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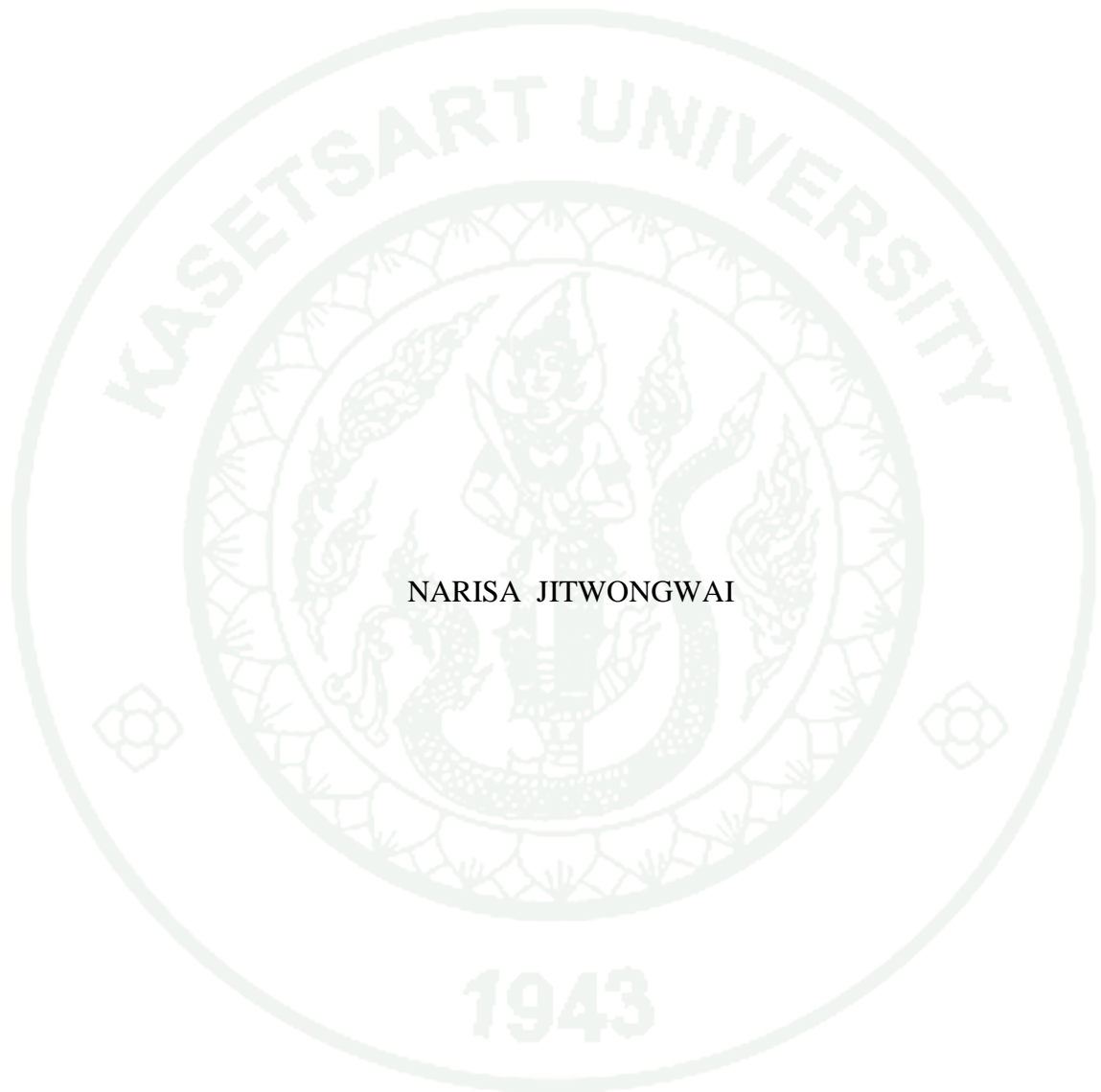
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THESIS

