10}	4.0×10^{7}	2.3×10^{6}
3	Plastic cap	50	Low	3.9×10^{11}	7.4×10^{11}	2.3×10^{6}
4	Ceramic	50	Low	2.3×10^{8}	4.5×10^{7}	2.3×10^{6}
5	Plastic cap	10	Low	7.9×10^{11}	2.3×10^{8}	2.3×10^{8}
6	Ceramic	10	Low	5.0×10^{7}	2.3×10^{8}	2.3×10^{5}
7	Plastic cap	10	High	4.0×10^{7}	8.3×10^{7}	0
8	Plastic cap	50	High	6.4×10^{7}	1.0×10^{8}	0
9	Ceramic	10	High	7.3×10^{7}	1.2×10^{8}	2.3×10^{5}
10	Ceramic	50	Low	2.6×10^{9}	2.3×10^{8}	0
11	Plastic cap	50	High	3.5×10^{9}	2.3×10^{8}	0
12	Ceramic	10	High	1.8×10^{12}	2.3×10^{8}	4.9×10^{5}
13	Plastic cap	10	Low	9.7×10^{9}	2.3×10^{8}	0
14	Ceramic	50	High	1.5×10^{8}	1.3×10^{8}	0
15	Plastic	50	Low	6.3×10^{11}	2.3×10^{8}	0
16	Ceramic	10	Low	2.0×10^{8}	2.3×10^{8}	0

*Low = water spray 30 min; stop 30 min, High = water spray 60 min; stop 10 min

** In this part of the study onwards, pH-adjusted TSA medium (pH=4) was utilized instead of the MWG medium. This was done to determine the actual cell numbers capable of growing on the acid medium as TSA contained higher concentration of thiosulfate than MWG.

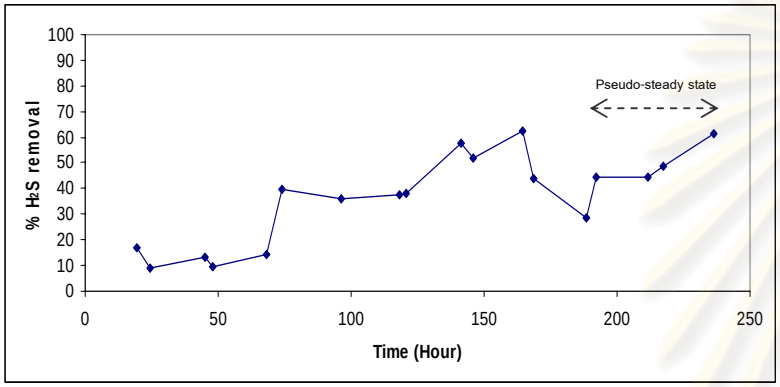
cfu/L of microorganisms were observed on NYA, the only medium used that contained organic carbon. Cultures appeared on this medium, therefore, supposed mainly to be mainly the heterotrophs. Though some heterotrophic species have been reported to be able to oxidizing H_2S, e.g. denitrifiers (Soreanu et al., 2008), it was less likely that those species would exist on the NYA medium.This assumption is reasonable as NYA did not contain any compounds required by those sulfide-oxidizing heterotrophs, e.g. NO_3^-, sulfur. Therefore, results of culture count revealed that communities of microorganisms on packing materials after inoculation process comprised both autotrophs and heterotrophs. However, only the sulfide-oxidizing autotrophs preferring medium pH range were dominantly present in these communities at the beginning of all biofilter experiments.

H_2S removal efficiency during the experimental time period of each test indicated in Table 4.6 is shown in Figure 4.2. All tests were done until the pseudo-steady state was reached. The total period of time for each test was not shorter than 200 hours to ensure that the system proceeded to the point that H_2S removal efficiency observed truly represented its performance at each studied condition. The pseudo-steady state was expected to be reached in stead of the true-steady state because, as mentioned in Chapter 3, the biogas generated from an aerobic digester treating piggery wastewater was used in this study. H_2S contained in the biogas was strongly dependent on wastewater characteristics, so its concentrations, in this case, were not controllable (H_2S inlet concentration of each test is tabulated in Table 4.7).

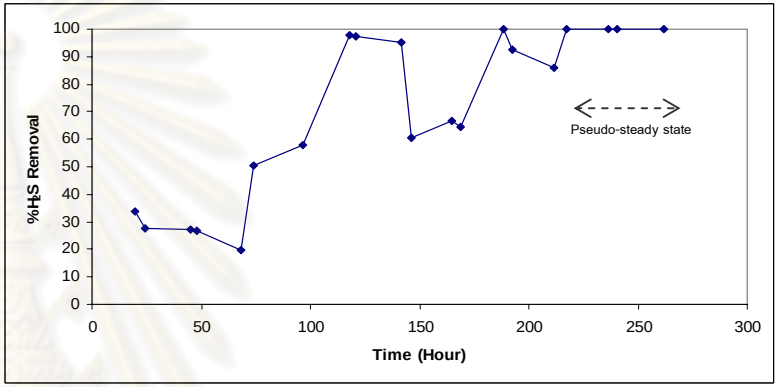
Variation of inlet H_2S concentrations resulted in the pseudo rather than true-steady state being reached. The period indicated in each of the graphs of Figure 4.2 shows all data used in the calculation of H_2S removal efficiency at each studied condition.

Though the maximum removal efficiencies obtained at different conditions were obviously different, changes of H_2S removal by time shared the same pattern. At the start of each test, pertinent cultures inoculated on packing materials were acclimatizing to the condition used. It can be observed that longer acclimation period was required when the biofilter received higher H_2S load (at higher SV). After this adaptation period, H_2S removal efficiency was increased. Again, rate of this increase was relatively gradual when higher SV value was utilized. Increase of H_2S removal proceeded to the highest level where changes of removal efficiency were not significant. At this point, performance of the system was claimed to be at pseudo-steady state. Almost complete H_2S removal was found to be achieved when biofilter was operated at low SV (10 h^{-1}), while $\leq$ 50% removal was obtained at almost all higher SV (50 h^{-1}) experiments. It has to be mentioned, however, that as high as nearly 90% H_2S removal was also found in some tests when the biofilter was operated at SV equal to 50 h^{-1} and the inlet H_2S concentrations were relatively low, e.g. Test Order 15. This implies that effects of inlet H_2S concentration on H_2S removal by biofilter may also need to be assessed apart from those of the studied factors. Therefore, statistical analysis using the Two-way ANOVA and the multiple regression analysis of the effect of studied factors and also inlet H_2S concentration were done. This analysis is presented in the next Sections.

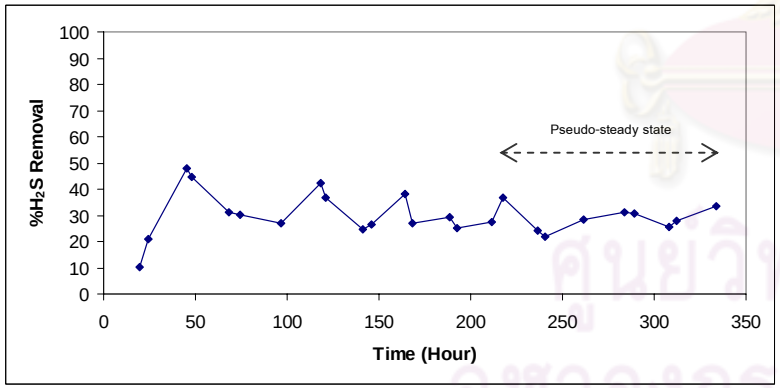
Test Order 1: Ceramic, SV = 50 h^{-1}, rate of sprayed water = High



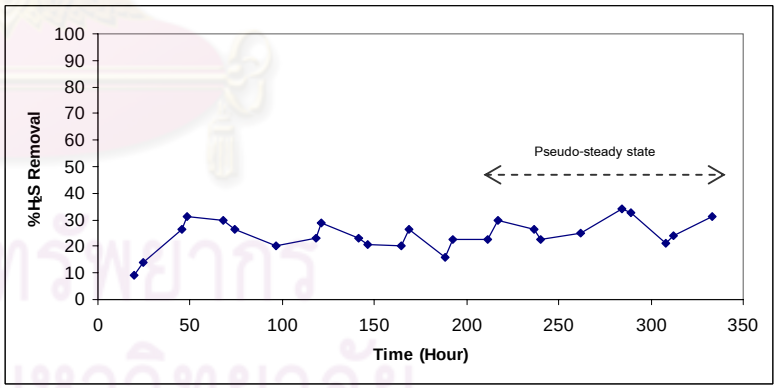
Test Order 2: Plastic cap, SV = 10 h^{-1}, rate of sprayed water = High



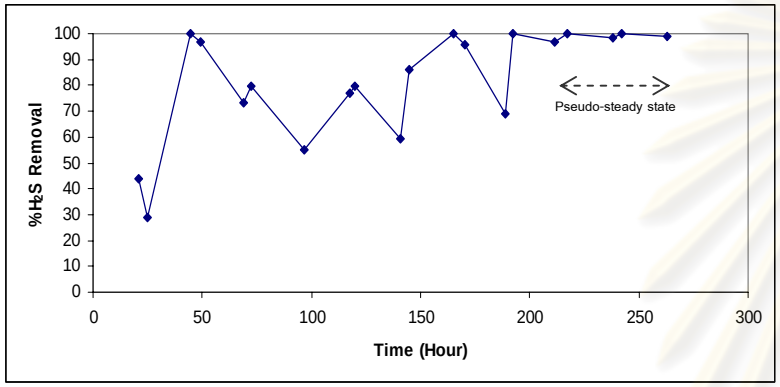
Test Order 3: Plastic cap, SV = 50 h^{-1}, rate of sprayed water = Low



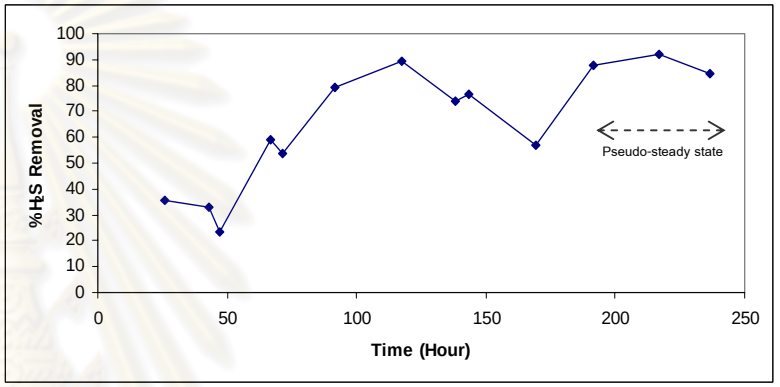
Test Order 4: Ceramic, SV = 50 h^{-1}, rate of sprayed water = Low



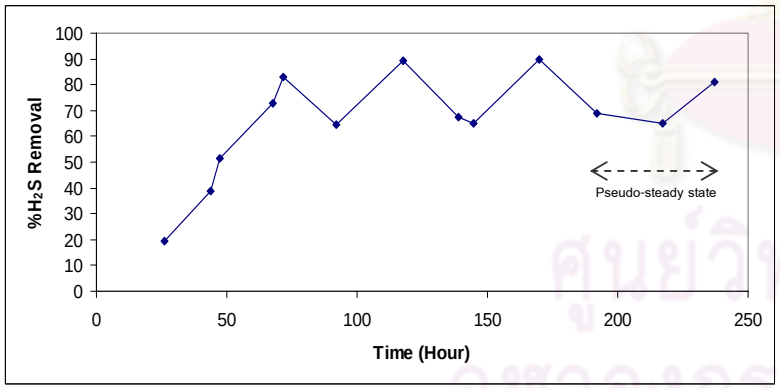
Test Order 5: Plastic cap, SV = 10 h^{-1}, rate of sprayed water = Low



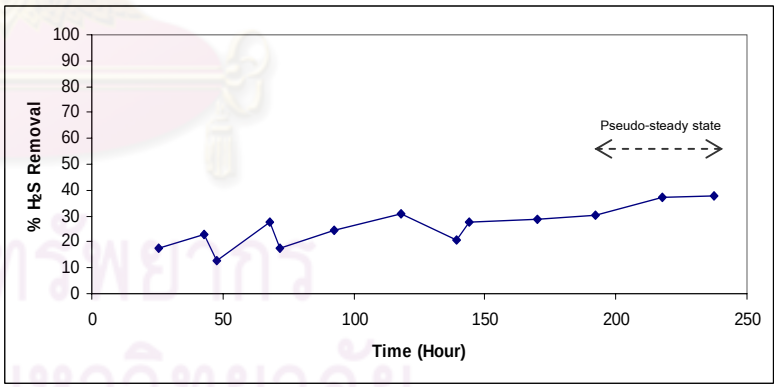
Test Order 6: Ceramic, SV = 10 h^{-1}, rate of sprayed water = Low



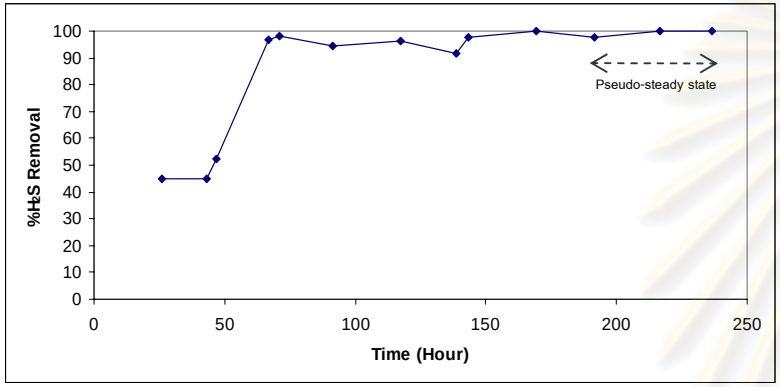
Test Order 7: Plastic cap, SV = 10 h^{-1}, rate of sprayed water = High



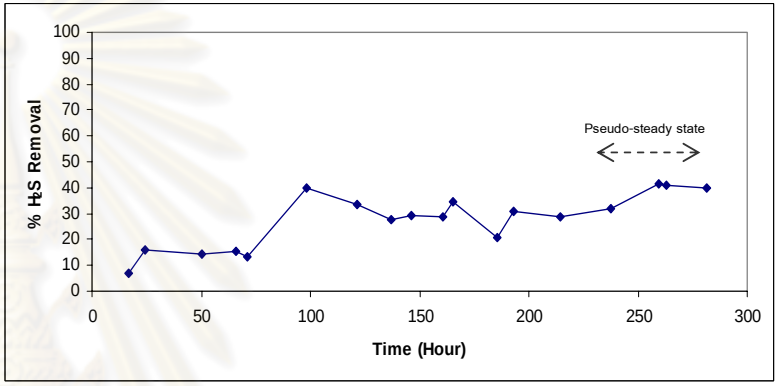
Test Order 8: Plastic cap, SV = 50 h^{-1}, rate of sprayed water = High



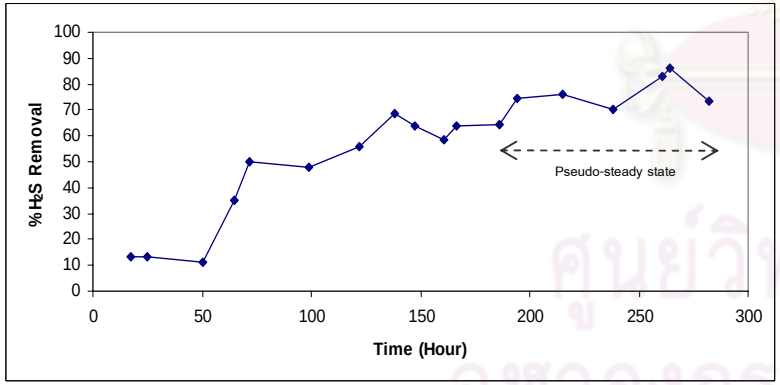
Test Order 9: Ceramic, SV = 10 h^{-1}, rate of sprayed water = High



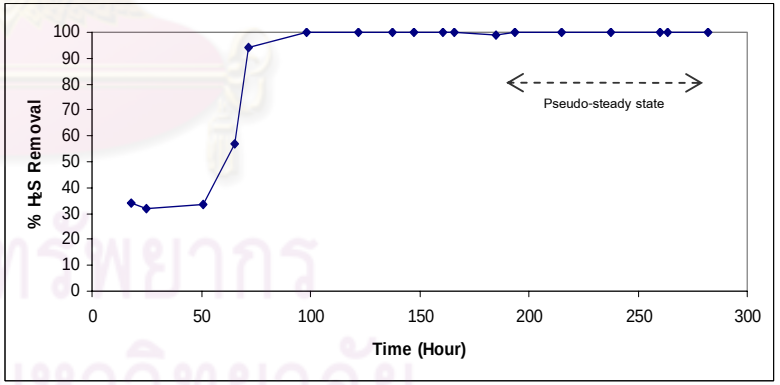
Test Order 10: Ceramic, SV = 50 h^{-1}, rate of sprayed water = Low



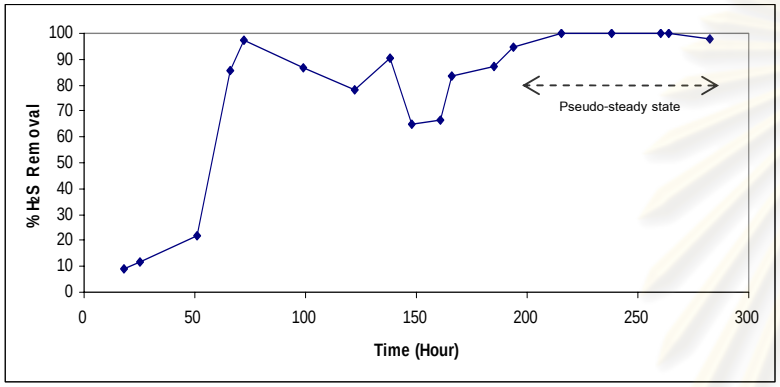
Test Order 11: Plastic cap, SV = 50 h^{-1}, rate of sprayed water = High



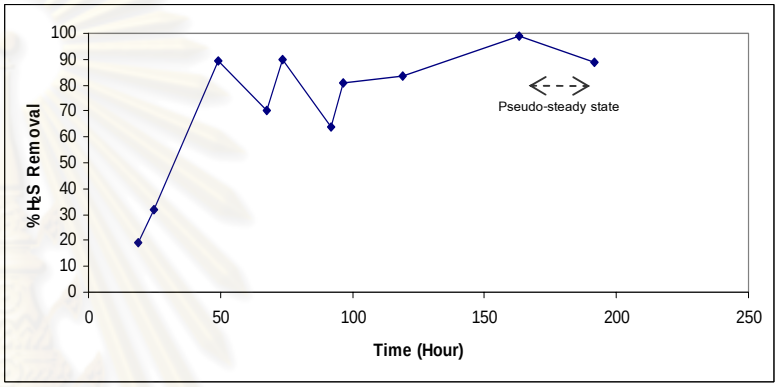
Test Order 12: Ceramic, SV = 10 h^{-1}, rate of sprayed water = High



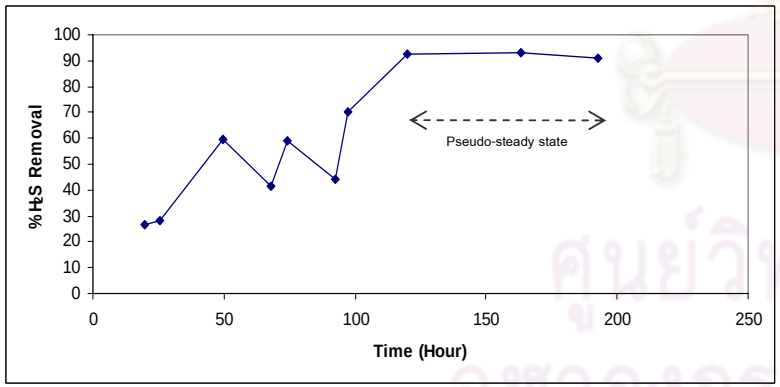
Test Order 13: Plastic cap, SV = 10 h^{-1}, rate of sprayed water = Low



Test Order 14: Ceramic, SV = 50 h^{-1}, rate of sprayed water = High



Test Order 15: Plastic cap, SV = 50 h^{-1}, rate of sprayed water = Low



Test Order 16: Ceramic, SV = 10 h^{-1}, rate of sprayed water = Low

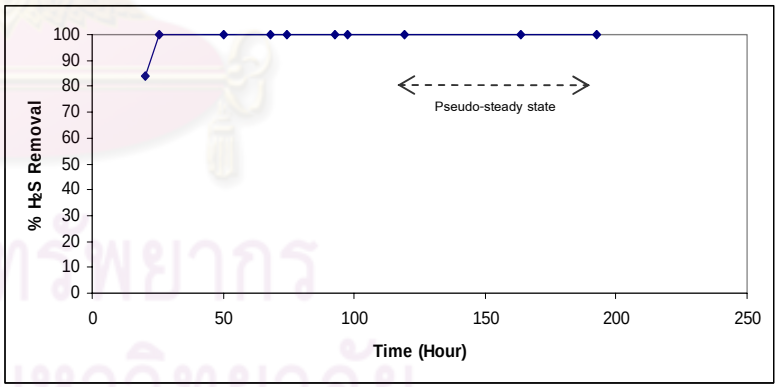


Figure 4.2 The relationship of H_2S removal and period of time

4.3.3 Factorial Analysis

To analyze the result obtained from the full factorial designed experiment, performance of the biofilter in terms of H_2S removal was set as the variable. However, as the inlet H_2S concentrations were varied, they were also included in the analysis as the covariate. This was done to see whether inlet H_2S concentration had any effects on the biofilter performance. The inlet H_2S concentrations used in the analysis were the average values of all concentrations during the specified pseudo-steady state. Both H_2S removal efficiency achieved for each test and inlet concentration are shown in Table 4.7.

Both the variables and covariate were statistically analyzed using the Two-way ANOVA to reveal the effects of studied factors. Level of effect and the coefficient were generated using the multiple liner regression analysis. The level of significance (α) used in the current study was 0.05.

Results of factorial analysis using the Two-way ANOVA and the multiple regression analysis are shown in Table 4.8 and Table 4.9, respectively. At 95% confidence level, only the main effect was calculated to be significant ($P = 0.008$), while all interaction effects were shown not to significantly affect H_2S removal ($P > 0.05$) efficiency.

Table 4.7 Inlet concentrations and H_2S removal efficiencies of each test

Test Order	Packing material	Space Velocity (h^{-1})	Rate of water spraying	Inlet H_2S conc. (ppmv)	H_2S Removal Efficiency (%)
1	Ceramic	50	High	2461.3	47.68
2	Plastic cap	10	High	2363	100.00
3	Plastic cap	50	Low	4222.8	28.67
4	Ceramic	50	Low	4415	27.50
5	Plastic cap	10	Low	4079.5	99.30
6	Ceramic	10	Low	3861.7	88.25
7	Plastic cap	10	High	3874	73.88
8	Plastic cap	50	High	3905.4	32.24
9	Ceramic	10	High	3887	99.03
10	Ceramic	50	Low	2341.3	40.80
11	Plastic cap	50	High	2405.7	77.20
12	Ceramic	10	High	2391.5	100.00
13	Plastic cap	10	Low	2261.3	100.00
14	Ceramic	50	High	1628.5	87.98
15	Plastic cap	50	Low	1506.3	92.13
16	Ceramic	10	Low	1481.4	100.00

Table 4.8 The Two-way ANOVA analysis

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Covariates	1	2416.4	2449.49	2449.49	9.09	0.020
Main Effects	3	7510.4	7450.81	2483.60	9.22	0.008
2-Way Interactions	3	632.5	623.07	207.69	0.77	0.546
3-Way Interactions	1	11.5	11.45	11.45	0.04	0.843
Residual Error	7	1886.2	1886.16	269.45		
Total	15	12456.9				

Table 4.9 The multiple regression analysis

Term	Effect	Coefficient	P
Constant		113.51	0.000
H_2S conc.		-0.01	0.020
Packing material	-5.07	-2.54	0.560
SV	-42.95	-21.47	0.001
Water	3.10	1.55	0.718
Packing material*SV	-5.44	-2.72	0.529
Packing material*Water	10.72	5.36	0.237
SV*Water	4.02	2.01	0.645
Packing material*SV*Water	-1.76	-0.88	0.843

R^2 = 84.86 %, R^2 (adjust) = 67.55%

As expected, the inlet H_2S concentration was also found to significantly affect H_2S removal efficiency (P = 0.020). Results from the multiple regression analysis (Table 4.9) indicated that the only factor significantly affect H_2S removal efficiency was the SV (P = 0.001). These results agreed with the calculated level of effects (Table 4.9 and Figure 4.3), which showed that level of effect of SV was the highest (-42.95) while level of effects of the others were much smaller (equal to 3.1 and -5.07 for rate of water spraying and type of packing material, respectively). The negative sign of these levels means that increasing of the factor value (e.g. SV) adversely affected the response (i.e. H_2S removal efficiency).

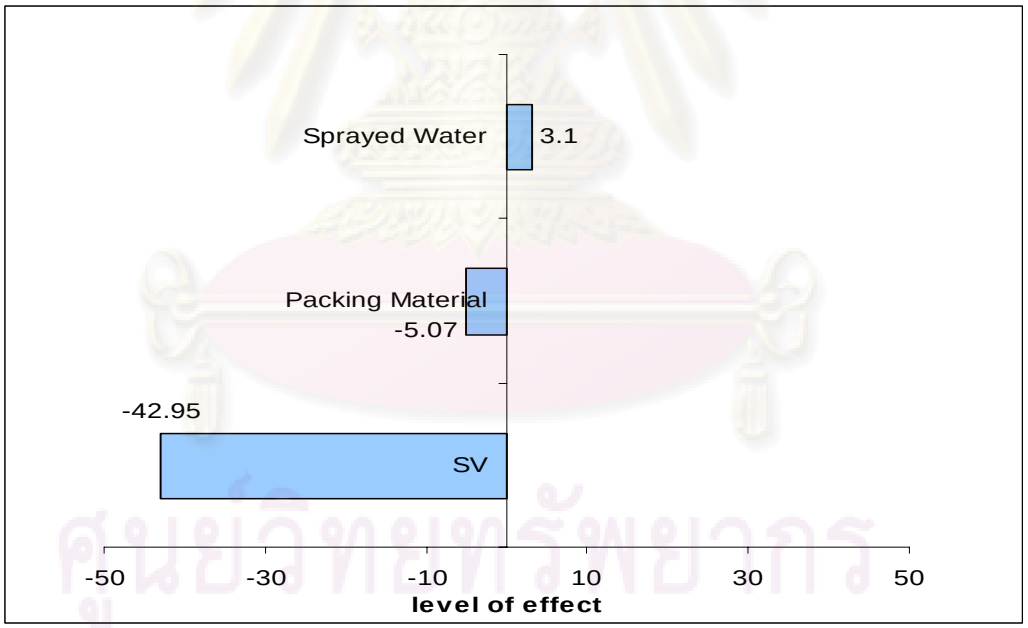


Figure 4.3 Level of effects of studied operating factors on H_2S removal

4.3.3.1 Factorial Plot of the Interaction Effect

The full factorial design allowed both the main and more importantly, interaction effects of studied factors to be revealed. To correctly assess the impact of each factor on H_2S removal performance (i.e. main effect), the interaction (i.e. effect of one factor depends on the level of the other) needs to be firstly analyzed.

The interaction plot generated from the interaction effect analysis is shown in Figure 4.4. Though the results obtained from the Two-way ANOVA analysis (Table 4.8) indicated that there were no significant interaction effects existed ($P > 0.05$), graph in Figure 4.4 show some tendencies of the possible interaction among studied factors. Significant interaction effects might have been observed, if levels of some studied factors, SV in particular, had been changed.

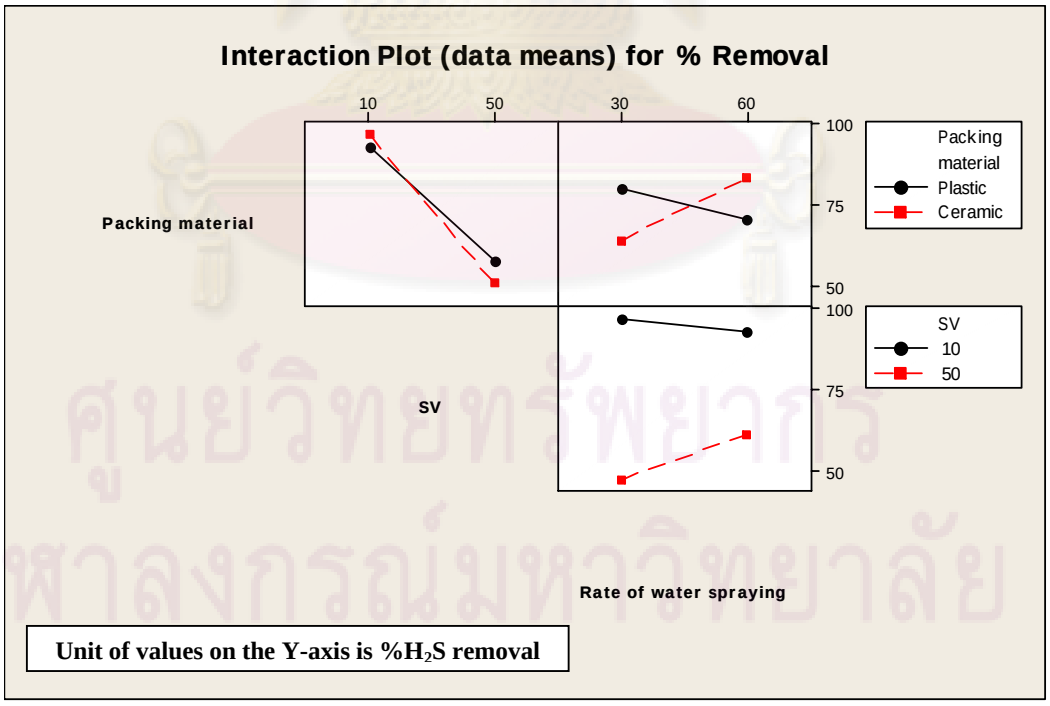


Figure 4.4 Interaction effects of studied factors on H_2S removal

Interaction effect between type of packing material and SV was not found to be meaningful because dramatically greater H_2S removal efficiency was seen at lower SV value regardless of the type of packing material used. The most likely interaction effect, however, was found between type of packing material and rate of water spraying. Higher H_2S removal was achieved at higher rate of water spraying when ceramic was utilized as the packing material. On the other hand, when plastic cap was used as the packing material, lower rate of water spraying was preferred to get high H_2S removal efficiency (Figure 4.4). Even though plastic cap was calculated to have higher surface area (541 m^2/m^3 versus 182 m^2/m^3 for ceramic), greater amounts of microorganisms tended to be found on ceramic at the end of each test (Table 4.13). Lower cell count found on the plastic cap may be caused by its slippery surface, to which sulfide-oxidizing cultures screened from the chosen source (Source B) may not be able to firmly attach. This might be the reason why higher H_2S removal efficiency was observed when the lower rate of water spraying was operated. Unlike the plastic cap, ceramics surface was visibly rougher and facilitate microbial attachment. Higher amounts of bacteria counted on ceramic could be responsible for the requirement of higher rate of water spraying to increase the mass transfer rate of substrates into the relatively thicker biofilm (Li et al., 2002a).

The possible interaction effect between SV and rate of water spraying was very interesting. While nearly complete H_2S removal was always achieved at low SV, considerable removal improvement (from 45% to 60% removal efficiency) could be attained at high SV if the higher rate of water spraying was utilized. As the suitable moisture content of packing material, is the other key parameter necessary for the

well-performing biofilter, rate of water spraying can either improve or deteriorate the biofilter performance. Too high of moisture level will inhibit the mass transfer from gas phase to the biofilm. On the contrary, drying out of the media will definitely harm the healthy growth of microorganisms that are immobilized on the supporting media surface (Huiqi et al., 2006, Morales et al., 2003). Improvement of H_2S removal efficiency at high SV found in this current study was possibly caused by increase of H_2S in the dissolved forms, when using the higher rate of water spraying. As microorganisms can utilize H_2S only in these forms, the more H_2S dissolved, the better H_2S can be biologically oxidized.

4.3.3.2 Factorial Plot of the Main Effect

Statistical analysis using the Two-way ANOVA (Table 4.8) and multiple regression (Table 4.9) revealed that SV significantly affected (P = 0.001) H_2S removal efficiency by the biofilter, while type of packing material (P = 0.560) and to greater extent rate of water spraying (P = 0.718) did not.

Almost complete H_2S removal was achieved (Figure 4.5) when a biofilter was operated at lower SV (10 h^{-1}), while only about 50% H_2S removal was observed at higher SV (50 h^{-1}). Chung et al. (1996b) reported that at SV between 51.43 h^{-1} and 108.57 h^{-1}, H_2S removal efficiencies showed little variation. However, significantly different in H_2S removal was found when SV was increase to 214.28 h^{-1}. Lee et al. (2006) utilized A. *thiooxidans* AZ11 immobilized biofilter in removing H_2S from the gas stream. H_2S removal efficiency of 99.95% was reported at the SV ranging from 200 – 400 h^{-1} and inlet H_2S concentration of 200 ppmv. When SV

increased to 500 h^{-1}, H_2S removal efficiency was reduced to 98% and further deteriorated to 94% at SV of 600 h^{-1}. Reduction of H_2S removal efficiency found in Lee et al.'s work at higher SV was not as obvious as observed in the current study because H_2S concentration used in their study was much lower (200 ppmv compared to > 2,000 ppmv used in the current study).

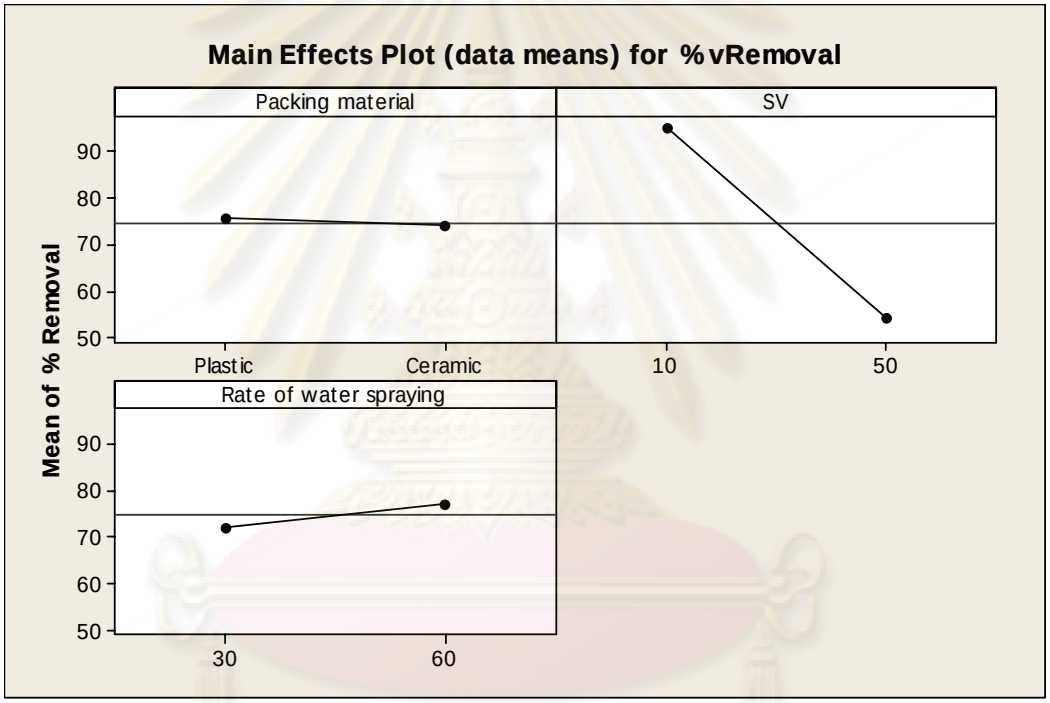


Figure 4.5 Main effects of studied factors on H_2S removal

Results from statistical analysis (Table 4.8 and 4.9) also indicated that inlet H_2S concentration, as a covariate, also significantly affected H_2S removal efficiency (P = 0.020). Considering that SV is the ratio of biogas flow rate and volume of packing material, different SV values used in this work were actually the indication of different biogas flow rate. That the flow rate and inlet concentration

significantly affected the biofilter performance means H_2S removal by the biofilter was influenced by H_2S loading rate. Kim et al. (2008) evaluated the performance of the immobilized cells to changes in inlet H_2S loading rate. The initial loading rate during the starting phase for the biofilter was 1 g H_2S m^{-3} h^{-1} at a concentration of 12 ppm. During every step increase in the loading rate (from 1 to 1.7, 2.5, 6 and 8 g H_2S /m^3.h, respectively), it was observed that the biofilter took a few days to adapt to the new concentration and reached a new steady state value shortly. Though the loading rate of H_2S was gradually increased, the response of removal efficiency was a sudden decline. Barona et al. (2004) investigated the response of biofilter to abrupt changes in H_2S gas concentration at a constant gas flow rate 0.78 m^3 /h. An increase in concentration of H_2S from low to high levels (from 19.7 ppmv to 210.5 ppmv) was found to reduce removal efficiency significantly (from 97 % to 83 %). In this current study, H_2S was removed completely at SV = 10 h^{-1} when the average inlet concentration was in the range of 2261.3 – 2391.5 ppmv. When the average inlet concentration increased to the range of 3861.7 – 4079.5 ppmv, H_2S removal efficiency reduced to only 74 %. This result indicated that higher inlet concentration adversely affected biofilter performance. Rattanapan et al. (2009), however, observed only slight decrease in H_2S removal efficiency when inlet concentrations were varied from 100 to 400 ppmv. The maximum H_2S removal (98.7%) was achieved at initial H_2S concentration of 200 ppmv, while as much as 98% removal was still obtained at the concentration of 4000 ppmv. Superiority of Rattanapan et al. (2009)'s biofilter to that used in this current study may due to the fact that granular activated carbon was utilized as the packing material. Greater specific surface area of achieved carbon increased both numbers of microorganisms and contact time between H_2S gas and the

sprayed liquid. Moreover, activated carbon itself was also capable of adsorbing H_2S as significant amounts of H_2S was reported to be removed in the biofilter without cell immobilization (Rattanapan et al., 2009).

4.3.3.3 Cube Plot

Combination of optimum factor values in which the highest H_2S removal efficiencies were obtained is presented in forms of cube plot in Figure 4.6. Up to 99.65% H_2S removal efficiency was achieved using plastic cap as packing material when values of SV and rate of water spraying equated to 10 h^{-1} and 30:30 min (spray:stop), respectively. For ceramic, 99.52% of H_2S was removed when values of SV and rate of sprayed water equaled to 10 h^{-1} and 60:10 min (spray:stop), respectively. As effect of SV was the greatest for H_2S removal, more than 86% of H_2S could be removed at low SV (10 h^{-1}), regardless of values of other factors.

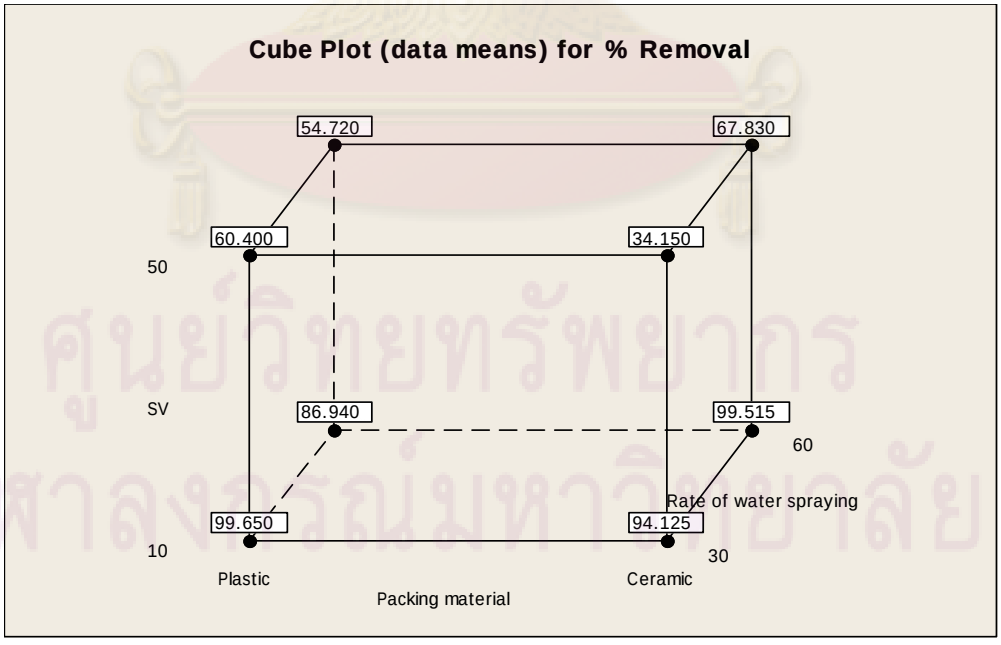


Figure 4.6 Cube plot

4.3.4 Multiple Regression Analysis

As shown in Table 4.9, among all studied factors, only SV and the inlet H_2S concentration (set as a covariate) were found to affect H_2S removal efficiency significantly. In order to get more accurate values of coefficient and improve the coefficient of determination (R^2), other factors and all interactions had been dismissed. The refitted coefficients and the new calculated R^2 adjusted (R-Sq (adj.)) are presented in Table 4.10. The R-Sq (adj.) value represents the proportion of variation in the response data explained by the terms in the model. R-Sq (adj.) is a modified version of R-Sq that adjusts for the number of terms in the model. It is useful for comparing models from the same data with different number of terms. As expected, R-Sq (adj.) after refitting increased from 67.55% to 75.21%. Coefficients calculated in Table 4.10 can be used to construct an equation (Equation 4.1) for the prediction of H_2S removal efficiency. If the inlet H_2S concentration is known along with the required outlet H_2S concentration, either biogas flow rate or bed volume of a biofilter can be conveniently calculated. Accuracy of Equation 4.1 was tested and the results are illustrated in the next Section.

Table 4.10 Estimated Effects, Coefficients and P values after Refitting

Term	Effect	Coefficient	P
Constant		147.549	0.000
H_2S conc.		-0.0138	0.020
SV	-43.05	-1.0762	0.000

R-Sq = 67.55 % R-Sq (adj.) = 75.21 %

$$\% H_2S \text{ removal} = 147.549 - 0.0138(\text{Inlet } H_2S \text{ conc.}) - 1.0762(SV) \quad (4.1)$$

Considering that the approximate H_2S concentration in the produced from the piggery wastewater is equal to 2,500 ppmv, 92% removal needs to be achieved if the outlet concentration is not to be higher than 200 ppmv, the concentration required by most of the generator manufactures. Using Equation 4.1 with the condition stated above, the optimum SV can be calculated to be around 20 h^{-1}. It needs to be noted; however, that at this SV value, the limit of inlet H_2S concentration which can be used in Equation 4.1 is 9133 ppmv. Higher inlet H_2S concentration will result in the negative H_2S removal.

4.3.5 Optimum SV for H_2S Removal by the Biofilter

To determine the optimum SV for H_2S removal by the biofilter, three additional tests were conducted. In each test, the plastic cap was used as the packing material with the lower rate of water spraying. Three values of SV were utilized, i.e. 20, 30 and 40 h^{-1}. Efficiencies of H_2S removal by time of all tests are shown in Figure 4.7.