USE OF COMBUSTION EXHAUST GAS FOR DISINFECTION OF
WASTEWATER TREATMENT PLANT EFFLUENT



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High pressure CO₂ disinfection was found to effectively inactivate many types of pathogens. Supercritical CO₂ was developed for water disinfection. The objectives of this study are to investigate the inactivation effectiveness on fecal coliform by using CO₂ produced from fuel combustion at various pressures in the range of 0.1-0.4 mega-pascals (MPa) with varying contact time from 5 to 25 minutes, and to compare the results with similar study using ambient air at the same pressure and detention time. In order to ensure the validity for effectiveness of the CO₂ produced from fuel combustion, the inactivation effectiveness on heterotrophic bacteria was investigated. The obtained results reveal that inactivation of microorganisms caused by high-pressure air is significantly lower than the inactivation caused by high-pressure exhaust gas at every operating pressure. It is believed that CO₂ in the exhaust gas plays an important role on the inactivation performance because CO₂ has much higher solubility compared with oxygen in the ambient air. Thus, the exhaust gas at sufficiently high pressure can be used to inactivate microorganisms in wastewater effluent.

Student's signature

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LIST OF ABBREVIATIONS

DBPs	=	Disinfection by-products
THMs	=	Trihalomethanes
HAAs	=	Haloacetic acids
UV	=	Ultraviolet
HPCD	=	High pressure carbon dioxide disinfection
CO ₂	=	Carbon dioxide
T _C	=	Temperature critical
P _C	=	Pressure critical
MPA	=	Mega Pascal
<i>E. coli</i>	=	Escherichia coli.
%	=	Present
H ₂ O	=	Water
°C	=	Degree Celsius
Ca(OCl) ₂	=	Hypochlorite
NaOCl	=	Sodium hypochlorite
O ₃	=	Ozone
HO ₂	=	Hydrogen peroxy
OH	=	Hydroxyl
H ₂ CO ₃	=	Carbonic acid
HCO ₃ ⁻	=	Bicarbonate ions
CO ₃ ²⁻	=	Carbonate ions
O ₂	=	Oxygen
CH ₄	=	Methane
CO	=	carbon monoxide
C	=	Carbon
TS	=	Total Solid
SS	=	Suspended Solid

USE OF COMBUSTION EXHAUST GAS FOR DISINFECTION OF WASTEWATER TREATMENT PLANT EFFLUENT

INTRODUCTION

Disinfection of drinking water and wastewater is critical to the protection of public health. All water and wastewater systems should use some form of disinfection process to remove or inactivate microorganisms that can cause disease in humans. Several techniques have been used for disinfection. Among them, chlorination has been widely used due to its effectiveness and low cost. However, it is found that some disinfection by-products (DBPs) occur as chlorine reacts with organic matters in water and wastewater (Mosteo *et al.*, 2009). Some DBPs such as Trihalomethanes (THMs) and haloacetic acids (HAAs) are carcinogenic (Hong, Song and Karanfil, 2013). Some microorganisms have been reported to be chlorine resistant, such as *Cryptosporidium* (Kristen *et al.*, 2000) and *Giardia* (Lywryshyn and Cairing, 2003). Ozone is more effective than chlorine in destroying viruses and bacteria but some by-products are also formed in ozonation (Cho *et al.*, 2010). Ozone reacts with bromide ions in water to produce suspected carcinogen bromate (Wang *et al.*, 2014). Moreover, ozonation requires equipment and efficient contacting system. Ultraviolet (UV) disinfection is effective at inactivating microorganisms (Hijnen *et al.*, 2006). UV disinfection effectiveness decreases as turbidity, so it requires pre-filtration to control turbidity (Brahmi *et al.*, 2010). UV treatment requires materials that may not be easily acquired or purchased in developing countries. Solar water disinfection has been reported inactivating microorganisms and without any danger of bacterial re-growth if the disinfected water is properly stored for one week, it is an alternative option for small quantity of drinking water at household level (Bichai *et al.*, 2012). The membrane filtration process does not produce DBPs, but it is a complicated disinfection process and quite expensive.