Owing to the difficulties of anaerobic digester operation, the inlet H_2S concentration was unexpectedly low during the time of all additional tests. H_2S concentrations in the biogas produced from the digester during this period ranged only between 1300 to 1700 ppmv, nearly 3 folds lower than concentrations observed in the previous tests (1247 - 4556 ppmv). As the result of these low concentrations, complete H_2S removal was achieved in all tests, regardless of the SV used, at the end

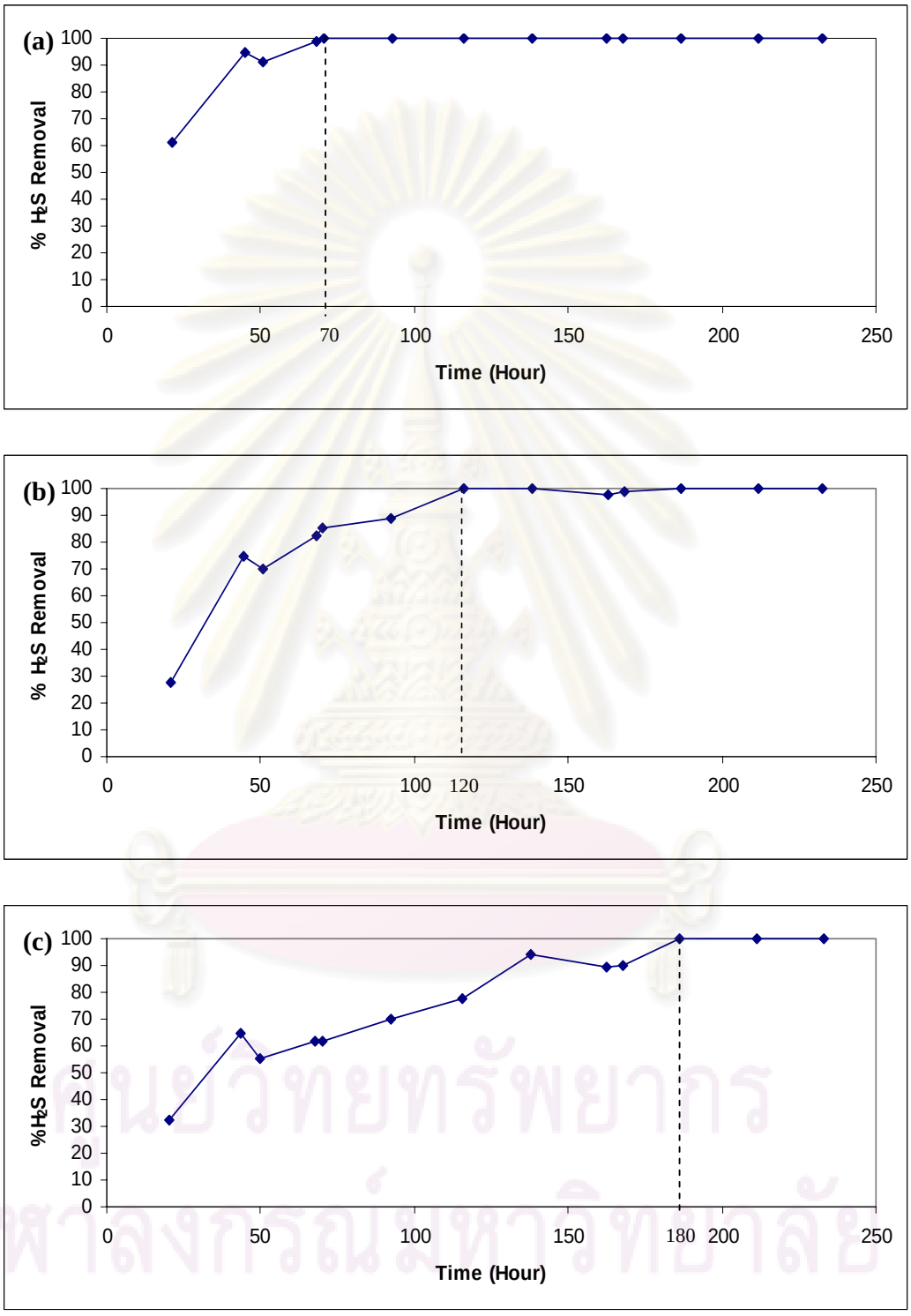


Figure 4.7 H_2S removal efficiency by time at SV equal to

(a) 20 h^{-1}, (b) 30 h^{-1} and (c) 40 h^{-1}

of each test (i.e. at the pseudo-steady state). Nevertheless, the time required to reach the highest removal of each test was obviously different. Interestingly, these required time periods were proportionally increased with the increase of SV used (the time periods required were 70, 120 and 180 hours for the biofilter operated at SV 20, 30 and 40 h^{-1}, respectively). Huiqi et al. (2006) reported the feasibility of using a biological activated carbon as a novel packing material. Two identical laboratory-scale biofilters, one was operated with biological activated carbon (BAC) and another with virgin carbon without bacteria immobilization (VAC). The relationship between the inlet H_2S concentration, GRT, and H_2S removal efficiency was studied. The H_2S concentration varied from 20 to 100 ppmv and at each H_2S setting, the GRT for the biofilter was changed from 6 to 1 s. BAC can work efficiently at a GRT of 4 s or above in spite of the changes in the influent concentrations of H_2S. Reducing GRT further (<4 s) resulted in lower H_2S removal. Nevertheless removal efficiency of 98% was commonly reached for inlet H_2S concentrations as high as 30 ppmv when the system was operated at GRT as short as 2s. In this current study, gas retention time calculated at high SV (50 h^{-1}) and low SV (10 h^{-1}) were 1.2 and 6 min, respectively. Though inlet H_2S concentrations were considerably higher than those used by Huiqi et al. (2006), H_2S removal efficiency was obviously improved when longer GRT was utilized.

Using results obtained from the addition tests along with the tests conducted at SV 10 and 50 h^{-1} for the same type of packing material and rate of water spraying, accuracy of Equation 4.1 was evaluated. Figure 4.8 shows the comparison between % H_2S removal at different SV values achieved from the experiments and

those calculated from Equation 4.1. Both the Pearson correlation coefficient (r = 0.944) and the P-value (0.016) indicated that Equation 4.1 can be, to some extent, utilized in the prediction of % H_2S removal. Likewise, as stated earlier, this equation can also be used in the design or operation of a biofilter if the others parameters have been pre-determined, e.g. inlet and the required outlet H_2S concentrations.

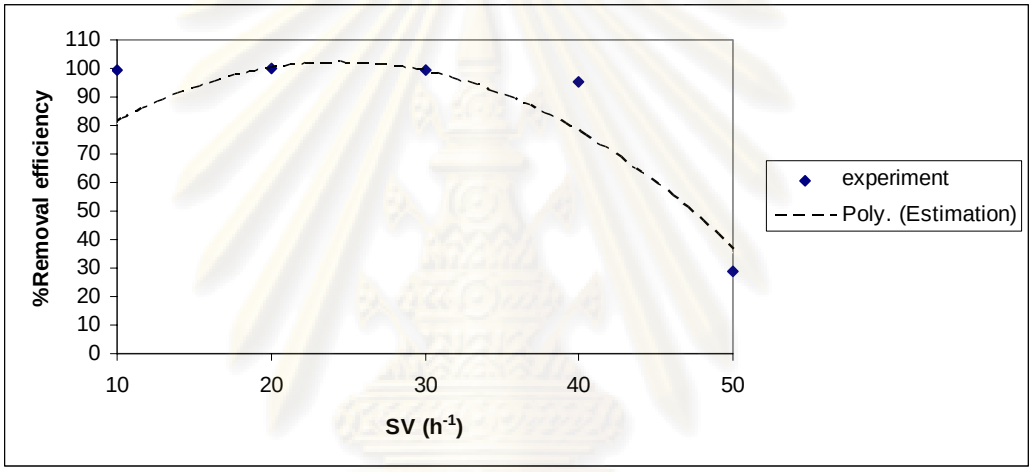


Figure 4.8 Comparison of removal efficiency from the experiments and estimated values calculated from Equation 4.1

4.3.6 Mass Balance of sulfur

The mass balance of sulfur was conducted to determine amounts of some possible end products of H_2S oxidation in the biofilter. SO_4^{2-} and SO_3^{2-} were detected and quantified in the water sprayed through the bed of packing material and stored at the bottom of the biofilter within the period of 20 min. Amounts of elemental sulfur (S^0) were assumed to be equal to the difference between mass of H_2S entering the biofilter during 20 min and the sum of mass of H_2S in the outlet gas and SO_4^{2-} plus

SO_3^{2-} detected in the sprayed water. Since pH of sprayed water was in the range of 5.31 – 6.16, S^{2-} was not expected to be in this water and therefore its concentration was not measured. Mass balance of sulfur conducted was thus emphasized only for the speciation dissolved in water, excluding those in the solid forms.

Table 4.11 shows each produced end product normalized to the percentage of the removed H_2S. While not higher than 1% of SO_3^{2-} was found to be produced regardless of the operating condition, amounts of SO_4^{2-} and S^0 seemed to be dependent on SV value. At SV equal to 10 h^{-1}, 76% of removed H_2S was transformed to SO_4^{2-}. However, when SV was increased to 50 h^{-1}, 60% of removed H_2S was oxidized to SO_4^{2-}, while that oxidized to S^0 was increased from 23% at SV = 10 h^{-1} to 39% at SV = 50 h^{-1} (Table 4.11).

Table 4.11 Sulfur mass balance in the biofilter at low and high SV

Condition	H_2S removed (mg)	SO_4^{2-} (%)	SO_3^{2-} (%)	S (%)
SV 10 h^{-1}	120	76	1	23
SV 50 h^{-1}	261	60	1	39

Under oxygen limiting conditions, sulfur is the major end product, while sulfate is formed when sulfide is limited. This can be represented by the following reactions:

$$2HS^- + O_2 \rightarrow 2S^0 + 2OH^- \quad (4.2)$$

$$2S^0 + 3O_2 + 2OH^- \rightarrow 2SO_4^{2-} + 2H^+ \quad (4.3)$$

$$H_2S + 2O_2 \rightarrow SO_4^{2-} + 2H^+ \quad (4.4)$$

In aerobic autotrophic oxidation of sulfide, the following reaction would occur (Kuenen, 1975):

$$H_2S + CO_2 + \text{nutrients} + O_2 \rightarrow \text{cells} + S \text{ and/or } SO_4^{2-} + H_2O \quad (4.5)$$

The incomplete oxidation of H_2S is generally reflected by high values of SO_3^{2-} and S^{2-}. In this current study, majority of removed H_2S were transformed to SO_4^{2-}, while the remaining portion was transformed to elemental sulfur and other end products. Elias et al. (2002) observed in a biofilter receiving a loading rate of 45 g H_2S m^{-3} h^{-1} that the conversion products were mainly S^0 (82%), followed by SO_4^{2-} and thiosulfates (<18%). Similarly, in a biofilter packed with biomedia, encapsulated by sodium alginate and polyvinyl alcohol (PVA), the main H_2S oxidation products were in order as S^0 (53%), SO_4^{2-} (38%), SO_3^{2-} (6%) and S^{2-} (3%). As O_2 is the key parameter controlling the levels of oxidation (Alcantara et al., 2004), relatively higher amount of SO_4^{2-} detected as the end product of H_2S oxidation found in this current study may be the result of higher amount of O_2 mixed with the inlet biogas. This claim was verified after result from the calculation indicated that amount of air used in this current study (10% by volume of the biogas flow rate) provided O_2 to the amount exceeding that required to transform H_2S to SO_4^{2-} (Equation 4.4). From the

above explanation, therefore, higher amount of S^0 found at SV = 50 h^{-1} was more likely to be contributed by the shorter GRT rather than the problem of O_2 deficiency.

4.3.7 Changes of Biogas Composition after H_2S Removal

Biogas produced from piggery farm in this current study contained 62 - 81% of CH_4, 18 - 29% of CO_2, and 0 - 3% of O_2. CH_4 is the most desirable gas because it has a high calorific value (≈ 9,000 kcal/m^3). The approximate heat value of the biogas is 4,500 – 6,300 kcal/m^3, depending on the contents of other gases besides CH_4 (Polprasert, 1989).

Changes of the percentage of biogas composition were defected after being treated in the biofilter. Slight reduction of CO_2 (from 18 - 29% to 15 – 25.9%) was found. As CO_2 present in the biogas as the second highest composition, the remained CO_2 needs to be removed to increase CH_4 ratio in the biogas. Insignificant removal of CO_2 by the biofilter used in this current study was possibly contributed from the pH of sprayed water which was in the medium range. To effectively adsorb CO_2, pH of the sprayed liquid needs to be equal or higher than 11. As expected, amounts of O_2 were increased from 0 - 3 % to 0.9 - 4.4 % after treatment. However maximum percentage of O_2 in the treated biogas was not higher than 5%, which is the explosive concentration of O_2 in biogas. Concentration of O_2 could possibly be reduced without any effect on biofilter performance because, as explained in Section 4.3.6, exceeding amount of air was mixed with the biogas to ensure that H_2S oxidation would not be limited by O_2 concentration. Having stated that, CH_4

percentage in the treated biogas was still in the usable range (55.2 – 77.4%) at every studied condition.

4.3.8 Microbial Activities in the Biofilter

4.3.8.1 Microbial Cell Number

Table 4.12 shows cell numbers immobilized on both types of packing materials before and after the experiment of each condition (excluded those of the repeated experiments).

In all tested conditions, cell numbers counted on both the TSA (pH = 7) and TSA (pH = 4) appeared to be increased at the end of each condition. Though not very obvious, increase of cell numbers tended to be more dramatic on the packing material collected at Port 1, particularly for those on the TSA (pH = 7). Higher cell numbers found at Port 1 was possibly due to the fact that microorganisms growing at this port received the highest H_2S loading. To the greater extent, increase of cell numbers at the end of each test was obvious on TSA (pH = 4), even when there was no cell appeared on this medium before the test. H_2S removal activities occurred in this current study, therefore were likely to be mediated by the sulfide-oxidizing bacteria capable of growing at both the medium and low pH ranges. Unlike those found on the TSAs, cell numbers observed on the NYA tended to decrease at the end of each test. As only the heterotrophs supposed to grow on this medium, reduction of the cell number implied that condition used in each test may not support the growth of these microorganisms. Hirai et al. (2001) also observed decrease of cell number on NYA. They attributed this decrease to the nutrient insufficiency. Decreased amounts

Table 4.12 Cell number immobilized on both type of packing material at the start and end experiment (cfu/L of packing matrial)

Packing Material	SV (h^{-1})	Sprayed Water	Port	Medium					
				NYA		TSA (pH=7)		TSA (pH=4)	
				Before	After	Before	After	Before	After
Plastic Cap	10	Low	1	7.9×10^{11}	1.2×10^{10}	2.3×10^{8}	5.3×10^{11}	2.3×10^{8}	1.1×10^{14}
			2	7.9×10^{11}	1.8×10^{12}	2.3×10^{8}	2.4×10^{13}	2.3×10^{8}	2.3×10^{16}
			3	7.9×10^{11}	1.2×10^{10}	2.3×10^{8}	6.3×10^{13}	2.3×10^{8}	8.5×10^{15}
	10	High	1	4.0×10^{7}	2.3×10^{6}	8.3×10^{7}	2.2×10^{10}	0	4.9×10^{11}
			2	4.0×10^{7}	2.3×10^{9}	8.3×10^{7}	2.3×10^{9}	0	5.9×10^{17}
			3	4.0×10^{7}	8.5×10^{6}	8.3×10^{7}	3.3×10^{9}	0	4.0×10^{17}
	50	Low	1	3.9×10^{11}	2.0×10^{6}	7.4×10^{11}	7.2×10^{15}	2.3×10^{6}	1.1×10^{16}
			2	3.9×10^{11}	2.3×10^{6}	7.4×10^{11}	8.5×10^{13}	2.3×10^{6}	4.1×10^{11}
			3	3.9×10^{11}	2.1×10^{6}	7.4×10^{11}	1.6×10^{16}	2.3×10^{6}	6.7×10^{15}
	50	High	1	6.4×10^{7}	3.1×10^{9}	1.0×10^{8}	2.2×10^{10}	0	7.2×10^{11}
			2	6.4×10^{7}	5.4×10^{7}	1.0×10^{8}	3.0×10^{11}	0	2.6×10^{9}
			3	6.4×10^{7}	2.4×10^{6}	1.0×10^{8}	2.3×10^{9}	0	2.3×10^{9}

Table 4.12 (cont.) Cell number immobilized on both type of packing material at the start and end experiment (cfu/L of packing matrial)

Packing Material	SV (h^{-1})	Sprayed Water	Port	Medium					
				NYA		TSA (pH=7)		TSA (pH=4)	
				Before	After	Before	After	Before	After
Ceramic	10	Low	1	6.3×10^{11}	5.6×10^{5}	2.3×10^{8}	1.2×10^{8}	0	7.0×10^{5}
			2	6.3×10^{11}	3.7×10^{5}	2.3×10^{8}	2.3×10^{7}	0	9.3×10^{5}
			3	6.3×10^{11}	5.4×10^{5}	2.3×10^{8}	2.3×10^{7}	0	2.3×10^{6}
	10	High	1	7.3×10^{7}	6.4×10^{9}	1.2×10^{8}	5.5×10^{17}	2.3×10^{5}	1.5×10^{10}
			2	7.3×10^{7}	1.1×10^{8}	1.2×10^{8}	2.3×10^{9}	2.3×10^{5}	2.3×10^{10}
			3	7.3×10^{7}	5.2×10^{9}	1.2×10^{8}	6.7×10^{9}	2.3×10^{5}	2.4×10^{9}
	50	Low	1	2.3×10^{8}	2.3×10^{6}	4.5×10^{7}	7.5×10^{15}	2.3×10^{6}	1.4×10^{14}
			2	2.3×10^{8}	2.6×10^{7}	4.5×10^{7}	1.3×10^{16}	2.3×10^{6}	2.1×10^{16}
			3	2.3×10^{8}	8.5×10^{11}	4.5×10^{7}	2.6×10^{15}	2.3×10^{6}	1.7×10^{16}
	50	High	1	2.7×10^{9}	2.3×10^{6}	1.8×10^{8}	1.1×10^{12}	1.1×10^{8}	2.3×10^{12}
			2	2.7×10^{9}	4.5×10^{5}	1.8×10^{8}	4.9×10^{11}	1.1×10^{8}	2.3×10^{12}
			3	2.7×10^{9}	2.3×10^{6}	1.8×10^{8}	2.4×10^{11}	1.1×10^{8}	2.3×10^{12}

of heterotrophs found in this current study putatively indicated that the sulfide-oxidizing autotrophic bacteria were mainly responsible in oxidizing H_2S in the tested biofilter.

4.3.8.2 Kinetic of Microorganisms

Amounts of bacteria on packing materials before and after some experiments and the corresponding specific removal rate are presented in Table 4.13 Since only SV values were found to be significantly affected H_2S removal efficiency, comparisons were made between biofilters operating at different SV.

Table 4.13 Comparison of the microbial specific removal rate in biofilters operated at high and low SV levels

packing material	water spray (min)	SV (h^{-1})	Port*	TSA (pH 7) cfu/L packing material		Specific removal rate (mg H_2S removed/ cfu.min)	% Overall removal H_2S
				Before	After		
Ceramic	30	50	1	4.5×10^{7}	7.5×10^{15}	1.2×10^{-16}	27.5
			2	4.5×10^{7}	1.3×10^{16}	3.6×10^{-17}	
			3	4.5×10^{7}	2.6×10^{15}	3.5×10^{-16}	
Plastic	30	10	1	2.3×10^{8}	5.3×10^{11}	8.4×10^{-12}	99.3
			2	2.3×10^{8}	2.4×10^{13}	1.1×10^{-13}	
			3	2.3×10^{8}	6.3×10^{13}	2.7×10^{-14}	

*Port 1, 2, and 3 are located at 12.5, 25.0, and 37.5 cm from the bottom of the bed of packing material, respectively; The specific removal rate was the averaged value altering the pseudo-steady state and equal to $Q(S_0 - S) / V \times$ cell number, where; Q is flow rate (L/min); S_0, H_2S concentration in the previous port (mg/L); S, H_2S concentration in the next port (mg/L); V, the volume of packing bed (L); cell number (cfu/L of packing material).

From Table 4.13, it can be seen that, though higher cell number were detected on the packing material at different heights of the biofilter bed operating at high SV (50 h^{-1}), the overall specific H_2S removal rate was found to be lower than that of the biofilter operating at low SV (10 h^{-1}). This revealed the higher kinetic activity of bacteria in the biofilter operated at low SV, resulting in the superiority of this reactor in removing of H_2S.

4.3.8.3 Microbial Removal Capacity

Capability of different cultures used in removing H_2S can be compared in terms of the removal capacity (g H_2S removed/m^3.h). The removal capacity is defined as the amount of pollutant degraded per unit of time, normalized to the volume of the packed bed (Chung et al., 1996). Comparison of the removal capacities is tabulated in Table 4.14.

Maximum removal capacities obtained in this current study when using plastic cap and ceramic as the packing material were 132 and 118 g H_2S /m^3.h, respectively. As shown in Table 4.14, these values are considerably higher than most of those achieved previous works. This does not certainly mean that cultures used in this current study were much more effective; but, in fact, it was likely to be the result of using higher inlet H_2S concentrations. Majority of works presented in Table 4.14 were done to investigate odor elimination by the biofilter, hence using much lower H_2S concentrations. Having stated that; however, cultures used in this current study could function to the levels comparable to those obtained from cultures immobilized

on the GAC (Rattanapan et al., 2009) and porous ceramic (Hirai et al., 2001), both of which having exceptionally high specific surface area.

Table 4.14 Comparison of the Removal Capacities Obtained from Different Cultures

Immobilized material	Microorganism	H_2S removal capacity (g $H_2S/m^3/h$)	References
Porous ceramic	*A. thiooxidans KS1*	51	Shinabe et al.(1995)
Na-aginate beads	*Pesudomonas putida* CH11	20	Chung et al.(1996a)
Na-aginate beads	*T. novellas* CH3	25	Chung et al.(1997)
Porous ceramic	Sludge	145.8	Hirai et al.(2001)
Calcinated and Calcinated soil	Sludge	66.7	Hirai et al.(2001)
Pall rings	Sludge	24	Jin et al.(2005a)
Pall rings	Sludge	31.12	Jin et al.(2005b)
Megallanic peat	*T. thioparus* Var. Beijerinck	55	OyarzÚn et al.(2003)
Granulated sludge	Sludge	26.7	Malhaytier et al.(2003)
Organic waste-based granule	Pig manure and sawdust	46	Barona et al.(2004)
Sodium alginate and polyvinyl alcohol	Sludge	8	Kim et al.(2008)
GAC	Sulfide oxidizing bacteria	125	Rattanapan et al.(2009)
Plastic	Sludge	132	This study
Ceramic	Sludge	118	This study

CHAPTER V

CONCLUSIONS

1. Activated sludge from the tofu anaerobic wastewater treatment plant was superior to that from an aerobic domestic wastewater treatment plant in terms of amounts of sulfide-oxidizing microorganisms capable of growing on studied packing materials.
2. Optimum inoculating condition provided the highest amount of immobilized cell on the packing materials was condition 3. The initial mixture of wastewater and sludge was at 1:1 (by volume). After that a mixture of 3:1 (wastewater:sludge) was added after some amounts of container content were removed once per day. The highest cell numbers determined on plastic cap (1.2×10^{11} cfu/L of packing material) and on ceramic (2.8×10^{11} cfu/L of packing material) using TSA medium (pH = 7) were achieved after 3 and 5 days, respectively.
3. Space velocity significantly affected H_2S removal efficiency by the biofilter inoculated with the selected activated sludge. Nearly complete H_2S removal could be achieved at low SV ($10\ h^{-1}$).
4. In addition, possible interaction effects were found between type of packing materials and rate of water spraying. High H_2S removal efficiency was achieved with plastic cap at lower rate of water spraying, while ceramic preferred higher amount of sprayed water. At high SV ($50\ h^{-1}$), H_2S removal efficiency was also found to be increased when rate of water spraying increased.

5. The inlet H_2S concentration, set as a covariate, was also found to significantly affect H_2S removal efficiency. That both SV and inlet H_2S concentration influenced H_2S removal means H_2S loading rate needs to be considered in evaluating the biofilters performance.
6. An equation constructed to predict % H_2S removed by the biofilter was;

   % H_2S removal = 147.549 - 0.0138(Inlet H_2S conc.) - 1.0762(SV)

   This equation could satisfactorily predict % H_2S removal achieved from the experiments. Moreover, this equation can be used in the design or operation of a biofilter.
7. SO_4^{2-} was found to be the main end product of H_2S removal in the biofilter. However, at high SV values or shorter GRT, higher amount of H_2S were transformed to S^0.
8. Microorganisms functioning in the biofilter operating at low SV showed higher kinetic activity than those in the biofilter operating at high SV, which could be a reason for its better H_2S removing efficiency.
9. The maximum removal capacity achieved in this study was 132 g H_2S /m^3/h for the plastic cap at H_2S loading rate of 183 g/m^3/h and 118 g H_2S /m^3/h for the ceramic at H_2S loading rate of 124 g/m^3/h.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORKS

The following statements are recommended for future studies;

1. As the type of H_2S oxidation end product is dependent on amounts of oxygen provided, it will be useful to investigate the effect of oxygen quantity on both the biofilter performance and the end products generated.
2. Long-term operation of a biofilter using the effective condition obtained in this study needs to be investigated to assess the consistent of biofilter performance. Besides, the relationship between pressure drop and operating time should also be evaluated.
3. To be able to scale-up the biofilter so that it can be used to treat the actual biogas flow rate, the optimum procedure for microbial inoculation is required. This is to ensure the sufficient amount of the sulfide-oxidizing bacteria in a full-scale biofilter.

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APPENDIX

Table 1 Experiment Data: Test Order 1, Condition: Ceramic, SV= 50 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
18/10/51	1	14.00	19.50	2980	2750	2693	2528	2480	77.4	69.5	69.4	69.6	69.4	21.1	18.9	19.0	18.8	18.8
		16.00	24.50	3460	3225	3120	3124	3147	77.5	69.8	70.2	70.2	63.9	20.8	18.9	19.0	18.8	17.2
19/10/51	2	12.00	45.17	3437	3205	3204	3085	2989	75.1	68.7	68.7	68.8	68.6	21.5	19.8	19.8	19.8	19.7
		14.00	48.00	2961	2714	2698	2668	2678	75.6	69.5	69.3	69.0	68.9	21.8	20.1	20.1	20.0	20.0
		16.00	68.00	3582	3251	3260	3163	3073	76.2	69.6	69.8	69.8	69.5	22.3	20.6	20.4	20.1	20.3
20/10/51	3	12.00	74.00	3270	2837	2631	2212	1974	76.1	69.5	69.7	69.7	69.7	22.1	20.4	20.4	20.1	20.4
		14.00	96.33	3062	2830	2560	2163	1960	76.6	69.5	69.4	69.5	69.5	22.5	20.6	20.5	20.5	20.6
		16.00	118.00	3397	2682	2592	2397	2125	75.0	66.9	66.5	66.5	66.7	22.6	20.5	20.3	20.3	20.0
21/10/51	4	12.00	120.75	3148	2500	2259	1941	1949	68.6	62.0	61.4	61.3	61.5	21.0	19.1	18.9	18.8	18.9
		14.00	141.50	2739	1862	1520	1051	1157	74.1	68.6	68.4	68.1	68.1	23.1	21.3	21.2	21.1	21.1
		16.00	146.00	3087	2417	2161	1755	1479	75.0	67.2	68.7	68.7	68.6	23.5	21.2	21.7	21.6	21.7
22/10/51	5	12.00	164.50	2567	2194	1442	943	967	71.4	63.6	63.8	64.4	65.4	22.8	20.6	20.6	20.8	20.7
		16.00	168.50	2875	2269	2076	1649	1609	75.1	67.8	67.7	67.7	67.9	24.5	22.4	22.4	22.4	22.4
23/10/51	6	13.00	188.50	2549	2237	2097	1942	1825	71.8	64.3	62.3	64.2	65.6	23.6	21.3	20.6	21.4	21.6
24/10/51	7	12.00	192.25	2280	1849	1687	1525	1265	74.4	69.0	69.1	69.1	69.2	24.8	23.1	23.1	23.2	23.2
		16.00	211.50	2342	1815	1582	1297	1297	74.4	67.7	66.6	66.4	66.5	25.3	23.4	23.0	22.9	22.8
25/10/51	8	14.00	217.33	2275	1714	1511	1420	1172	65.6	59.1	59.5	59.9	60.1	21.7	19.6	19.8	19.9	20.0
26/10/51	9	12.00	236.33	2341	1551	1364	1216	905	74.0	67.7	67.8	67.8	67.8	25.8	23.8	23.8	23.9	23.9

Table 1(cont.) Experiment Data: Test Order 1, Condition: Ceramic, SV= 50 h^{-1}, Rate of spraying water = High

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh (%)		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
18/10/51	1	14.00	19.50	0.1	1.9	1.8	1.8	1.8	1.4	9.7	9.8	9.8	10.0	6.09	70.28	87.67	28.2	28.68	spray	
		16.00	24.50	0.2	1.7	1.7	1.6	2.0	1.5	9.5	9.1	9.4	16.0	5.87	56.2	84.28	31	31.33	spray	
19/10/51	2	12.00	45.17	0.0	1.6	1.6	1.6	1.5	3.4	9.9	9.9	9.9	10.2	5.86	62.34	89.96	28.87	29.43		
		14.00	48.00	0.1	1.5	1.5	1.5	1.5	2.5	8.9	9.1	9.5	9.6	5.77	61.48	86.96	28.84	29.42	spray	
		16.00	68.00	0.1	1.6	1.6	1.6	1.6	1.4	8.2	8.2	8.5	8.6	5.86	68.71	86.09	27.42	27.3	spray	
20/10/51	3	12.00	74.00	0.1	1.5	1.5	1.5	1.4	1.7	8.6	8.4	8.7	8.5	5.9	60.59	82.06	28.59	28.8	spray	
		14.00	96.33	0.1	1.7	1.6	1.6	1.6	0.8	8.2	8.5	8.4	8.3	5.85	70.92	83.78	28.13	28.89	spray	
		16.00	118.00	0.2	1.9	1.9	1.8	1.9	2.2	10.7	11.3	11.4	11.4	5.76	62.77	84.17	29.74	29.91	spray	
21/10/51	4	12.00	120.75	0.1	1.7	1.6	1.6	1.6	10.3	17.2	18.1	18.3	18.0	5.81	62.34	83.59	29.08	29.66	spray	
		14.00	141.50	0.2	1.7	1.8	1.8	1.6	1.6	8.4	8.6	9.0	9.1		64.77	85.12	30.43	31.14		
		16.00	146.00	0.1	2.0	1.7	1.7	1.6	1.4	9.6	7.9	8.0	8.1		72.65	88.16	28.88	29.41	spray	
22/10/51	5	12.00	164.50	0.2	1.7	1.8	1.7	1.7	5.6	14.1	13.8	13.0	12.2		56.7	84.65	31.3	31.25		
		16.00	168.50	0.2	1.7	1.7	1.7	1.7	0.2	8.1	8.2	8.2	8.1	5.68	68.06	85.99	28.16	28.98		
23/10/51	6	13.00	188.50	0.2	1.4	1.6	1.6	1.5	4.4	13.0	15.5	12.8	11.6	5.77	59.2	86.25	29.68	30.75	spray	
24/10/51	7	12.00	192.25	0.1	1.3	1.3	1.3	1.3	0.7	6.6	6.5	6.4	6.3	5.75	51.77	84.2	30.64	30.61	spray	6.48
		16.00	211.50	0.2	1.6	1.9	1.9	1.9	0.1	7.3	8.5	8.8	8.8	5.7	55.04	81.22	27.84	28.17	spray	
25/10/51	8	14.00	217.33	0.1	1.5	1.5	1.5	1.5	12.6	19.8	19.2	18.7	18.4	5.74	60.24	83.41	28.04	28.52	spray	
26/10/51	9	12.00	236.33	0.1	1.5	1.5	1.5	1.4	0.1	7.0	6.9	6.8	6.9	5.66	47.79	76.29	28.35	28.54	spray	6.57

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Table 2 Experiment Data: Test Order 2, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
18/10/51	1	14.00	19.50	2903	2640	2328	2030	1923	77.4	69.5	69.4	69.6	69.4	21.1	18.9	19.0	18.8	18.8
		16.00	24.50	3526	3036	3037	2609	2545	77.5	69.8	70.2	70.2	63.9	20.8	18.9	19.0	18.8	17.2
		17.00	45.17	3111	2606	2597	2252	2271	75.1	68.7	68.7	68.8	68.6	21.5	19.8	19.8	19.8	19.7
19/10/51	2	10.00	48.00	3285	2527	2520	2339	2406	75.6	69.5	69.3	69.0	68.9	21.8	20.1	20.1	20.0	20.0
		12.00	68.00	3248	2311	2196	2440	2611	76.2	69.6	69.8	69.8	69.5	22.3	20.6	20.4	20.1	20.3
		14.00	74.00	3005	1842	1660	1462	1485	76.1	69.5	69.7	69.7	69.7	22.1	20.4	20.4	20.1	20.4
20/10/51		16.00	96.33	3125	1604	1386	1218	1314	76.6	69.5	69.4	69.5	69.5	22.5	20.6	20.5	20.5	20.6
	3	12.00	118.00	3420	1284	819	66	70	75.0	66.9	66.5	66.5	66.7	22.6	20.5	20.3	20.3	20.0
		14.00	120.75	3182	346	63	0	84	68.6	62.0	61.4	61.3	61.5	21.0	19.1	18.9	18.8	18.9
21/10/51		16.00	141.50	3407	1766	1248	566	166	74.1	68.6	68.4	68.1	68.1	23.1	21.3	21.2	21.1	21.1
	4	12.00	146.00	3047	1768	1244	1130	1200	75.0	67.2	68.7	68.7	68.6	23.5	21.2	21.7	21.6	21.7
		14.00	164.50	2766	1560	972	875	924	71.4	63.6	63.8	64.4	65.4	22.8	20.6	20.6	20.8	20.7
		16.00	168.50	3014	1365	1337	1426	1070	75.1	67.8	67.7	67.7	67.9	24.5	22.4	22.4	22.4	22.4
22/10/51	5	12.00	188.50	2778	641	186	0	0	71.8	64.3	62.3	64.2	65.6	23.6	21.3	20.6	21.4	21.6
		16.00	192.25	2881	986	641	278	220	74.4	69.0	69.1	69.1	69.2	24.8	23.1	23.1	23.2	23.2
23/10/51	6	13.00	211.50	2588	1060	767	431	360	74.4	67.7	66.6	66.4	66.5	25.3	23.4	23.0	22.9	22.8
24/10/51	7	12.00	217.33	2319	259	0	0	0	65.6	59.1	59.5	59.9	60.1	21.7	19.6	19.8	19.9	20.0
		16.00	236.33	2359	336	34	0	0	74.0	67.7	67.8	67.8	67.8	25.8	23.8	23.8	23.9	23.9
25/10/51	8	14.00	240.42	2344	0	0	0	0	73.5	67.0	67.2	67.2	66.9	25.7	23.6	23.7	23.8	23.6
26/10/51	9	12.00	261.75	2430	670	184	0	0	73.0	67.1	66.8	66.7	66.9	25.9	24.2	24.1	24.0	23.6

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Table 2(cont.) Experiment Data: Test Order 2, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh (%)		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
18/10/51	1	14.00	19.50	0.1	1.9	1.8	1.8	1.8	1.4	9.7	9.8	9.8	10.0	6.09	70.28	87.67	28.2	28.68	spray	
		16.00	24.50	0.2	1.7	1.7	1.6	2.0	1.5	9.5	9.1	9.4	16.0	5.87	56.2	84.28	31	31.33	spray	
		17.00	45.17	0.0	1.6	1.6	1.6	1.5	3.4	9.9	9.9	9.9	10.2	5.86	62.34	89.96	28.87	29.43		
19/10/51	2	10.00	48.00	0.1	1.5	1.5	1.5	1.5	2.5	8.9	9.1	9.5	9.6	5.77	61.48	86.96	28.84	29.42	spray	
		12.00	68.00	0.1	1.6	1.6	1.6	1.6	1.4	8.2	8.2	8.5	8.6	5.86	68.71	86.09	27.42	27.3	spray	
		14.00	74.00	0.1	1.5	1.5	1.5	1.4	1.7	8.6	8.4	8.7	8.5	5.9	60.59	82.06	28.59	28.8	spray	
20/10/51		16.00	96.33	0.1	1.7	1.6	1.6	1.6	0.8	8.2	8.5	8.4	8.3	5.85	70.92	83.78	28.13	28.89	spray	
	3	12.00	118.00	0.2	1.9	1.9	1.8	1.9	2.2	10.7	11.3	11.4	11.4	5.76	62.77	84.17	29.74	29.91	spray	
		14.00	120.75	0.1	1.7	1.6	1.6	1.6	10.3	17.2	18.1	18.3	18.0	5.81	62.34	83.59	29.08	29.66	spray	
21/10/51		16.00	141.50	0.2	1.7	1.8	1.8	1.6	1.6	8.4	8.6	9.0	9.1		64.77	85.12	30.43	31.14		
	4	12.00	146.00	0.1	2.0	1.7	1.7	1.6	1.4	9.6	7.9	8.0	8.1		72.65	88.16	28.88	29.41	spray	
		14.00	164.50	0.2	1.7	1.8	1.7	1.7	5.6	14.1	13.8	13.0	12.2		56.7	84.65	31.3	31.25		
		16.00	168.50	0.2	1.7	1.7	1.7	1.7	0.2	8.1	8.2	8.2	8.1	5.68	68.06	85.99	28.16	28.98		
22/10/51	5	12.00	188.50	0.2	1.4	1.6	1.6	1.5	4.4	13.0	15.5	12.8	11.6	5.77	59.2	86.25	29.68	30.75	spray	
		16.00	192.25	0.1	1.3	1.3	1.3	1.3	0.7	6.6	6.5	6.4	6.3	5.75	51.77	84.2	30.64	30.61	spray	6.48
23/10/51	6	13.00	211.50	0.2	1.6	1.9	1.9	1.9	0.1	7.3	8.5	8.8	8.8	5.7	55.04	81.22	27.84	28.17	spray	
24/10/51	7	12.00	217.33	0.1	1.5	1.5	1.5	1.5	12.6	19.8	19.2	18.7	18.4	5.74	60.24	83.41	28.04	28.52	spray	
		16.00	236.33	0.1	1.5	1.5	1.5	1.4	0.1	7.0	6.9	6.8	6.9	5.66	47.79	76.29	28.35	28.54	spray	6.57
25/10/51	8	14.00	240.42	0.1	1.5	1.5	1.5	1.5	0.7	7.9	7.6	7.5	8.0	5.74	49.33	82.42	26.67	27.11		6.59
26/10/51	9	12.00	261.75	0.1	1.4	1.5	1.4	1.4	1.0	7.3	7.6	7.9	8.1	5.71	43.21	80.68	28.21	28.57	spray	6.65

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Table 3 Experiment Data: Test Order 3, Condition: Plastic cap, SV= 50 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
18/11/51	1	11.15	19.50	3094	2855	2840	2683	2777	77.4	69.5	69.4	69.6	69.4	21.1	18.9	19.0	18.8	18.8
		16.20	24.50	3135	2860	2883	2706	2485	77.5	69.8	70.2	70.2	63.9	20.8	18.9	19.0	18.8	17.2
19/11/51	2	12.35	45.17	3157	2568	2172	2006	1648	75.1	68.7	68.7	68.8	68.6	21.5	19.8	19.8	19.8	19.7
		15.25	48.00	3317	2648	2274	2166	1830	75.6	69.5	69.3	69.0	68.9	21.8	20.1	20.1	20.0	20.0
20/11/51	3	11.15	68.00	3403	2898	2691	2480	2341	76.2	69.6	69.8	69.8	69.5	22.3	20.6	20.4	20.1	20.3
		16.00	74.00	3524	2988	2785	2392	2462	76.1	69.5	69.7	69.7	69.7	22.1	20.4	20.4	20.1	20.4
21/11/51	4	15.00	96.33	3760	3145	3006	2869	2750	76.6	69.5	69.4	69.5	69.5	22.5	20.6	20.5	20.5	20.6
22/11/51	5	12.00	118.00	3500	2895	2673	2425	2019	75.0	66.9	66.5	66.5	66.7	22.6	20.5	20.3	20.3	20.0
		15.00	120.75	3072	2515	2285	2100	1947	68.6	62.0	61.4	61.3	61.5	21.0	19.1	18.9	18.8	18.9
23/11/51	6	12.00	141.50	3790	3280	3132	2975	2855	74.1	68.6	68.4	68.1	68.1	23.1	21.3	21.2	21.1	21.1
		17.20	146.00	3965	3313	3197	3051	2908	75.0	67.2	68.7	68.7	68.6	23.5	21.2	21.7	21.6	21.7
24/11/51	7	11.00	164.50	3419	2718	2541	2440	2121	71.4	63.6	63.8	64.4	65.4	22.8	20.6	20.6	20.8	20.7
		17.20	168.50	4022	3420	3275	3154	2944	75.1	67.8	67.7	67.7	67.9	24.5	22.4	22.4	22.4	22.4
25/11/51	8	12.00	188.50	3475	2929	2554	2680	2459	71.8	64.3	62.3	64.2	65.6	23.6	21.3	20.6	21.4	21.6
		15.50	192.25	4238	3528	3358	3372	3175	74.4	69.0	69.1	69.1	69.2	24.8	23.1	23.1	23.2	23.2
26/11/51	9	11.00	211.50	4170	3579	3333	3214	3030	74.4	67.7	66.6	66.4	66.5	25.3	23.4	23.0	22.9	22.8
		16.50	217.33	3088	2352	2218	2149	1960	65.6	59.1	59.5	59.9	60.1	21.7	19.6	19.8	19.9	20.0
27/11/51	10	12.45	236.33	4496	3847	3738	3606	3409	74.0	67.7	67.8	67.8	67.8	25.8	23.8	23.8	23.9	23.9
		16.45	240.42	4535	3984	3846	3711	3536	73.5	67.0	67.2	67.2	66.9	25.7	23.6	23.7	23.8	23.6
28/11/51	11	14.30	261.75	4365	3983	3681	3532	3117	73.0	67.1	66.8	66.7	66.9	25.9	24.2	24.1	24.0	23.6
29/11/51	12	12.35	284.08	4556	3785	3661	3312	3145	73.0	65.2	65.3	65.3	66.1	26.6	23.8	24.0	23.8	23.6
		17.50	289.17	4100	3520	3352	3224	2849	70.4	63.2	63.3	63.3	61.3	25.0	22.7	22.8	22.8	22.2
30/11/51	13	12.25	308.00	4521	4058	3810	3730	3373	72.9	66.8	66.6	67.2	67.5	26.9	24.8	24.7	24.9	24.6
		16.26	312.00	4341	3908	3642	3483	3139	72.2	65.2	65.3	65.0	65.6	26.1	24.0	24.0	23.9	23.6
1/12/51	14	13.55	333.50	4056	3550	3236	2772	2698	73.9	68.7	68.8	69.0	68.9	25.7	23.8	23.6	23.5	23.3

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Table 3(cont.) Experiment Data: Test Order 3, Condition: Plastic cap, SV= 50 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
18/11/51	1	11.15	19.50	0.1	1.9	1.8	1.8	1.8	1.4	9.7	9.8	9.8	10.0	6.09	70.28	87.67	28.2	28.68	spray	
		16.20	24.50	0.2	1.7	1.7	1.6	2.0	1.5	9.5	9.1	9.4	16.0	5.87	56.2	84.28	31	31.33	spray	
19/11/51	2	12.35	45.17	0.0	1.6	1.6	1.6	1.5	3.4	9.9	9.9	9.9	10.2	5.86	62.34	89.96	28.87	29.43		
		15.25	48.00	0.1	1.5	1.5	1.5	1.5	2.5	8.9	9.1	9.5	9.6	5.77	61.48	86.96	28.84	29.42	spray	
20/11/51	3	11.15	68.00	0.1	1.6	1.6	1.6	1.6	1.4	8.2	8.2	8.5	8.6	5.86	68.71	86.09	27.42	27.3	spray	
		16.00	74.00	0.1	1.5	1.5	1.5	1.4	1.7	8.6	8.4	8.7	8.5	5.9	60.59	82.06	28.59	28.8	spray	
21/11/51	4	15.00	96.33	0.1	1.7	1.6	1.6	1.6	0.8	8.2	8.5	8.4	8.3	5.85	70.92	83.78	28.13	28.89	spray	
22/11/51	5	12.00	118.00	0.2	1.9	1.9	1.8	1.9	2.2	10.7	11.3	11.4	11.4	5.76	62.77	84.17	29.74	29.91	spray	
		15.00	120.75	0.1	1.7	1.6	1.6	1.6	10.3	17.2	18.1	18.3	18.0	5.81	62.34	83.59	29.08	29.66	spray	
23/11/51	6	12.00	141.50	0.2	1.7	1.8	1.8	1.6	1.6	8.4	8.6	9.0	9.1		64.77	85.12	30.43	31.14		
		17.20	146.00	0.1	2.0	1.7	1.7	1.6	1.4	9.6	7.9	8.0	8.1		72.65	88.16	28.88	29.41	spray	
24/11/51	7	11.00	164.50	0.2	1.7	1.8	1.7	1.7	5.6	14.1	13.8	13.0	12.2		56.7	84.65	31.3	31.25		
		17.20	168.50	0.2	1.7	1.7	1.7	1.7	0.2	8.1	8.2	8.2	8.1	5.68	68.06	85.99	28.16	28.98		
25/11/51	8	12.00	188.50	0.2	1.4	1.6	1.6	1.5	4.4	13.0	15.5	12.8	11.6	5.77	59.2	86.25	29.68	30.75	spray	
		15.50	192.25	0.1	1.3	1.3	1.3	1.3	0.7	6.6	6.5	6.4	6.3	5.75	51.77	84.2	30.64	30.61	spray	6.48
26/11/51	9	11.00	211.50	0.2	1.6	1.9	1.9	1.9	0.1	7.3	8.5	8.8	8.8	5.7	55.04	81.22	27.84	28.17	spray	
		16.50	217.33	0.1	1.5	1.5	1.5	1.5	12.6	19.8	19.2	18.7	18.4	5.74	60.24	83.41	28.04	28.52	spray	
27/11/51	10	12.45	236.33	0.1	1.5	1.5	1.5	1.4	0.1	7.0	6.9	6.8	6.9	5.66	47.79	76.29	28.35	28.54	spray	6.57
		16.45	240.42	0.1	1.5	1.5	1.5	1.5	0.7	7.9	7.6	7.5	8.0	5.74	49.33	82.42	26.67	27.11		6.59
28/11/51	11	14.30	261.75	0.1	1.4	1.5	1.4	1.4	1.0	7.3	7.6	7.9	8.1	5.71	43.21	80.68	28.21	28.57	spray	6.65
29/11/51	12	12.35	284.08	0.2	1.9	2.0	1.8	1.8	0.2	9.1	8.7	9.1	8.5	5.6	42.78	72.39	27.16	27.42	spray	6.51
		17.50	289.17	0.2	1.9	1.8	1.8	2.3	4.4	12.2	12.1	12.1	14.2	5.62	67.39	88.61	22.29	23.81	spray	
30/11/51	13	12.25	308.00	0.1	1.6	1.7	1.5	1.5	0.1	6.8	7.0	6.4	6.4	5.58	41.83	83.06	25.24	26.01	spray	6.51
		16.26	312.00	0.2	1.7	1.7	1.8	1.8	1.5	9.1	9.0	9.3	9.0	5.64	42.88	87.36	25.2	25.81	spray	
1/12/51	14	13.55	333.50	0.2	1.7	1.6	1.6	1.6	0.2	5.8	6.0	5.9	6.2	5.73	39.8	69.49	25.7	26.88	spray	