High pressure CO₂ disinfection (HPCD) was found to effectively inactivate many types of pathogens. HPCD is used as an alternative non-thermal pasteurization technique for food. Using CO₂ as a sterile has several benefits, e.g. CO₂ is not flammable and non-toxic. In the HPCD technique, food will contact with supercritical CO₂ for certain period in a batch process. Supercritical CO₂ is CO₂ at temperature and pressure above the critical point values ($T_c = 31.1$ °C. and $P_c = 7.38$ MPA) and exists as a single phase (Garcia-Gonzalez *et al.*, 2007). Ishikawa *et al.* (1995) developed a semi-continuous system using the filter to increase concentration of dissolved CO₂, they used the filter increased the concentration of dissolved CO₂ and very effective in inactivating microorganisms. The Supercritical CO₂ was developed for water disinfection and it was reported that this method could kill all fecal coliforms in 13 minutes at 10 MPA (Kobayashi *et al.*, 2009). This is a new finding in water disinfection. However, the high pressure was a handicap. Cheng *et al.* (2011) used high levels of dissolved CO₂ at lower pressure of 0.3-0.6 MPA and found that effective inactivation on *E. coli* and bacteriophage T4 could occur by using low and medium initial dissolved CO₂ concentrations under 0.3 MPa in 20-minute detention time.

In order to reduce the disinfection cost, the use of combustion exhaust gas which contains about 5% of CO₂ by volume is considered in this study. This process will be applied to disinfect wastewater treatment plant effluent which contains large amount of coliform bacteria.

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OBJECTIVES

The main objectives of this study are

1. Investigate the inactivation effectiveness on fecal coliform by using CO₂ produced from fuel combustion at various pressures in the range of 0.1-0.4 mega-pascal (MPA) with varying contact time from 5 to 25 minutes under with circulation and without circulation and varying CO₂ content in the range of 5-10 % by volume.
2. Investigate the inactivation effectiveness on heterotrophic bacteria by using CO₂ produced from fuel combustion at various pressures in the range of 0.1-0.4 mega-pascal (MPA) with varying contact time from 5 to 25 minutes under with circulation and without circulation and varying CO₂ content in the range of 5-10 % by volume.
3. Conduct similar study using ambient air at the same pressure and contact time. Compare the results of these two experiments.

LITERATURE REVIEW

1. Disinfection

Disinfection is considered to be the primary mechanism for the inactivation and destruction of pathogenic organisms to prevent the spread of waterborne diseases to downstream users and the environment. It is important that wastewater be adequately treated prior to disinfection in order for any disinfectant to be effective. Table 1 lists some common microorganisms found in domestic wastewater and the diseases associated with them.

Table 1 Infectious agents potentially present in untreated domestic wastewater

Organism	Disease Caused
1. Bacteria	
- <i>Escherichia coli</i> (<i>enterotoxigenic</i>)	Gastroenteritis
- <i>Leptospira</i> (spp.)	Leptospirosis
- <i>Salmonella typhi</i>	Typhoid fever
- <i>Salmonella</i> (=2,100 serotypes)	Salmonellosis
- <i>Shigella</i> (4 spp.)	Shigellosis (bacillary dysentery)
- <i>Vibrio cholerae</i>	Cholera
2. Protozoa	
- <i>Balantidium coli</i>	Balantidiasis
- <i>Cryptosporidium parvum</i>	Cryptosporidiosis
- <i>Entamoeba histolytica</i>	Amebiasis (amoebic dysentery)
- <i>Giardia lamblia</i>	Giardiasis
3. Helminths	
- <i>Ascaris lumbricoides</i>	Ascariasis
- <i>T. solium</i>	Taeniasis

Table 1 Infectious agents potentially present in untreated domestic wastewater
(Continued)

Organism	Disease Caused
4. Viruses	
- Enteroviruses (72 types, e.g., polio, echo, and coxsackie viruses)	Gastroenteritis, heart anomalies, meningitis
- Hepatitis A virus	Infectious hepatitis
- Norwalk agent	Gastroenteritis

Source: EPA (1999)

Disinfection can be achieved by any method that destroys pathogens. There are many categories.