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Table 4 Experiment Data: Test Order 4, Condition: Ceramic, SV= 50 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
18/11/51	1	10.30	19.50	3136	2896	2902	2857	2845	78.1	70.0	69.8	70.1	69.8	21.6	19.5	19.3	19.2	18.8
		15.30	24.50	3083	2834	2798	2783	2658	75.6	68.6	68.2	68.2	68.3	20.7	18.7	18.7	18.6	18.4
19/11/51	2	12.10	45.17	3178	2625	2532	2465	2333	76.0	66.9	67.0	68.0	68.4	21.7	19.4	19.4	19.5	19.3
		15.00	48.00	3407	2877	2725	2554	2342	76.0	67.7	67.5	67.4	67.5	21.9	19.7	19.7	19.6	19.4
20/11/51	3	11.00	68.00	3419	2875	2819	2679	2395	76.3	68.4	68.9	69.3	22.3	20.3	20.3	20.5	20.5	20.1
		17.00	74.00	3502	3007	2916	2797	2577	75.3	67.8	67.8	68.1	67.9	22.0	20.0	20.0	20.0	20.0
21/11/51	4	15.20	96.33	3768	3399	3365	3275	3011	76.0	67.5	67.5	67.6	67.6	22.3	20.1	20.1	20.1	19.7
22/11/51	5	13.00	118.00	3805	3214	3206	3080	2930	76.3	67.0	67.5	67.5	68.1	22.9	20.4	20.5	20.4	20.3
		15.45	120.75	3800	3122	3109	3016	2710	75.6	66.0	66.2	66.5	67.2	22.7	20.0	20.1	20.1	20.0
23/11/51	6	12.30	141.50	3859	3317	3277	3169	2970	75.2	66.7	66.6	66.5	66.4	23.2	20.8	20.8	20.7	20.7
		17.00	146.00	4000	3497	3452	3362	3169	75.6	67.1	67.2	67.3	67.4	23.6	21.2	21.1	21.3	21.2
24/11/51	7	11.30	164.50	3814	3218	3233	3240	3042	74.7	65.8	66.4	66.9	67.0	23.8	21.3	21.5	21.7	21.6
		16.30	168.50	4036	3545	3499	3370	2976	75.2	66.7	66.7	66.7	67.1	24.5	22.0	22.1	21.9	21.8
25/11/51	8	12.30	188.50	3406	3164	3213	3138	2862	70.6	63.7	64.7	64.9	64.8	23.2	21.3	21.6	21.7	21.6
		16.15	192.25	4336	3765	3718	3595	3353	74.6	66.6	66.7	66.7	66.8	24.9	22.5	22.5	22.5	22.5
26/11/51	9	11.30	211.50	4203	3585	3531	3497	3260	74.5	65.6	65.9	66.0	65.8	25.3	22.6	22.7	22.7	22.7
		17.20	217.33	3390	2642	2595	2530	2380	67.4	59.2	59.4	59.8	60.2	22.5	19.8	19.8	20.0	20.2
27/11/51	10	12.20	236.33	4471	3996	3854	3688	3288	73.9	68.3	66.8	66.8	67.0	25.9	24.0	23.6	23.6	23.2
		16.25	240.42	4530	3972	3955	3791	3514	73.5	66.3	66.3	66.2	66.1	25.6	23.3	23.4	23.3	23.3
28/11/51	11	13.45	261.75	4415	4133	4013	3773	3319	73.4	66.3	65.7	65.8	65.9	26.3	24.1	23.9	23.9	23.5
29/11/51	12	12.05	284.08	4616	4002	4007	3826	3033	72.9	64.8	66.0	65.9	55.2	26.8	24.0	24.3	24.3	20.6
		17.10	289.17	4022	3460	3295	2910	2700	70.0	62.1	61.6	61.7	62.6	24.8	22.5	22.2	22.1	22.2
30/11/51	13	12.00	308.00	4537	4028	3953	3767	3584	72.8	66.0	65.9	66.0	66.0	27.0	24.7	24.6	24.6	24.7
		16.00	312.00	4381	3950	3863	3645	3327	72.3	64.5	64.5	64.4	64.4	26.3	23.9	23.8	23.8	23.7
1/12/51	14	13.30	333.50	4153	3822	3782	3319	2852	73.8	69.1	69.6	69.4	68.0	25.8	24.3	24.6	24.4	23.4

Table 4(cont.) Experiment Data: Test Order 4, Condition: Ceramic, SV= 50 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
18/11/51	1	10.30	19.50	0.1	1.8	1.8	1.8	1.8	0.2	8.7	9.1	8.9	9.5	6.07	70.28	98.15	28.2	29.34	spray	
		15.30	24.50	0.0	1.9	1.9	1.9	1.9	3.9	10.8	11.2	11.3	11.4	5.92	56.09	86.35	30.65	31.15	spray	
19/11/51	2	12.10	45.17	0.1	1.8	1.8	1.7	1.8	2.2	11.9	11.8	10.8	10.5	5.85	62.09	90.15	29.06	29.61	spray	
		15.00	48.00	0.1	1.9	1.8	1.8	1.8	2.0	10.7	11.1	11.2	11.3	5.83	61	84.35	28.88	29.61	spray	
20/11/51	3	11.00	68.00	0.1	1.9	1.8	1.8	1.8	1.3	9.4	8.8	8.4	8.8	5.81	66.66	82.9	27.17	28.62	spray	
		17.00	74.00	0.1	1.7	1.7	1.7	1.7	2.6	10.5	10.5	10.2	10.4	5.84	62.03	84.54	28.34	28.98	spray	
21/11/51	4	15.20	96.33	0.1	2.1	2.0	2.0	2.0	1.6	10.3	10.4	10.4	10.7	5.85	69.49	84.93	28.17	28.67	spray	
22/11/51	5	13.00	118.00	0.0	1.9	1.9	1.9	1.8	0.8	10.7	10.1	10.3	9.8	5.77	62.77	87.87	29.74	30.15	spray	
		15.45	120.75	0.0	1.8	1.8	1.8	1.8	1.7	12.2	11.9	11.6	11.0	5.81	62.34	83.31	29.08	29.64	spray	
23/11/51	6	12.30	141.50	0.1	2.0	2.0	2.0	2.0	1.5	10.5	10.6	10.8	10.9		64.77	80.77	30.43	32.6		
		17.00	146.00	0.1	1.9	1.8	1.9	1.9	0.7	9.8	9.9	9.5	9.5		72.65	85.3	28.88	30.18		
24/11/51	7	11.30	164.50	0.1	1.7	1.6	1.7	1.7	1.4	11.2	10.5	9.7	9.7		56.7	75.66	31.3	31.22		
		16.30	168.50	0.1	2.0	2.0	2.0	1.9	0.2	9.3	9.2	9.4	9.2	5.64	68.06	87.17	28.16	29.78	spray	
25/11/51	8	12.30	188.50	0.1	1.8	1.7	1.7	1.7	6.1	13.2	12.0	11.7	11.8	5.67	59.2	88.25	29.68	29.87		
		16.15	192.25	0.1	1.8	1.8	1.8	1.8	0.4	9.1	9.0	9.0	8.9	5.48	55.91	71.08	29.82	30.04		6.48
26/11/51	9	11.30	211.50	0.1	2.1	1.9	2.0	2.0	0.1	9.7	9.5	9.3	9.5	5.58	48.14	78.04	28.78	29.34	spray	
		17.20	217.33	0.1	1.6	1.6	1.6	1.7	10.0	19.4	19.2	18.6	17.9	5.66	63.81	85.79	27.42	27.4	spray	
27/11/51	10	12.20	236.33	0.1	1.4	1.8	1.8	1.7	0.1	6.3	7.8	7.8	8.1	5.65	46.39	78.27	28.26	28.22	spray	6.57
		16.25	240.42	0.1	1.8	1.7	1.7	1.7	0.8	8.6	8.6	8.8	8.9	5.75	50.03	73.93	26.77	27.01		6.59
28/11/51	11	13.45	261.75	0.1	1.7	1.8	1.8	1.8	0.1	7.9	8.6	8.4	8.8	5.67	44.13	74.46	27.99	28.09		6.65
29/11/51	12	12.05	284.08	0.2	2.1	1.9	1.9	4.4	0.1	9.1	7.8	7.9	19.7	5.56	38.29	84.14	27.45	27.63	spray	6.51
		17.10	289.17	0.2	2.1	2.2	2.2	2.0	5.0	13.3	14.0	14.0	13.2	5.54	63.96	82.17	23.9	24.08	spray	
30/11/51	13	12.00	308.00	0.1	1.8	1.8	1.7	1.7	0.1	7.5	7.7	7.7	7.6	5.55	43.25	85.48	25.94	26.25		6.51
		16.00	312.00	0.1	2.0	2.1	2.1	2.0	1.3	9.6	9.6	9.7	9.9	5.56	42.88	82.13	25.23	25.62		
1/12/51	14	13.30	333.50	0.2	1.9	1.9	1.9	2.0	0.2	4.7	3.9	4.3	6.6	5.73	44.56	78.01	24.94	25.97		

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Table 5 Experiment Data: Test Order 5, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
18/11/51	1	11.45	20.75	3021	2308	2102	1689	1695	77.2	69.1	70.2	71.6	71.8	20.9	18.3	18.3	17.5	17.5
		15.50	24.83	3066	2335	2390	2326	2185	75.5	70.9	70.6	70.5	70.4	20.7	18.9	19.2	19.2	19.2
19/11/51	2	11.30	44.50	3060	1180	162	0	0	75.4	68.6	68.4	69.0	68.7	21.6	19.8	19.4	17.9	17.9
		16.30	49.50	3130	1464	716	130	96	72.5	66.9	66.8	67.7	67.8	21.1	19.5	19.2	18.2	18.2
20/11/51	3	12.00	69.00	3490	2465	1778	977	940	76.4	71.5	71.6	72.1	72.1	22.3	20.8	20.4	19.5	19.5
		15.30	72.50	3613	2331	1699	704	725	76.0	71.3	71.1	71.2	71.6	22.2	20.6	20.5	19.1	19.3
21/11/51	4	16.00	97.00	3744	3396	3320	3210	1686	76.5	69.4	69.4	69.5	57.6	22.5	20.5	20.5	20.6	16.0
22/11/51	5	12.30	117.50	3550	1765	1328	1033	817	75.1	64.4	65.6	67.3	68.6	22.6	19.9	19.9	19.4	19.1
		14.45	119.75	3802	2327	1722	957	769	76.0	69.7	69.5	70.3	70.4	22.7	20.8	20.5	19.6	19.2
23/11/51	6	11.30	140.50	3821	2368	1888	1652	1552	69.9	75.6	69.5	69.5	69.5	21.8	23.3	21.2	21.3	21.3
		16.00	145.00	3939	2691	1846	1164	551	75.1	68.6	68.9	69.5	70.3	23.5	21.6	21.4	20.9	19.9
24/11/51	7	12.00	165.00	3098	1747	889	217	0	64.5	68.0	62.9	62.3	61.0	20.9	21.7	20.4	19.0	18.0
		17.00	170.00	4038	2165	1529	613	172	75.1	69.6	69.5	70.3	70.5	24.5	22.7	22.7	21.8	21.6
25/11/51	8	11.40	188.67	2965	2284	1949	1517	912	66.7	66.9	67.7	68.1	68.7	22.0	22.0	22.2	22.0	21.4
		15.15	192.25	4187	1928	1072	288	0	74.6	69.6	69.7	69.9	70.3	24.7	22.8	22.8	21.7	21.0
26/11/51	9	10.30	211.50	4185	2016	1334	189	140	74.3	68.9	69.0	70.3	70.2	25.5	23.7	23.5	21.9	21.8
		16.20	217.33	2870	961	229	0	0	64.4	58.7	58.1	58.0	57.8	21.1	19.4	19.0	18.5	18.6
27/11/51	10	13.00	238.00	4436	2783	1515	624	72	74.0	65.9	66.4	66.7	62.6	25.8	23.3	23.3	22.7	20.2
		17.10	242.17	4517	2440	1518	265	7	73.6	65.8	65.9	66.8	67.3	25.8	23.2	23.1	21.9	21.5
28/11/51	11	14.00	263.00	4495	2012	1286	387	53	73.5	65.2	65.9	66.9	66.9	26.2	23.4	23.4	22.4	23.0

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Table 5(cont.) Experiment Data: Test Order 5, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
18/11/51	1	11.45	20.75	0.1	1.8	1.7	1.6	1.5	1.8	10.8	9.8	9.3	9.2	5.99	70.28	82.17	28.2	31.27	spray	
		15.50	24.83	0.1	1.4	1.3	1.4	1.4	3.7	8.8	8.9	8.9	9.0	5.88	57.28	77.45	30.53	31.13	spray	
19/11/51	2	11.30	44.50	0.1	1.5	1.5	1.5	1.6	2.9	10.1	10.7	11.6	11.8	5.86	62.31	87.38	29.08	29.88	spray	
		16.30	49.50	0.0	1.3	1.4	1.3	1.3	6.4	12.3	12.6	12.8	12.7	5.78	60.17	83.07	28.98	29.32	spray	
20/11/51	3	12.00	69.00	0.0	1.2	1.3	1.2	1.2	1.3	6.5	6.7	7.2	7.2	5.85	68.33	83.04	27.73	27.49	spray	
		15.30	72.50	0.1	1.4	1.4	1.5	1.3	1.7	6.7	7.0	8.2	7.8	5.86	59.7	76.7	28.69	28.89	spray	
21/11/51	4	16.00	97.00	0.1	1.6	1.6	1.5	1.4	0.9	8.5	8.5	8.4	22.0	5.56	69.49	85.67	28.17	28.54	spray	
22/11/51	5	12.30	117.50	0.1	1.9	1.7	1.5	1.5	2.2	13.8	12.8	11.8	10.8	5.84	61.68	85.35	29.31	29.66	spray	
		14.45	119.75	0.0	1.5	1.4	1.3	1.5	1.3	8.0	8.6	8.8	8.9	5.78	62.42	84.41	28.9	29.38	spray	
23/11/51	6	11.30	140.50	1.5	0.2	1.5	1.4	1.4	6.8	0.9	7.8	7.8	7.8		64.77	81.25	30.43	30.1	spray	
		16.00	145.00	0.1	1.4	1.4	1.3	1.3	1.3	8.4	8.3	8.3	8.5		73.78	84.83	28.9	29.26	spray	
24/11/51	7	12.00	165.00	1.4	0.0	1.4	1.4	1.3	12.2	0.3	15.3	17.3	19.7		61.53	81.97	29.19	31.01	spray	
		17.00	170.00	0.2	1.5	1.4	1.4	1.4	0.2	6.2	6.4	6.5	6.5	5.73	68.06	83.62	28.16	28.7	spray	
25/11/51	8	11.40	188.67	0.1	1.1	1.0	1.0	1.0	11.2	10.0	9.1	8.9	8.9	5.75	60.37	87.08	29.27	30.17	spray	
		15.15	192.25	0.1	1.2	1.2	1.2	1.2	0.4	6.4	6.3	7.2	7.5	5.72	53.6	77.88	30.81	30.89	spray	6.48
26/11/51	9	10.30	211.50	0.1	1.6	1.5	1.4	1.4	0.1	5.8	6.0	6.4	6.6	5.69	55.16	70.65	27.17	27.64	spray	
		16.20	217.33	0.1	1.6	1.6	1.5	1.4	14.4	20.3	21.3	22.0	22.2	5.67	49.66	80.75	29.28	28.64		
27/11/51	10	13.00	238.00	0.0	1.8	1.7	1.7	1.8	0.2	9.0	8.6	8.9	14.4	5.57	44.69	79.11	28.08	28.42	spray	6.57
		17.10	242.17	0.0	1.9	1.8	1.8	1.6	0.6	9.1	9.2	9.5	9.5	5.66	51.23	76.15	26.58	26.38	spray	6.59
28/11/51	11	14.00	263.00	0.0	1.7	1.6	1.5	1.2	0.3	9.7	9.1	9.2	8.9	5.66	43.21	74.49	28.21	28.87	spray	6.65

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Table 6 Experiment Data: Test Order 6, Condition: Ceramic, SV= 10 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
4/12/51	1	18.00	26.00	3662	3178	2889	2536	2355	74.2	68.9	68.6	69.5	66.6	24.2	22.8	22.3	21.2	20.5
5/12/51	2	11.00	43.00	3819	3134	2850	2720	2563	74.1	69.3	70.3	71.5	71.7	25.5	22.8	22.7	21.8	23.3
		15.00	47.00	3635	2591	2524	2578	2785	74.8	63.6	66.2	66.7	67.9	24.9	20.6	21.1	21.4	22
6/12/51	3	11.00	67.00	3859	2714	2431	1853	1574	74	69.4	70.7	71,1	72.5	25.8	22.6	22.7	21.6	21.2
		15.15	71.25	3812	2525	2205	1719	1755	74.3	65.5	66	66.7	68.2	25.6	21.4	21.7	21.8	22.3
7/12/51	4	11.45	91.75	3825	2219	1930	1172	791	74	63.1	65.5	66.5	69.5	25.7	20.9	21.5	20.8	20.7
8/12/51	5	13.30	117.50	3793	1798	1230	644	398	73.8	56.6	58.1	60	69.3	25.9	19	19.1	18.6	20.3
10/12/51	7	10.15	138.25	3776	2653	2180	1465	982	73.6	70.7	70.9	71.6	72.1	26	23.5	23.4	22.4	21.4
		15.30	143.50	3818	2102	1662	926	887	73.8	69.5	70.9	68.2	68.8	25.9	23	23.3	22.5	22.8
11/12/51	8	17.30	169.50	4045	3041	2696	2253	1739	74.2	73.1	73.3	73.3	73.6	25.5	23.7	23.7	23.7	23.9
12/12/51	9	15.45	191.75	4019	3158	2785	1136	485	74.2	73.7	73.8	64.5	67.9	25.5	23.8	23.9	20.6	20.6
13/12/51	10	17.00	217.00	3930	2318	1833	924	306	74.7	72.5	72.7	73.4	73.1	24.5	23.1	23.2	22.3	22.8
14/12/51	11	12.30	236.50	3636	2452	1831	1019	560	74.3	72.6	73.2	72.6	72.4	25.2	23.6	24.1	23.6	23.5

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Table 6(cont.) Experiment Data: Test Order 6, Condition: Ceramic, SV= 10 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
4/12/51	1	18.00	26.00	0.1	1.9	1.8	1.9	2	1.5	6.4	6.3	7.4	10.9		70.88	79.96	23.52	23.28		
5/12/51	2	11.00	43.00	0.2	1.8	1.7	1.4	1.7	0.2	6.1	5.3	5.3	3.3	5.77					spray	6.64
		15.00	47.00	0.1	3.2	2.7	2.6	2.3	0.2	12.6	10	9.3	7.8	5.87					spray	6.66
6/12/51	3	11.00	67.00	0.1	2.2	1.9	2.1	1.9	0.1	5.8	4.7	5.2	4.4	5.89					spray	6.62
		15.15	71.25	0	2.7	2.6	2.5	2.3	0.1	10.4	9.7	9	7.2	5.9					spray	6.59
7/12/51	4	11.45	91.75	0.1	3.5	3	3.9	2.4	0.2	12.5	10	9.8	7.4	5.91					spray	
8/12/51	5	13.30	117.50	0.2	5	4.8	4.5	2.5	0.1	19.4	18	16.9	7.9	5.89					spray	6.69
10/12/51	7	10.15	138.25	0.2	1.9	1.8	1.9	1.9	0.2	4.9	4.9	4.1	4.6	5.64	64.29	83.14	25.52	25.44	spray	6.67
		15.30	143.50	0.2	2.2	1.8	2.4	2.1	0.1	5.3	4	6.9	6.3	5.75	53.06	79.73	26.84	27.5	spray	
11/12/51	8	17.30	169.50	0.2	1.3	1.2	1.2	1.2	0.1	1.9	1.8	1.8	1.3	5.76	59.23	79.08	27	27.14		6.64
12/12/51	9	15.45	191.75	0.2	1.2	1.2	3.2	2.6	0.1	1.3	1.1	11.7	8.9	5.69	54.2	84.73	27.08	27.77	spray	
13/12/51	10	17.00	217.00	0.2	1.4	1.3	1.3	1.3	0.2	3	2.8	3	2.8	5.52	64.29	82.33	26.74	26.95	spray	6.6
14/12/51	11	12.30	236.50	0.3	1.6	1.4	1.4	1.5	0.2	2.2	1.3	2.4	2.6	5.63	64.01	82.4	26.48	27.14		6.56

Table 7 Experiment Data: Test Order 7, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
4/12/51	1	18.15	26.25	4124	4011	3520	3401	3320	74.8	68.6	68.8	68.7	68.8	24.9	22.5	22.3	22.2	22.3
5/12/51	2	11.45	43.75	3862	3244	3006	2415	2365	74	72.4	72.7	73.9	74	25.7	23.5	23.3	22.3	22.2
		15.30	47.50	3883	2649	2474	1961	1891	74.3	68.7	69.9	70.9	70.7	25.5	22.2	22.1	21.1	20.9
6/12/51	3	11.30	67.50	3831	2085	1653	1097	1042	74.1	70.5	71.3	72.3	72.5	25.7	22.9	22.8	21.6	21.5
		15.30	71.50	3851	1974	1369	700	653	74.2	68.4	69.3	70.6	72.5	25.6	22.2	22.1	20.9	21.2
7/12/51	4	12.00	92.00	3775	2305	1981	1319	1335	74.2	62.4	63.8	65.3	69.8	25.6	20.6	20.8	20.1	21.1
8/12/51	5	13.45	117.75	3792	1897	1384	418	402	73.9	63.2	64.3	65.7	71.4	25.9	21	21.3	20.1	21.4
10/12/51	7	10.45	138.75	3766	2695	2265	1424	1223	73.8	72.8	72.6	71.1	69.7	25.9	24.1	23.9	22.2	21.2
		16.30	144.50	3826	2820	2310	1509	1343	74	73.6	72.9	73.1	73.1	25.8	24.2	24	23	22.7
11/12/51	8	17.45	169.75	4026	2629	1934	552	415	74.3	74.2	74.1	75.2	75.3	25.5	23.9	24	23.1	22.8
12/12/51	9	16.00	192.00	4007	2889	2338	1195	1247	74.3	73.6	73.8	74.3	74.3	25.4	23.7	23.7	23.2	23.2
13/12/51	10	17.15	217.25	3945	2198	1635	1466	1382	74.7	62.5	72.1	72.3	72.4	25	20.1	23.1	23.1	23.1
14/12/51	11	13.00	237.00	3566	2063	1274	602	678	74.6	72.3	72.7	73.2	72.7	25	23.2	23.3	22.7	22.6

Table 7(cont.) Experiment Data: Test Order 7, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
4/12/51	1	18.15	26.25	0.2	1.5	1.7	1.7	1.7	0.1	7.4	7.2	7.4	7.2		74.83	84.31	22.7	23.12	spray	
5/12/51	2	11.45	43.75	0.1	1.5	1.5	1.4	1.4	0.2	2.6	2.5	2.4	2.4	5.88					spray	6.64
		15.30	47.50	0.1	2.3	2	1.8	1.6	0.1	6.8	6	6.2	6.8	5.89					spray	6.66
6/12/51	3	11.30	67.50	0.1	2	1.9	1.8	1.8	0.1	4.6	4	4.3	4.2	5.9					spray	6.62
		15.30	71.50	0.1	2.4	2.3	2.2	1.7	0.1	7	6.3	6.3	4.6	5.88					spray	6.59
7/12/51	4	12.00	92.00	0.1	3.7	3.4	3.3	2.3	0.1	13.3	12	11.3	6.8	5.89					spray	
8/12/51	5	13.45	117.75	0.1	3.5	3.3	3.1	2	0.1	12.3	11.1	11.1	5.2	5.84					spray	6.69
10/12/51	7	10.45	138.75	0.1	1.5	1.5	1.8	2.4	0.2	1.6	2	4.9	6.7	5.76	60.63	78.69	26.14	25.96	spray	6.67
		16.30	144.50	0.1	1.3	1.4	1.4	1.5	0.1	0.9	1.7	2.5	2.7	5.73	52.3	79.38	27.02	27.63	spray	
11/12/51	8	17.45	169.75	0.1	1.1	1.2	1	1	0.1	0.8	0.7	0.7	0.9	5.82	68.82	76.41	25.33	25.45	spray	6.64
12/12/51	9	16.00	192.00	0.1	1.3	1.2	1.2	1.2	0.2	1.4	1.3	1.3	1.3	5.62	54.14	78.98	27.21	27.64	spray	
13/12/51	10	17.15	217.25	0.2	3.6	1.5	1.4	1.4	0.1	13.8	3.2	3.2	3.1	5.31	68.95	80.95	25.93	26.34	spray	6.6
14/12/51	11	13.00	237.00	0.2	1.5	1.4	1.4	1.4	0.2	3	3.6	3.7	3.3	5.78	59.73	85.04	27.56	27.66	spray	6.56

Table 8 Experiment Data: Test Order 8, Condition: Plastic cap, SV= 50 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
4/12/51	1	18.30	25.50	4208	4005	3851	3693	3475	73.8	69.5	68.6	68.8	67.9	25.8	22.2	22.3	22.3	22.3
5/12/51	2	12.00	43.00	3879	3402	3347	3147	2986	74.0	69.3	69.2	69.1	69.6	25.7	22.9	22.8	22.6	22.3
		15.45	47.75	3362	2946	2932	2893	2932	75.4	67.7	67.7	68.2	67.9	24.3	21.8	21.8	21.9	21.9
6/12/51	3	11.45	67.75	3811	3090	3054	2940	2749	74.1	69.2	70.1	70.3	70.9	25.6	22.5	22.9	22.8	22.6
		16.00	72.00	3666	3205	3113	2990	3024	74.6	68.9	69.6	70.3	70.7	25.1	22.5	22.7	22.8	23.0
7/12/51	4	12.15	92.25	3840	3248	3138	3051	2906	74.1	70.9	71.1	71.5	72.0	25.6	23.2	23.2	23.3	23.1
8/12/51	5	14.00	118.00	3826	2810	2688	2618	2652	73.8	60.9	61.8	62.9	67.5	25.9	20.4	20.5	20.9	22.0
10/12/51	7	11.15	139.25	3748	3263	3210	3136	2963	73.8	72.5	72.1	72.2	72.3	25.8	23.0	23.9	23.8	23.6
		16.15	144.25	3792	3085	3050	2886	2750	74.0	68.7	70.1	70.0	69.5	25.7	22.7	23.2	23.0	22.7
11/12/51	8	18.00	170.00	4080	3354	3198	2995	2918	74.2	72.6	72.6	72.7	72.7	25.6	23.5	23.5	23.6	23.6
12/12/51	9	16.15	192.25	4037	3325	3102	2884	2817	74.3	72.0	71.5	71.9	71.8	25.4	23.4	23.2	23.2	23.3
13/12/51	10	17.30	217.50	4054	3248	3077	2847	2550	74.7	71.6	71.8	71.6	71.9	25.0	23.0	23.0	22.9	22.8
14/12/51	11	13.15	237.25	3564	2813	2626	2430	2213	74.7	71.6	71.6	71.8	72.0	24.9	23.1	23.0	23.0	22.7

Table 8 (cont.) Experiment Data: Test Order 8, Condition: Plastic cap, SV= 50 h^{-1}, Rate of spraying water = High

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
4/12/51	1	18.30	25.50	0.3	1.9	1.8	1.7	2.1	0.1	7.4	6.3	7.2	7.7		73.41	86.01	22.82	23.21	spray	
5/12/51	2	12.00	43.00	0.2	2.1	2.2	2.2	2.1	0.1	5.7	5.8	5.1	6.0	5.87					spray	6.64
		15.45	47.75	0.1	1.8	1.9	1.8	1.9	0.2	8.7	8.6	8.1	8.3	5.89					spray	6.66
6/12/51	3	11.45	67.75	0.1	2.2	2.0	2.0	1.9	0.2	6.1	5.0	4.9	4.6	5.93					spray	6.62
		16.00	72.00	0.1	2.2	2.0	1.9	1.7	0.2	6.4	5.7	5.0	4.6	5.88					spray	6.59
7/12/51	4	12.15	92.25	0.1	1.8	1.8	1.8	1.6	0.2	4.1	3.8	3.4	3.3	5.88					spray	
8/12/51	5	14.00	118.00	0.2	4.0	3.9	3.6	2.6	0.1	14.7	13.8	12.6	7.9	5.88					spray	6.69
10/12/51	7	11.15	139.25	0.2	1.6	1.6	1.6	1.6	0.2	2.9	2.4	2.4	2.5	5.8	60.34	85.16	26.26	26.11	spray	6.67
		16.15	144.25	0.2	2.3	1.9	2.0	2.1	0.1	6.3	4.8	5.0	5.7	5.76	53.6	77.72	27.16	27.71		
11/12/51	8	18.00	170.00	0.1	1.5	1.5	1.5	1.5	0.1	2.4	2.4	2.1	2.2	5.81	69.49	84.93	24.76	24.72	spray	6.64
12/12/51	9	16.15	192.25	0.1	1.6	1.8	1.6	1.6	0.2	2.0	3.5	3.3	3.3	5.7	54.49	86.29	27.17	27.54	spray	
13/12/51	10	17.30	217.50	0.2	1.6	1.5	1.6	1.6	0.1	3.8	3.7	3.9	3.7	5.7	71.02	73.92	25.45	25.6	spray	
14/12/51	11	13.15	237.25	0.3	1.6	1.7	1.6	1.6	0.2	3.7	3.6	3.6	3.7	5.77	56.61	83.8	28.28	28.72	spray	6.56

Table 9 Experiment Data: Test Order 9, Condition: Ceramic, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
4/12/51	1	19.00	26.00	4238	3805	3457	2900	2337	73.7	68.6	68.9	71.8	71.9	25.9	22.3	22.8	21.2	21.3
5/12/51	2	12.15	43.25	3874	3213	3004	2776	2133	74.1	71.9	70.9	72.1	74.8	25.6	23.5	23.0	22.9	21.9
		16.00	47.00	3483	2555	2431	2222	1665	75.4	67.6	68.4	69.4	71.9	24.4	21.7	21.7	21.6	20.5
6/12/51	3	12.00	67.00	3835	1460	1188	638	120	74.1	71.3	71.8	73.3	74.9	25.6	22.9	22.9	22.5	21.4
		16.00	71.00	3426	1465	916	402	57	75.1	68.2	70.9	71.7	71.3	24.7	22.0	22.7	22.3	20.6
7/12/51	4	12.30	91.50	3774	1680	1240	671	210	74.2	55.5	56.5	58.3	66.3	25.6	18.2	18.4	18.7	20.1
8/12/51	5	14.30	117.50	3803	1712	812	512	144	73.9	61.8	58.3	58.0	66.6	25.8	20.4	19.3	19.3	22.1
10/12/51	7	11.30	138.50	3734	1972	1527	1060	307	74.0	72.8	71.7	67.6	69.4	25.7	23.7	23.2	21.7	20.4
		16.30	143.50	3807	1954	1292	824	90	74.1	72.6	71.9	73.0	74.3	25.7	23.7	23.3	23.3	22.0
11/12/51	8	18.15	169.25	4026	2061	1117	426	0	74.2	72.3	72.4	72.5	73.8	25.6	23.5	23.4	23.1	21.8
12/12/51	9	16.30	191.50	4054	2592	2029	1167	100	74.4	73.4	73.4	73.5	74.6	25.4	23.8	23.8	23.7	22.2
13/12/51	10	17.45	216.75	4013	1928	1140	461	0	74.7	72.7	72.8	72.8	73.7	25.0	23.2	23.2	23.0	21.8
14/12/51	11	13.30	236.50	3535	1262	481	69	0	74.8	72.6	72.7	72.9	73.9	24.9	23.1	23.1	23.1	21.6

Table 9(cont.) Experiment Data: Test Order 9, Condition: Ceramic, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
4/12/51	1	19.00	26.00	0.3	1.8	1.8	1.9	1.8	0.1	6.3	6.5	6.1	6.0		72.53	82.3	23.02	23.3	spray	
5/12/51	2	12.15	43.25	0.2	1.5	1.8	1.6	1.2	0.1	3.1	4.3	3.4	1.1	5.9					spray	6.44
		16.00	47.00	0.1	2.0	1.8	1.7	1.5	0.1	8.7	8.1	7.3	6.1	5.91					spray	6.66
6/12/51	3	12.00	67.00	0.1	1.7	1.7	1.4	1.3	0.2	4.1	3.6	2.8	2.4	5.88					spray	6.62
		16.00	71.00	0.0	2.2	1.6	1.4	1.7	0.2	7.6	4.8	4.6	6.4	5.85					spray	6.59
7/12/51	4	12.30	91.50	0.1	5.3	5.1	4.7	3.0	0.1	21.0	20.0	18.3	10.6	5.87					spray	
8/12/51	5	14.30	117.50	0.2	3.9	4.7	4.7	2.7	0.1	13.9	17.7	18.0	8.6	5.84						6.69
10/12/51	7	11.30	138.50	0.2	1.5	1.7	2.6	2.4	0.1	2.0	3.4	8.1	7.8	5.69	60.07	76.29	27.33	27.36	spray	6.67
		16.30	143.50	0.1	1.5	1.6	1.4	1.3	0.1	2.2	3.2	2.3	2.4	5.78	53.6	82.47	27.16	27.65	spray	
11/12/51	8	18.15	169.25	0.1	1.5	1.4	1.5	1.4	0.2	2.7	2.8	2.9	3.0	5.78	71.54	80.92	24.02	24.28	spray	6.64
12/12/51	9	16.30	191.50	0.1	1.2	1.2	1.2	1.1	0.1	1.6	1.6	1.6	2.1	5.39	51.86	82.29	29.5	27.82	spray	
13/12/51	10	17.45	216.75	0.2	1.4	1.4	1.3	1.2	0.1	2.7	2.6	2.9	3.3	5.31	72.95	82.08	24.88	25.25	spray	
14/12/51	11	13.30	236.50	0.2	1.4	1.4	1.3	1.2	0.1	2.9	2.8	2.7	3.2	5.55	53.85	87.7	28.96	29.75	spray	6.56

Table 10 Experiment Data: Test Order 10, Condition: Ceramic, SV= 50 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
24/12/51	1	10.00	17.00	3482	3259	3245	3257	3238	73.6	70.7	70.6	70.8	70.5	25.8	23.6	23.6	23.7	23.6
		17.30	24.50	3498	3395	3141	3019	2945	73.5	70.1	70.1	70.4	70.6	25.7	23.5	23.5	23.5	23.2
25/12/51	2	19.00	50.00	3412	3178	3129	3108	2922	73.4	69.6	69.4	69.8	69.6	25.7	23.6	23.5	23.5	23.5
26/12/51	3	11.00	66.00	3370	3102	3074	2987	2858	73.6	67.5	67.6	67.9	68.0	25.5	22.0	22.0	22.9	22.7
		16.15	71.25	3160	2994	2954	2801	2747	74.1	68.4	67.8	67.9	68.5	24.9	23.0	22.7	22.5	22.5
27/12/51	4	19.00	98.00	3247	2761	2485	2275	1960	73.5	67.9	67.6	67.7	67.7	25.2	22.8	22.6	22.6	22.4
28/12/51	5	18.15	121.25	3124	2646	2514	2326	2074	73.2	69.0	69.2	69.1	69.6	25.9	23.6	23.6	23.6	23.3
29/12/51	6	10.15	137.25	2720	2361	2231	2109	1971	73.9	67.4	67.6	67.7	67.7	25.2	23.0	22.0	23.0	22.9
		19.30	146.50	2879	2521	2420	2236	2038	73.2	67.5	67.4	67.3	67.6	25.6	23.4	23.4	23.3	23.0
30/12/51	7	9.30	160.50	2723	2326	2270	2109	1946	73.1	66.1	67.1	67.5	67.5	25.7	23.1	23.5	23.3	23.0
		14.30	165.50	2517	1925	1847	1760	1650	73.3	69.5	69.5	69.8	69.8	26.1	23.6	23.6	23.6	23.4
31/12/51	8	10.30	185.50	2618	2388	2297	2183	2075	73.7	70.0	69.9	69.9	69.5	26.2	23.9	23.9	23.9	23.7
		18.15	193.25	2865	2283	2219	2108	1986	72.7	70.5	71.0	71.0	71.2	27.1	24.6	24.8	24.8	24.0
1/1/52	9	15.30	214.50	2394	2067	1991	1847	1712	73.3	67.6	67.5	67.4	67.6	26.6	24.4	24.4	24.4	24.4
2/1/52	10	14.30	237.50	2433	2111	2016	1837	1651	72.2	67.3	67.4	67.6	67.9	27.6	25.1	25.1	25.2	24.8
3/1/52	11	12.45	259.75	2347	1970	1867	1683	1370	72.0	67.5	68.1	68.3	68.5	27.8	25.4	25.7	25.8	25.5
		16.15	263.25	2246	1801	1699	1496	1325	73.1	66.8	67.2	67.3	67.6	26.8	24.2	24.5	24.4	24.2
4/1/52	12	10.30	281.50	2431	2047	1932	1757	1464	72.0	67.9	68.6	68.7	69.2	27.8	25.7	26.0	25.9	25.6

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Table 10(cont.) Experiment Data: Test Order 10, Condition: Ceramic, SV= 50 h^{-1}, Rate of spraying water = Low

				O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
date	day	time	hour	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
24/12/51	1	10.00	17.00	0.5	1.9	2.0	1.9	2.0	0.1	3.8	3.8	3.6	4.9	1.95	63.88	82.43	25.02	25.51		6.55
		17.30	24.50	0.6	2.0	2.0	1.9	2.0	0.2	4.4	4.3	4.1	4.2	6.3	62.93	82.76	25.76	26.28	spray	6.70
25/12/51	2	19.00	50.00	0.7	2.1	2.4	2.3	2.1	0.2	4.7	4.7	4.4	4.7	5.98	64.72	82.05	24.09	24.7		6.79
26/12/51	3	11.00	66.00	0.8	2.5	2.5	2.5	2.5	0.1	7.0	6.9	6.7	6.8	5.95	75.69	83.11	22.87	22.99	spray	
		16.15	71.25	0.8	2.1	2.4	2.4	2.2	0.2	6.5	7.1	7.2	6.8	5.95	85.79	86.8	21.89	22.61	spray	
27/12/51	4	19.00	98.00	1.0	2.5	2.8	2.8	2.6	0.1	6.9	7.0	6.9	6.9	5.97	80.9	86.9	22.77	23.28		
28/12/51	5	18.15	121.25	0.7	2.2	2.2	2.2	2.2	0.2	5.2	5.0	5.1	5.9	5.89	70.69	82.23	24.37	24.39	spray	
29/12/51	6	10.15	137.25	0.8	2.4	2.4	2.4	2.4	0.1	7.2	7.0	6.9	7.0	5.95	64.06	82.89	25.76	26.06		
		19.30	146.50	1.0	2.5	2.5	2.6	2.5	0.2	6.6	6.7	6.8	6.9	5.84	75.45	88.46	22.4	22.2		5.84
30/12/51	7	9.30	160.50	1.0	2.7	2.5	2.5	2.6	0.2	8.1	6.9	6.7	7.9	5.88	75.41	83.59	22.14	22.42		6.64
		14.30	165.50	0.4	2.1	2.1	1.9	2.0	0.2	4.8	4.8	4.7	4.8	5.85	51.62	81.03	27.65	28.82	spray	6.58
31/12/51	8	10.30	185.50	0.0	1.5	1.6	1.6	1.7	0.1	4.6	4.6	4.7	5.1	5.88	66.61	82.11	23.03	23.52		6.65
		18.15	193.25	0.0	1.8	1.6	1.6	1.5	0.2	3.1	2.6	2.6	2.3	5.84	67.53	87.22	23.96	24.38		6.62
1/1/52	9	15.30	214.50	0.0	1.4	1.3	1.3	1.3	0.1	7.6	6.8	6.9	6.7	5.93	48.79	81.6	29.35	29.65		6.67
2/1/52	10	14.30	237.50	0.0	1.7	1.6	1.5	1.5	0.2	5.9	5.9	5.7	5.8	5.83	58.46	80.81	26.06	26.2	spray	6.66
3/1/52	11	12.45	259.75	0.1	1.8	1.6	1.6	1.6	0.1	5.3	4.6	4.3	4.4	5.83	62.09	83.43	25.03	26.37	spray	6.77
		16.15	263.25	0.0	1.7	1.5	1.4	1.4	0.1	7.3	6.8	6.9	6.8	5.85	51.44	83.39	28.25	28.9	spray	6.68
4/1/52	12	10.30	281.50	0.0	1.7	1.5	1.4	1.4	0.2	4.7	3.9	4.0	4.8	6.16	64.39	82.99	24.66	24.58	spray	6.56

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Table 11 Experiment Data: Test Order 11, Condition: Plastic cap, SV= 50 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
24/12/51	1	10.30	17.50	3476	3239	3242	3258	3019	73.7	70.2	70.2	70.2	70.4	25.8	23.5	23.4	23.6	23.1
		17.45	24.75	3524	3210	3152	3098	3050	73.6	69.9	70.0	69.9	69.9	25.9	23.5	23.5	23.5	23.5
25/12/51	2	19.30	50.50	3383	3182	3115	3043	3010	73.5	68.5	68.3	68.4	68.3	25.3	23.3	23.2	23.2	23.1
26/12/51	3	10.00	65.00	3546	3026	2732	2412	2293	73.4	68.3	68.2	68.0	68.6	25.7	23.2	23.2	23.2	22.9
		16.30	71.50	3176	2498	2048	1838	1591	74.0	67.4	67.6	67.1	67.0	25.0	22.5	22.6	22.6	22.3
27/12/51	4	19.15	98.75	3212	2731	2535	2131	1678	73.6	67.4	67.6	67.3	67.3	25.1	22.6	22.7	22.6	22.3
28/12/51	5	18.30	122.00	3125	2458	2183	1836	1377	73.3	68.4	68.4	68.5	68.9	25.9	23.4	23.4	23.4	23.1
29/12/51	6	10.30	138.00	2657	2015	1717	1268	830	74.2	66.9	67.1	67.2	67.4	24.9	22.7	22.7	22.6	22.3
		20.00	147.50	2850	2175	1828	1208	1038	73.2	67.1	67.0	67.0	67.3	25.8	23.2	23.2	23.1	22.9
30/12/51	7	9.15	160.75	2722	2088	1846	1530	1126	73.1	67.1	67.2	67.0	67.4	25.8	23.4	23.4	23.3	23.0
		14.45	166.25	2560	1897	1773	1114	921	73.4	67.4	69.0	69.1	66.8	26.0	23.1	23.6	23.2	22.4
31/12/51	8	10.30	186.00	2582	2021	1712	1307	915	73.6	69.4	69.4	69.3	69.3	26.2	23.8	23.8	23.8	23.4
		18.30	194.00	2858	1965	1568	1126	727	72.6	70.1	70.2	70.0	70.3	27.3	24.6	24.7	24.6	24.2
1/1/52	9	15.45	215.25	2365	1645	1260	906	570	73.2	66.2	66.9	67.2	67.7	26.7	24.0	24.2	24.3	24.0
2/1/52	10	14.30	238.00	2305	1865	1573	1156	688	72.4	66.5	66.6	66.3	66.5	27.4	24.9	24.8	24.4	24.3
3/1/52	11	13.15	260.75	2296	1592	1204	892	386	72.2	66.3	67.0	67.1	67.1	27.6	25.0	25.3	25.3	25.3
		16.30	264.00	2245	1473	1034	692	316	73.1	65.7	66.0	66.1	66.5	26.8	24.1	24.2	24.2	23.9
4/1/52	12	10.45	282.25	2365	1587	1351	1033	627	72.2	66.3	67.4	67.6	67.9	27.6	24.9	25.3	25.3	25.0

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Table 11(cont.) Experiment Data: Test Order 11, Condition: Plastic cap, SV= 50 h^{-1}, Rate of spraying water = High

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
24/12/51	1	10.30	17.50	0.4	2.0	2.1	1.9	2.0	0.1	4.3	4.3	4.3	4.5	1.77	65.74	82.06	24.27	24.76		6.55
		17.45	24.75	0.3	2.0	2.0	2.1	2.1	0.2	4.6	4.5	4.5	4.5	5.91	62.62	83.53	25.93	26.61	spray	6.7
25/12/51	2	19.30	50.50	1.1	2.3	2.5	2.5	2.5	0.1	5.9	6.0	5.9	6.1	6.01	64.4	83.76	24.02	24.31	spray	6.79
26/12/51	3	10.00	65.00	0.8	2.4	2.4	2.4	2.4	0.1	6.1	6.2	6.4	6.1	6.01	73.78	82.38	22.97	23.04	spray	6.66
		16.30	71.50	0.9	2.5	2.5	2.4	2.4	0.1	7.6	7.3	7.9	7.3	5.96	82.5	88.94	22.56	22.11	spray	6.7
27/12/51	4	19.15	98.75	1.2	2.6	2.6	2.7	2.8	0.1	7.4	7.1	7.4	7.5	6.03	80.23	85.25	22.63	23	spray	6.66
28/12/51	5	18.30	122.00	0.6	2.4	2.4	2.3	2.3	0.2	5.8	5.8	5.8	5.7	5.95	70.57	81.05	24.29	24	spray	6.6
29/12/51	6	10.30	138.00	0.8	2.5	2.4	2.4	2.3	0.1	7.9	7.8	7.8	8.0	5.93	62.4	83.35	26.71	26.58	spray	6.68
		20.00	147.50	0.9	2.6	2.7	2.7	2.6	0.1	7.1	7.1	7.2	7.2	5.87	75.89	87.11	21.38	21.8	spray	6.63
30/12/51	7	9.15	160.75	1.0	2.6	2.6	2.6	2.6	0.1	6.9	6.8	7.1	7.0	5.92	75.8	84.2	22.24	22.88	spray	6.64
		14.45	166.25	0.4	2.4	2.0	2.1	2.5	0.2	6.1	5.4	5.6	8.3	5.89	49.64	80.66	27.86	28.3	spray	6.58
31/12/51	8	10.30	186.00	0.0	1.7	1.7	1.8	1.9	0.2	5.1	5.1	5.1	5.4	5.86	66.67	82.4	23.85	24.65	spray	6.65
		18.30	194.00	0.0	1.7	1.7	1.8	1.8	0.1	3.6	3.4	3.6	3.8	5.87	68.95	87.73	23.35	23.72	spray	6.62
1/1/52	9	15.45	215.25	0.0	1.7	1.5	1.4	1.4	0.1	8.1	7.4	7.1	6.9	5.94	50.31	78.62	28.67	29.44	spray	6.67
2/1/52	10	14.30	238.00	0.1	1.8	1.7	1.8	2.0	0.1	6.8	6.9	7.5	7.2	5.89	61.9	82.26	25.36	25.69	spray	6.66
3/1/52	11	13.15	260.75	0.1	2.0	1.8	1.8	1.7	0.1	6.7	5.9	5.8	5.9	5.82	60.24	83.7	25.48	25.71		6.77
		16.30	264.00	0.0	1.8	1.6	1.6	1.6	0.1	8.4	8.2	8.1	8.0	5.89	51.48	81.64	28.42	28.93	spray	6.68
4/1/52	12	10.45	282.25	0.0	1.9	1.6	1.6	1.5	0.2	7.9	5.7	5.5	5.6	5.85	63.88	83.4	25	24.94	spray	6.56

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Table 12 Experiment Data: Test Order 12, Condition: Ceramic, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
24/12/51	1	10.45	17.75	3365	3054	2908	2712	2216	73.7	72.7	72.3	73.2	73.6	25.8	24.0	23.7	23.4	22.2
		18.00	25.00	3525	3240	3206	2894	2398	73.5	71.5	71.2	71.5	72.3	25.9	23.8	23.9	23.4	22.2
25/12/51	2	19.45	50.75	3265	2910	2878	2674	2176	73.1	69.5	70.2	70.1	70.3	25.0	23.4	23.5	23.1	23.4
26/12/51	3	10.30	65.50	3467	2316	2608	2039	1500	73.5	70.2	69.4	70.0	70.9	25.5	23.8	23.6	23.8	22.8
		16.45	71.75	3112	1364	928	496	189	74.4	70.1	70.2	70.4	71.4	24.9	23.3	23.1	22.7	21.7
27/12/51	4	19.30	98.50	3218	1185	481	16	0	73.6	70.1	70.0	70.1	70.0	25.1	23.4	23.3	23.3	23.3
28/12/51	5	18.45	121.75	3151	983	368	34	0	73.3	67.2	68.1	69.2	70.7	25.9	23.1	23.4	23.2	22.1
29/12/51	6	10.45	137.75	2603	250	0	0	0	74.3	68.6	68.5	68.6	68.6	24.7	23.0	23.0	23.0	23.0
		20.30	147.50	2884	1046	507	108	0	73.2	69.1	69.1	69.3	70.4	25.8	23.8	23.7	23.5	22.2
30/12/51	7	9.45	160.75	2577	844	916	56	0	73.3	69.0	69.3	69.4	70.7	25.7	23.9	24.0	23.5	22.4
		15.00	166.00	2555	820	445	61	0	73.5	71.1	71.3	71.7	72.3	26.0	24.2	24.1	23.8	22.6
31/12/51	8	10.00	185.00	2564	859	433	199	34	73.5	72.0	71.9	72.2	72.5	26.4	24.7	24.7	24.6	23.8
		18.45	193.75	2891	422	319	32	0	72.6	71.1	70.6	71.4	71.8	27.1	25.0	24.8	25.1	25.3
1/1/52	9	16.00	215.00	2343	549	144	0	0	73.1	69.1	69.3	69.2	70.7	26.8	24.9	24.9	24.8	23.5
2/1/52	10	14.45	237.75	2330	783	317	9	0	72.5	68.6	68.7	69.9	70.0	27.2	25.3	25.4	25.1	23.8
3/1/52	11	13.15	260.25	2227	428	34	0	0	72.4	68.9	69.4	69.9	71.0	27.4	25.5	25.7	25.5	24.2
		16.45	263.75	2225	635	118	0	0	73.0	68.6	69.6	69.6	70.8	26.9	24.0	25.3	25.0	23.9
4/1/52	12	11.00	282.00	2333	919	359	2	0	72.3	70.0	70.6	70.8	71.8	27.6	26.0	26.2	26.1	24.6

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Table 12(cont.) Experiment Data: Test Order 12, Condition: Ceramic, SV= 10 h^{-1}, Rate of spraying water = High

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
24/12/51	1	10.45	17.75	0.4	1.5	1.7	1.4	1.6	0.1	2.8	2.3	2.0	2.6	5.46	67.68	80	24.01	24.7	spray	6.55
		18.00	25.00	0.4	1.7	1.8	1.9	2.2	0.2	3.0	3.1	3.2	3.3	5.95	59.32	79.62	26.34	25.64		6.7
25/12/51	2	19.45	50.75	1.8	2.6	2.3	2.3	2.5	0.1	4.5	4.0	4.5	3.8	6	66.17	87.22	23.32	23.93	spray	6.79
26/12/51	3	10.30	65.50	0.9	2.0	2.2	2.0	2.0	0.1	4.0	4.8	4.2	4.3	5.96	73.31	82.97	23.01	23.23	spray	6.66
		16.45	71.75	0.6	1.8	1.8	1.7	1.7	0.1	4.8	4.9	5.2	5.2	5.89	86.82	88.09	22.03	22.38	spray	6.7
27/12/51	4	19.30	98.50	1.2	2.0	2.1	2.1	2.2	0.1	4.5	4.6	4.5	4.5	5.92	79.12	81.33	22.79	22.4	spray	6.66
28/12/51	5	18.45	121.75	0.7	2.6	2.3	2.1	2.0	0.1	7.1	6.2	5.5	5.2	5.93	72.93	84.69	24.34	24.7	spray	6.6
29/12/51	6	10.45	137.75	0.8	2.0	2.0	2.0	1.9	0.2	6.4	6.5	6.4	6.5	5.92	62.41	79.83	25.6	26.12		6.68
		20.30	147.50	0.8	2.2	2.1	2.1	2.1	0.2	4.9	5.1	5.1	5.3	5.87	76.13	88.92	21.63	21.99	spray	6.63
30/12/51	7	9.45	160.75	0.8	2.2	2.0	2.2	1.9	0.2	4.9	4.7	5.9	5.0	5.89	75.38	85.73	21.94	22.97	spray	6.64
		15.00	166.00	0.4	1.6	1.6	1.5	1.5	0.1	2.1	3.0	3.0	3.6	5.87	48.74	83.76	28.24	28.29	spray	6.58
31/12/51	8	10.00	185.00	0.0	1.2	1.2	1.2	1.3	0.1	2.1	2.2	2.0	2.4	5.86	67.61	84.83	24.02	24.37	spray	6.65
		18.45	193.75	0.1	1.5	1.5	1.3	1.2	0.2	2.6	3.1	2.2	1.7	5.87	71.05	83	22.94	23.24		6.62
1/1/52	9	16.00	215.00	0.0	1.2	1.0	1.0	1.0	0.1	4.8	4.8	4.5	5.8	5.87	52.97	81.45	28.22	28.93	spray	6.67
2/1/52	10	14.45	237.75	0.2	1.4	1.2	1.2	1.2	0.1	4.7	4.7	4.8	5.0	5.88	60.89	84.4	25.71	26	spray	6.66
3/1/52	11	13.15	260.25	0.0	1.4	1.2	1.1	1.1	0.2	4.2	3.7	3.5	3.7	5.83	57.79	83.66	26.81	27.58	spray	6.77
		16.45	263.75	0.0	1.2	0.0	0.9	0.8	0.1	5.2	4.2	4.5	4.5	5.87	49.78	83.14	28.66	28.89	spray	6.68
4/1/52	12	11.00	282.00	0.0	1.1	0.9	0.9	0.8	0.1	2.9	2.3	2.2	2.8	5.99	62.15	86.75	25.46	25.55	spray	6.56

Table 13 Experiment Data: Test Order 13, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
24/12/51	1	11.15	18.25	3382	3271	3268	3232	3080	73.9	72.8	72.8	72.6	72.6	25.7	24.2	24.2	24.1	24.0
		18.15	25.25	3582	3373	3290	3205	3168	73.7	72.3	71.2	72.2	71.7	25.9	24.2	23.9	24.2	24.0
25/12/51	2	20.00	51.00	3313	3068	2757	2695	2587	73.4	68.5	69.1	68.6	68.3	25.3	23.3	23.2	23.3	23.2
26/12/51	3	10.45	65.75	3381	2043	1094	794	485	73.6	70.2	70.8	71.5	71.0	25.4	23.7	23.6	23.2	22.0
		17.00	72.00	3128	1679	642	283	90	74.3	70.4	70.6	70.9	71.7	25.0	23.4	23.2	22.9	21.6
27/12/51	4	19.45	98.75	3187	2001	1410	841	430	73.5	70.9	71.0	71.4	72.1	25.1	23.7	23.6	23.3	21.9
28/12/51	5	19.00	122.00	3049	1859	1491	898	665	73.3	71.3	70.5	70.7	71.0	26.0	24.3	24.1	24.2	24.2
29/12/51	6	11.15	138.25	2612	1049	393	0	253	74.3	68.9	68.8	68.8	69.0	24.9	22.9	23.0	23.0	23.1
		20.45	147.75	2875	2018	1687	1188	1011	73.2	69.7	69.8	70.2	70.3	25.8	24.1	24.2	24.2	24.2
30/12/51	7	10.00	161.00	2582	1525	879	440	860	73.4	69.6	69.6	69.8	69.8	25.7	24.0	24.1	24.1	24.0
		15.00	166.00	2543	1517	878	325	413	73.6	71.1	71.4	71.3	71.1	25.9	24.2	24.3	24.2	24.1
31/12/51	8	10.00	185.00	2577	1548	876	644	324	73.3	72.8	72.8	73.5	74.2	26.5	24.8	25.0	24.6	23.1
		18.45	193.75	2729	1522	915	425	143	72.6	73.1	73.0	73.1	73.8	27.3	25.6	25.5	25.3	24.1
1/1/52	9	16.15	215.25	2369	1042	280	27	0	73.1	69.2	69.7	70.9	71.0	26.8	25.9	25.1	24.8	23.2
2/1/52	10	15.15	238.25	2293	1070	508	75	0	72.7	68.7	68.5	68.6	70.7	27.2	25.3	25.3	24.7	23.5
3/1/52	11	13.30	260.50	2173	999	216	0	0	72.5	69.4	69.7	69.9	69.9	27.4	25.6	25.8	25.8	25.8
		17.00	264.00	2210	722	25	0	0	73.3	68.5	68.9	68.8	68.8	26.6	25.0	25.2	25.1	25.1
4/1/52	12	11.15	282.25	2258	1075	328	0	46	72.3	68.9	69.5	69.8	69.7	27.6	25.7	25.9	26.0	25.9

Table 13(cont.) Experiment Data: Test Order 13, Condition: Plastic cap, SV= 10 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
24/12/51	1	11.15	18.25	0.3	1.4	1.3	1.4	1.5	0.1	1.6	1.7	1.9	1.9	5.89	62.91	82.43	25.84	25.35		6.55
		18.15	25.25	0.3	1.5	1.8	1.6	1.7	0.1	2.0	3.1	2.0	2.6	6.04	62.78	72.36	25.06	25.58		6.7
25/12/51	2	20.00	51.00	1.2	2.3	2.3	2.4	2.5	0.1	5.9	5.4	5.7	6.0	6.01	65.63	85.47	23.31	23.9		6.79
26/12/51	3	10.45	65.75	0.8	2.0	1.9	1.8	1.8	0.2	4.1	3.7	3.5	4.2	5.95	75.56	84.42	22.96	23.12	spray	6.66
		17.00	72.00	0.6	1.7	1.6	1.6	1.6	0.1	4.5	4.6	4.6	5.1	5.91	87.1	89.08	22	22.01	spray	6.7
27/12/51	4	19.45	98.75	1.3	1.8	1.9	1.9	1.9	0.1	3.6	3.5	3.4	3.1	5.98	79.39	84.84	22.84	23.32	spray	6.66
28/12/51	5	19.00	122.00	0.5	1.7	1.8	1.8	1.7	0.2	2.7	3.6	3.3	3.1	5.94	72.32	83.54	24.33	24.53		6.6
29/12/51	6	11.15	138.25	0.7	2.0	2.0	1.9	1.8	0.1	6.2	6.2	6.3	6.1	5.93	60.77	79.53	26.32	27.09		6.68
		20.45	147.75	0.9	2.0	2.0	1.9	1.9	0.1	4.2	4.0	3.7	3.6	5.89	75.29	87.25	22.48	22.13		6.63
30/12/51	7	10.00	161.00	0.8	2.0	2.9	1.9	1.9	0.1	4.4	4.4	4.2	4.3	5.85	75.61	83.82	22.24	22.28		6.64
		15.00	166.00	0.4	1.5	1.5	1.5	1.5	0.1	3.2	2.8	3.0	3.3	5.84	50.07	82.39	27.76	28.41		6.58
31/12/51	8	10.00	185.00	0.0	1.3	1.1	1.0	1.1	0.2	1.1	0.9	0.9	1.5	5.83	67.93	79.26	23.71	23.24		6.65
		18.45	193.75	0.0	1.0	1.0	1.0	1.1	0.1	0.3	0.5	0.6	1.0	5.83	70.82	84.56	22.98	23.25	spray	6.62
1/1/52	9	16.15	215.25	0.0	1.1	1.0	0.9	0.9	0.1	4.8	4.2	4.4	5.9	5.85	52.79	81.59	28.22	28.71	spray	6.67
2/1/52	10	15.15	238.25	0.0	1.3	1.3	1.2	1.1	0.1	4.7	4.9	5.5	4.7	5.84	60.19	81.65	25.32	25.46	spray	6.66
3/1/52	11	13.30	260.50	0.0	1.2	1.0	0.9	0.9	0.1	3.8	3.5	3.4	3.4	5.84	55.06	80.86	27.53	28.04		6.77
		17.00	264.00	0.0	1.1	1.0	0.9	0.9	0.1	5.4	5.9	5.2	5.2	5.81	49.78	80.85	28.72	29.02	spray	6.68
4/1/52	12	11.15	282.25	0.0	1.3	1.0	0.9	0.9	0.1	4.1	3.6	3.3	3.5	5.99	61.81	82.93	24.99	26.02		6.56

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Table 14 Experiment Data: Test Order 14, Condition: Ceramic, SV= 50 h^{-1}, Rate of spraying water = High

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
26/1/52	1	10.00	19.00	1521	1363	1327	1262	1231	80.5	77.0	77.2	77.3	77.4	19.2	17.6	17.6	17.5	17.4
		16.00	25.00	1316	1018	1002	911	896	81.2	72.7	74.5	74.5	74.0	18.3	16.4	16.8	16.7	16.5
27/1/52	2	16.15	49.25	1311	575	265	150	141	80.6	68.4	63.5	62.9	63.8	18.5	16.1	15.2	14.9	15.0
28/1/52	3	10.30	67.50	1541	940	644	394	457	79.0	71.8	74.2	73.5	75.4	20.0	18.4	19.0	18.8	19.0
		16.45	73.75	1430	710	341	101	145	79.1	71.4	72.1	72.7	70.2	20.1	18.3	18.5	18.5	17.7
29/1/52	4	10.45	91.75	1569	926	737	501	567	78.1	73.2	75.4	75.3	75.8	21.3	19.7	20.2	19.8	19.8
		15.30	96.50	1593	858	490	198	308	78.7	73.4	73.5	73.3	73.5	21.0	19.2	19.3	19.1	19.0
30/1/52	5	14.00	119.00	1605	863	433	139	264	77.1	72.7	74.6	70.4	70.0	22.5	20.5	21.2	20.3	17.7
01/02/52	7	10.00	163.00	1571	433	84	0	17	64.5	53.5	55.7	55.7	57.7	20.7	17.5	18.3	18.6	18.4
2/2/52	8	14.45	191.75	1745	932	602	106	196	74.0	65.3	65.8	67.0	70.5	24.9	22.9	23.8	23.5	23.2

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
26/1/52	1	10.00	19.00	0.2	1.5	1.4	1.4	1.4	0.1	3.9	3.8	3.8	3.8	6.08	64.91	84.23	24.76	25.52	spray	6.66
		16.00	25.00	0.4	2.0	1.6	1.7	1.8	0.1	9.9	6.1	7.1	7.7	6.13	48.53	78.63	30.32	30.31		6.8
27/1/52	2	16.15	49.25	0.7	2.7	3.5	3.6	3.4	0.2	12.8	17.8	18.6	18.8	6.16	43.58	76.83	30.43	30.48	spray	6.73
28/1/52	3	10.30	67.50	0.8	2.1	1.7	1.8	1.4	0.2	7.7	5.1	5.9	4.2	6.11	63.51	80.74	24.77	26.12	spray	6.72
		16.45	73.75	0.7	2.1	2.0	1.8	2.3	0.1	8.2	7.4	6.0	9.8	6.11	47.63	78.11	28.22	28.92	spray	6.75
29/1/52	4	10.45	91.75	0.4	1.8	1.4	1.4	1.3	0.2	5.3	3.0	3.5	3.1	6.1	55.22	84.17	25.85	26.51	spray	6.79
		15.30	96.50	0.2	1.7	1.6	1.6	1.6	0.1	5.7	5.6	6.0	5.9	6.16	35.78	81.77	29.14	29.86	spray	6.74
30/1/52	5	14.00	119.00	0.2	1.9	1.6	1.2	1.4	0.2	5.9	2.6	8.1	10.9	5.99	42.15	84.77	30.39	31.35	spray	6.74
1/2/52	7	10.00	163.00	3.0	5.3	4.9	4.7	4.1	11.8	23.7	21.1	21.0	19.8	5.75	48.03	80.82	28.72	29.18	spray	6.76
2/2/52	8	14.45	191.75	0.9	2.3	1.7	1.7	1.8	0.2	8.5	10.7	7.8	4.5	5.98	48.84	83.64	29.9	30.52	spray	6.75

Table 15 Experiment Data: Test Order 15, Condition: Plastic cap, SV= 50 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
26/1/52	1	10.45	19.75	1574	1263	1299	1200	1158	80.6	74.6	76.6	75.5	75.7	19.1	17.1	17.4	17.2	17.3
		16.30	25.50	1410	1205	1171	1063	1010	79.8	74.1	75.2	75.3	75.6	18.0	16.8	17.0	17.0	16.9
27/1/52	2	16.45	49.75	1356	957	781	562	550	78.0	69.6	69.8	70.2	70.6	18.5	16.6	16.7	16.5	16.5
28/1/52	3	11.00	68.00	1505	1162	1109	1020	882	79.2	72.8	74.6	74.4	74.2	20.5	18.4	18.8	18.8	18.7
		17.15	74.25	1465	1043	933	792	600	79.3	70.9	72.3	72.4	72.3	20.2	18.1	18.4	18.4	18.3
29/1/52	4	11.15	92.25	1574	1196	1108	1041	880	78.5	73.1	74.1	74.1	74.2	21.3	19.3	19.6	19.5	19.3
		16.15	97.25	1397	1060	862	528	416	74.4	71.9	72.1	71.0	69.6	19.5	18.9	18.9	18.5	18.1
30/1/52	5	14.45	119.75	1428	876	595	334	103	76.8	67.2	66.2	64.1	63.0	21.0	18.6	18.4	17.8	17.4
1/2/52	7	10.30	163.50	1469	768	571	334	105	65.3	54.8	58.0	58.5	58.5	20.7	17.5	18.5	18.7	18.7
2/2/52	8	15.30	192.50	1622	1034	726	440	150	74.2	65.5	65.8	66.1	66.0	24.4	21.7	21.8	21.9	21.9

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
26/1/52	1	10.45	19.75	0.2	1.8	1.4	1.7	1.5	0.1	6.5	4.6	5.6	5.5	6.06	63.09	78.55	25.42	26.01	spray	6.66
		16.30	25.50	0.5	1.6	1.4	1.4	1.4	1.7	7.4	6.4	6.3	6.1	6.13	49.27	79.65	29.78	30.12	spray	6.8
27/1/52	2	16.45	49.75	0.7	2.4	2.3	2.2	2.2	2.8	11.4	11.2	11.1	10.7	6.13	45.03	80.67	29.48	29.92	spray	6.73
28/1/52	3	11.00	68.00	0.2	1.8	1.4	1.5	1.5	0.1	7.0	5.2	5.3	5.6	6.06	57.26	81.68	27.28	27.33		6.72
		17.15	74.25	0.4	2.0	1.7	1.7	1.7	0.1	9.0	7.6	7.5	7.7	6.11	46.41	62.61	28.46	28.59		6.75
29/1/52	4	11.15	92.25	0.1	1.6	1.4	1.4	1.4	0.1	6.0	5.9	5.0	5.1	6.03	50.68	82.58	26.1	26.95		6.79
		16.15	97.25	1.4	1.8	1.8	2.0	2.3	4.7	7.4	7.2	8.5	10.0	6.02	36.57	74.84	29.72	30.24	spray	6.74
30/1/52	5	14.45	119.75	0.8	2.4	2.6	3.0	3.2	1..4	11.8	12.8	15.1	16.4	5.95	38.75	82.62	31.23	31.55	spray	6.74
1/2/52	7	10.30	163.50	2.7	4.7	4.1	4.0	3.9	11.3	23.0	19.4	19.8	19.9	5.72	45.18	79.57	29.49	29.64	spray	6.76
2/2/52	8	15.30	192.50	0.7	2.4	2.2	2.3	2.2	0.7	10.4	10.2	9.7	9.9	5.88	45.94	81.79	31.02	31.53		6.75

Table 16 Experiment Data: Test Order 16, Condition: Ceramic, SV= 10 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	out	inlet	port1	port2	port3	out	inlet	port1	port2	port3	out
26/1/52	1	11.15	20.25	1481	607	587	531	234	80.9	73.5	74.7	74.8	75.6	18.8	16.5	16.9	16.8	16.6
		16.45	25.75	1493	72	0	0	0	81.3	70.9	71.5	71.6	72.1	18.4	16.2	16.2	16.2	16.0
27/1/52	2	17.00	50.00	1435	0	0	0	0	79.9	72.7	72.2	72.1	72.5	18.9	17.3	17.2	17.1	17.1
28/1/52	3	11.15	68.25	1516	0	0	0	0	79.3	74.0	73.2	73.4	73.8	20.3	18.6	18.5	18.5	18.6
		17.30	74.50	1468	0	0	0	0	79.1	72.3	70.8	70.9	71.8	19.9	18.4	18.0	18.0	18.3
29/1/52	4	11.30	92.50	1587	2	0	0	0	78.6	74.2	73.7	73.8	74.0	21.2	19.6	19.5	19.5	19.5
		16.30	97.50	1476	0	0	0	0	73.6	68.4	68.2	67.9	68.5	19.3	18.0	18.0	17.7	16.7
30/1/52	5	14.00	119.00	1247	0	0	0	0	68.6	60.5	60.8	61.5	62.4	18.9	17.1	17.0	16.8	15.8
1/2/52	7	10.45	163.75	1465	0	0	0	0	65.6	58.3	58.4	58.1	58.3	20.7	18.8	18.9	18.9	18.9
2/2/52	8	15.45	192.75	1646	0	0	0	0	74.5	66.3	67.0	67.0	69.1	24.5	22.1	22.0	21.6	19.5

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
26/1/52	1	11.15	20.25	0.1	1.9	1.6	1.6	1.5	0.2	7.1	6.8	6.8	6.3	6.03	58.66	82.53	27.07	27.84		6.66
		16.45	25.75	0.2	2.2	2.0	2.0	1.9	0.1	10.7	10.3	10.2	10.0	6.12	48.01	79.29	29.64	29.82		6.8
27/1/52	2	17.00	50.00	0.4	1.7	1.8	1.8	1.6	0.8	8.3	8.8	9.0	8.8	6.15	46.25	75.38	29.1	29.54		6.73
28/1/52	3	11.15	68.25	0.3	1.5	1.6	1.6	1.4	0.1	5.9	6.7	6.4	6.2	6.14	54.98	80.17	27.97	27.58		6.72
		17.30	74.50	0.4	1.7	2.0	2.8	1.7	0.6	7.6	9.2	9.3	8.2	6.13	47.72	79	28.71	29.03		6.75
29/1/52	4	11.30	92.50	0.1	1.3	1.3	1.4	1.2	0.1	4.9	5.5	5.3	5.3	6.06	50.01	79.76	27.27	27.52		6.79
		16.30	97.50	1.5	2.5	2.4	2.5	2.4	5.6	11.1	11.4	11.9	12.4	6.16	38.6	73.55	29.57	30.02	spray	6.74
30/1/52	5	14.00	119.00	2.3	3.6	3.6	3.4	3.3	10.2	18.8	18.6	18.3	18.5	5.99	37.18	78.93	30.88	31.38	spray	6.74
1/2/52	7	10.45	163.75	2.6	3.6	3.4	3.4	3.4	11.1	19.3	19.3	19.6	19.4	5.99	44.3	74.11	30.01	30.08		6.76
2/2/52	8	15.45	192.75	0.6	2.0	1.8	1.7	1.8	0.4	9.6	8.2	8.7	9.6	6.19	44.73	75.38	30.94	31.24	spray	6.75

Table 17 Experiment Data: Test Order 17, Condition: Plastic cap, SV= 40 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
12/3/2552	1	13.30	20.50	1544	1263	1156	1057	1048	74.6	57.2	58.4	56.3	59.3	23.8	17.5	17.0	16.9	16.8
13/3/2552	2	13.15	43.75	1394	1018	801	557	493	66.6	60.3	58.9	58.6	58.6	23.3	21.2	20.8	20.6	20.3
		19.30	50.00	1598	1140	923	723	717	67.3	60.2	60.4	60.6	60.7	23.5	21.3	21.2	21.0	21.0
14/3/2552	3	12.45	67.75	1465	944	751	523	562	67.3	59.9	59.9	59.8	59.9	23.8	21.5	21.4	21.0	21.0
		15.00	70.00	1445	935	723	536	551	66.1	61.3	61.3	60.4	60.4	22.9	21.4	21.4	20.8	21.0
15/3/2552	4	13.15	92.25	1407	898	658	441	425	67.0	59.7	59.7	60.2	60.2	24.7	22.6	22.5	22.4	22.3
16/3/2552	5	12.45	115.75	1458	703	556	292	330	67.1	59.7	60.0	60.6	60.4	26.5	24.2	24.2	24.0	24.1
17/3/2552	6	11.45	138.00	1642	735	395	105	96	66.5	58.4	59.8	60.0	60.1	28.0	24.0	25.4	25.1	25.1
18/3/2552	7	12.00	162.25	1635	909	444	184	177	67.7	61.1	61.4	61.7	61.7	28.3	25.8	25.0	25.6	25.5
		17.30	167.75	1656	830	449	169	168	68.1	59.5	61.4	61.8	61.9	28.4	25.3	25.9	25.7	25.7
19/3/2552	8	11.15	186.00	1609	835	225	0	0	69.3	62.2	61.9	62.2	62.3	28.6	26.2	26.1	25.9	25.8
20/3/2552	9	12.30	211.50	1562	502	112	0	0	67.7	60.7	60.7	60.7	60.8	27.8	25.3	25.3	25.3	25.1
21/3/2552	10	9.30	233.00	1619	769	361	0	0	68.2	61.5	61.1	60.9	60.7	28.9	26.5	26.4	25.9	25.9

Table 17 (cont.) Experiment Data: Test Order 17, Condition: Plastic cap, SV= 40 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
12/3/2552	1	13.30	20.50	1.0	2.4	2.4	2.4	2.5	0.6	22.9	22.2	25.1	21.6	6.17	38.5	81.89	31	34.41	spray	6.68
13/3/2552	2	13.15	43.75	0.9	2.3	2.5	2.6	2.6	9.2	16.2	17.8	18.2	18.5		42.65	72.76	32.87	33.28	spray	
		19.30	50.00	0.8	2.3	2.3	2.3	2.3	8.4	16.2	16.1	16.1	16.0		50.25	74.09	28.69	29.14	spray	
14/3/2552	3	12.45	67.75	0.8	2.3	2.3	2.5	2.4	8.1	16.3	16.4	16.7	16.7	6.02	54.41	84.96	28.84	29.13	spray	
		15.00	70.00	0.9	1.9	1.9	2.1	2.1	10.1	15.4	15.4	16.7	16.5		52.18	86.05	28.95	29.27	spray	
15/3/2552	4	13.15	92.25	1.0	2.5	2.6	2.4	2.4	7.3	15.1	15.2	15.0	15.1		41.64	76.21	29	30.47	spray	
16/3/2552	5	12.45	115.75	0.7	2.2	2.2	2.2	2.1	5.7	13.9	13.6	13.2	13.4		54.72	82.14	28.54	30.11	spray	
17/3/2552	6	11.45	138.00	0.2	2.9	1.5	1.5	1.5	5.3	15.7	13.3	13.4	13.3		53	81.3	32.41	32.76	spray	
18/3/2552	7	12.00	162.25	0.0	1.5	1.4	1.3	1.4	3.0	11.6	11.2	11.4	11.4		69.6	81.87	27.62	28.56	spray	
		17.30	167.75	0.0	1.8	1.4	1.4	1.3	3.5	13.4	11.3	11.1	10.1		69.52	81.83	27.29	27.8	spray	
19/3/2552	8	11.15	186.00	0.1	1.7	1.6	1.6	1.6	2.0	9.9	10.4	10.3	10.3		57.55	86.48	27.96	29.66	spray	
20/3/2552	9	12.30	211.50	0.1	1.6	1.6	1.6	1.6	4.4	12.4	12.4	12.4	12.5	5.83	45.57	82.78	34.07	34.47	spray	6.51
21/3/2552	10	9.30	233.00	0.2	1.8	1.7	1.7	1.8	2.7	10.2	10.8	11.5	11.6		67.81	80.95	27.11	27.51	spray	

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Table 18 Experiment Data: Test Order 18, Condition: Plastic cap, SV= 30 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
12/3/2552	1	13.45	20.75	1345	1131	1097	962	976	73.2	60.9	62.7	64.2	64.5	22.9	19.3	19.8	19.9	19.9
13/3/2552	2	13.30	44.50	1394	821	612	330	351	66.2	59.5	59.3	59.1	58.9	23.0	21.0	20.8	20.4	20.3
		19.45	50.75	1592	1006	790	458	475	67.2	59.8	59.7	60.0	59.8	23.5	21.1	21.0	20.7	20.6
14/3/2552	3	13.00	68.00	1453	804	602	357	256	67.0	59.4	59.5	59.7	59.3	23.7	21.3	21.2	21.1	21.2
		15.15	70.25	1413	695	562	327	211	67.2	60.2	60.0	60.0	60.1	23.8	21.6	21.6	21.4	21.3
15/3/2552	4	13.30	92.50	1336	676	439	135	152	66.1	57.1	57.2	57.2	57.2	24.4	21.4	21.5	21.0	21.0
16/3/2552	5	13.00	116.00	1435	671	332	0	0	66.7	61.1	60.1	59.9	59.7	26.3	24.5	24.1	23.6	23.4
17/3/2552	6	11.30	138.50	1681	437	279	0	0	66.7	55.5	58.3	58.9	59.1	28.1	23.9	24.0	24.7	24.8
18/3/2552	7	11.45	162.75	1619	695	487	31	41	67.6	58.7	60.1	60.8	60.9	28.3	25.1	25.5	25.3	25.2
		17.15	168.25	1644	670	476	0	19	67.8	58.6	60.4	60.8	61.0	28.3	24.9	25.6	25.1	25.2
19/3/2552	8	11.30	186.50	1557	621	255	0	0	69.1	61.6	61.5	61.5	61.7	28.3	26.1	26.1	25.5	25.4
20/3/2552	9	12.45	211.75	1534	568	175	0	0	67.7	61.2	61.1	61.3	61.5	27.8	25.5	25.4	25.0	24.9
21/3/2552	10	9.45	232.75	1617	609	163	0	0	68.0	59.9	59.7	60.0	60.0	29.0	26.0	25.9	25.5	25.4

Table 18(cont.) Experiment Data: Test Order 18, Condition: Plastic cap, SV= 30 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
12/3/2552	1	13.45	20.75	1.1	3.3	2.9	2.7	2.6	2.8	16.5	14.6	13.2	12.0	6.99	25.88	76.04	35.76	35.67	spray	6.68
13/3/2552	2	13.30	44.50	0.8	2.3	2.4	2.4	2.4	10.0	17.2	17.5	18.1	18.4		41.83	76.82	33.06	33.46	spray	
		19.45	50.75	0.8	2.4	2.4	2.4	2.4	8.5	16.7	16.9	16.9	17.2		50.89	80.5	28.5	28.95	spray	
14/3/2552	3	13.00	68.00	0.8	2.4	2.4	2.4	2.4	8.5	16.9	16.9	16.8	17.1	5.99	54.86	85.05	29.08	29.43	spray	
		15.15	70.25	0.9	2.4	2.4	2.4	2.4	8.1	15.8	16.0	16.2	16.2		53.88	82.18	28.71	29.51	spray	
15/3/2552	4	13.30	92.50	1.1	3.0	2.9	3.0	3.0	8.4	18.5	18.4	18.8	18.8		41.26	79.44	30.23	30.82	spray	
16/3/2552	5	13.00	116.00	0.7	2.9	2.1	2.2	2.2	6.3	12.5	13.7	14.3	14.7		51.38	80.9	29.76	30.81	spray	
17/3/2552	6	11.30	138.50	0.3	2.6	2.9	1.8	1.8	4.9	18.0	14.8	14.6	14.3		53.68	82.01	31.78	32.42	spray	
18/3/2552	7	11.45	162.75	0.1	2.0	1.7	1.6	1.5	3.0	14.2	12.7	12.3	12.4		69.74	82.32	27.72	27.88	spray	
		17.15	168.25	0.1	2.0	1.6	1.6	1.3	4.8	14.5	12.4	12.5	12.5		68.17	82.02	27.1	27.88	spray	
19/3/2552	8	11.30	186.50	0.2	1.8	1.8	1.8	1.7	2.4	10.5	10.6	11.2	11.2		54.4	84.42	29.06	30.11	spray	
20/3/2552	9	12.45	211.75	0.2	1.5	1.5	1.5	1.5	4.3	11.8	12.0	12.2	12.1	5.87	46.38	82.28	33.49	34.26	spray	6.51
21/3/2552	10	9.45	232.75	0.2	1.9	1.8	1.8	1.8	2.8	12.2	12.6	12.7	12.8		66.54	82.07	27.7	28.52	spray	

Table 19 Experiment Data: Test Order 19, Condition: Plastic cap, SV= 20 h^{-1}, Rate of spraying water = Low

date	day	time	hour	H_2S (ppm)					CH_4 (%)					CO_2 (%)				
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet
12/3/2552	1	14.15	21.25	1343	1020	449	490	523	72.1	65.7	57.4	62.4	64.7	22.5	20.4	16.4	17.7	18.2
13/3/2552	2	13.45	44.75	1397	655	435	157	74	66.0	60.3	60.3	61.0	61.2	22.9	20.7	20.6	19.8	19.3
		20.00	51.00	1565	762	475	118	137	67.2	61.3	61.4	61.0	62.0	23.5	21.3	21.1	19.9	20.0
14/3/2552	3	13.15	68.25	1440	748	385	148	14	67.1	60.9	61.1	61.5	61.8	23.6	21.7	21.5	21.0	20.3
		15.30	70.50	1418	652	379	124	0	67.1	60.6	60.9	61.5	61.2	23.8	21.7	21.5	20.3	20.3
15/3/2552	4	13.45	92.75	1333	493	127	0	0	65.7	59.6	59.8	60.3	60.2	24.3	22.1	21.8	21.4	21.3
16/3/2552	5	13.15	116.25	1410	662	152	0	0	66.8	60.2	60.2	60.3	60.4	26.3	24.1	24.0	23.8	23.7
17/3/2552	6	11.15	138.25	1556	439	116	0	0	66.3	55.5	58.6	59.8	60.1	28.0	23.9	24.8	25.2	25.2
18/3/2552	7	11.30	162.50	1639	554	255	2	0	67.5	57.7	60.2	61.1	61.4	28.4	24.7	25.7	25.0	25.8
		17.00	168.00	1654	720	313	0	0	67.5	60.4	61.4	61.4	61.7	28.2	25.6	26.0	25.9	25.7
19/3/2552	8	11.45	186.75	1520	294	0	0	0	69.2	60.6	60.6	60.6	60.7	28.4	25.2	25.3	25.2	25.0
20/3/2552	9	13.00	212.00	1522	0	0	0	0	67.7	57.8	57.8	58.6	59.1	27.8	24.1	24.0	24.2	24.1
21/3/2552	10	9.50	232.83	1616	173	0	0	0	68.0	60.1	60.0	60.1	60.2	28.9	26.1	26.0	25.8	25.6

Table 19(cont.) Experiment Data: Test Order 19, Condition: Plastic cap, SV= 20 h^{-1}, Rate of spraying water = Low

date	day	time	hour	O_2 (%)					Bal (%)					pH	Rh%		Temp		water spray	pH spray
				inlet	port1	port2	port3	outlet	inlet	port1	port2	port3	outlet		outer	inner	outer	inner		
12/3/2552	1	14.15	21.25	1.0	2.4	4.1	3.1	2.6	4.4	11.5	23.1	17.8	14.5	6.5	28.51	70.09	36	36.16	spray	6.68
13/3/2552	2	13.45	44.75	0.9	2.0	2.0	2.1	2.0	10.2	17.0	17.1	17.1	17.5		42.8	71.44	33.16	3.42	spray	
		20.00	51.00	0.8	2.1	2.1	2.1	2.1	8.5	15.3	15.4	16.0	15.9		53.28	86.62	28.33	29.31	spray	
14/3/2552	3	13.15	68.25	0.8	2.1	2.1	2.1	2.1	8.5	15.3	15.3	15.4	15.8	6.24	53.84	82.59	29.74	30	spray	
		15.30	70.50	0.9	2.2	2.3	2.2	2.3	8.2	15.5	15.3	16.0	16.2		54.34	86.44	29.24	29.97	spray	
15/3/2552	4	13.45	92.75	1.2	2.4	2.4	2.2	2.3	8.8	15.9	16.0	16.1	16.2		38.69	81.6	30.6	31.26	spray	
16/3/2552	5	13.15	116.25	0.6	2.1	2.1	2.0	2.0	6.3	13.6	13.7	13.9	13.9		48.42	82.39	30.73	31.66	spray	
17/3/2552	6	11.15	138.25	0.2	2.5	1.8	1.6	1.5	5.5	18.1	14.8	13.4	13.2		53.59	84.25	31.28	31.97	spray	
18/3/2552	7	11.30	162.50	0.1	2.2	1.7	1.4	1.4	3.0	15.4	12.4	11.5	11.4		70.72	85.75	27.48	27.84	spray	
		17.00	168.00	0.1	1.6	1.4	1.4	1.3	4.2	12.4	11.2	11.3	11.3		67.26	83.32	27.44	27.87	spray	
19/3/2552	8	11.45	186.75	0.2	1.9	1.8	1.8	1.8	2.2	12.3	12.3	12.4	12.5		55.03	83.55	29.82	31.17	spray	
20/3/2552	9	13.00	212.00	0.1	2.2	2.2	1.9	1.9	4.4	15.9	16.0	15.3	14.9	5.8	42.34	80.86	34.29	34.52	spray	6.51
21/3/2552	10	9.50	232.83	0.1	1.8	1.7	1.7	1.7	3.0	12.0	12.3	12.4	12.5		64.43	82.65	28.42	29.16	spray	

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Table 20 Mass balance of sulfur

Test Order	Packing material	SV (h^{-1})	Flow rate (L/min)	Rate of water spraying	%RE	volume water (L)	conc.H_2S RE (ppm)	conc.H_2S RE (mg/l)	SO_4^{2-} (mg/l)	SO_3^{2-} (mg/l)
1	Ceramic	50	3.275	High	61.34	2.38	1436	2.183	89.51	1.75
2	Plastic	10	0.655	High	100	2.44	2430	3.695	38.96	0.5
3	Plastic	50	3.275	Low	33.48	2.09	1358	2.065	114.42	0.62
4	Ceramic	50	3.275	Low	31.33	1.82	1301	1.978	101	1
5	Plastic	10	0.655	Low	91.76	1.78	3788	5.760	90.25	0.5
6	Ceramic	10	0.655	Low	84.6	1.185	3076	4.677	110.5	0.62
7	Plastic	10	0.655	High	80.99	1.155	2888	4.391	152.44	0.62
8	Plastic	50	3.275	High	37.91	0.975	1351	2.054	114.02	0.75
9	Ceramic	10	0.655	High	100	1.155	3535	5.375	144.79	0.5
10	Ceramic	50	3.275	Low	39.78	2.43	967	1.470	105.03	0.62
11	Plastic	50	3.275	High	73.49	2.41	1738	2.643	11.39	0.25
12	Ceramic	10	0.655	High	100	2.11	2333	3.547	94.67	0.87
13	Plastic	10	0.655	Low	97.96	2.23	2212	3.363	133.05	0.62
14	Ceramic	50	3.275	High	88.77	2.37	1549	2.355	145.28	0.75
15	Plastic	50	3.275	Low	90.75	2.09	1472	2.238	185.75	0.75
16	Ceramic	10	0.655	Low	100	2.32	1646	2.503	66.67	0.62
17	Plastic	40	2.62	Low	95.53	2.34	1619	2.462	17.42	0.62
18	Plastic	30	1.97	Low	99.47	2.3	1617	2.459	8.61	0.37
19	Plastic	20	1.31	Low	100	1.5	1616	2.457	99.55	1.12

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