1.1 Chlorination

Chlorination has received wide application in water and wastewater. It is used for many applications including disinfection, taste and odor control, and color removal. The most common chlorine compounds used in water and wastewater treatment plants are chlorine (Cl_2), calcium hypochlorite [$\text{Ca}(\text{OCl})_2$], sodium hypochlorite (NaOCl), and chlorine dioxide (ClO_2). Selection of these compounds depends on the size of the treatment facility, objective, economics, and safety considerations.

When chlorine is used to control microbial contaminants in drinking water, it reacts with naturally occurring organic and inorganic matter in water such as decomposing plant and animal materials. It is found that some disinfection by-products (DBPs) such as trihalomethanes (THM) and haloacetic acids (HAA₅).

THM is a group of four chemical are chloroform, bromodichloromethane, dibromochloromethane, and bromoform. THM can cause human carcinogens, table 2 shows probability of cancer for varying exposure levels.

Table 2 Probability of cancer for varying exposure levels

Compound	Cancer Potency Factor
Chloroform	0.0061 mg/kg/day
Bromodichloromethane	0.062 mg/kg/day
Dibromochloromethane	0 mg/kg/day (not cancerous)
Bromoform	0.0079 mg/kg/day

Source: USEPA (2003)

Bromodichloromethane has the highest factor, whereas chloroform and bromoform an order of magnitude lower, and dibromochloromethane considered not cancerous. EPA has concluded that there is evidence to support a potential association between long term exposure to high levels of THMs and bladder cancer as well as suggestions of an association with colon and rectal cancers.

HAA₅ is a group of chemical is monochloroacetic acid, dichloroacetic acid trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid. HAA₅ group has also been related to an increase in the risk of cancer. The parts easily affected by over exposure to haloacetic acids are the kidney, liver and nervous system. HAAs can be removed by adsorption with an activated carbon filter.

Changing the disinfection process to ozonation can be very effective in reducing HAAs, but it is fairly expensive and there is a problem with bromated formation in high bromide containing waters. Switching to UV disinfection eliminates all HAA formation and is less expensive than ozonation. A disinfectant residual using chloramines or free chlorine still needs to be provided in the distribution system for

both ozone and UV treatment. Use of chlorine dioxide, a strong oxidant, does not produce significant HAAs, but will produce some amount of chlorite, which is a no the regulated DBP.

The disinfection efficiency of chlorine depends on contact time, chlorine dosage, temperature, pH, nature of liquid and suspended matter and type and number of organism, table 3 shows total coliform remaining in the effluent.

Table 3 Total coliform remaining in the effluent.

Total chlorine residual (mg/l)	Total coliform (Numbers/100 ml)	
	Primary Effluent	Secondary Effluent
0.5-1.5	24,000-400,000	1,000-12,000
1.5-2.5	6,000-24,000	200-1,000
2.5-3.5	2,000-6,000	60-200
3.5-4.5	1,000-2,000	30-60

Source: Syed R.qasim (1994)

For disinfection of wastewater a chlorine residual of 0.5 mg/l after 20-30 min of contact period is required. The effluent quality to be disinfected must be evaluated for chemical dosage and contact periods. Organic matter will also reduce effectiveness by adsorption and by protecting entrapped organisms.

1.2 Ozone disinfection

Ozone is produced when oxygen (O_2) molecules are dissociated by an energy source into oxygen atoms and subsequently collide with an oxygen molecule to form an unstable gas, ozone (O_3), which is used to disinfect wastewater. Most wastewater treatment plants generate ozone by imposing a high voltage alternating current (6 to 20 kilovolts) across a dielectric discharge gap that contains an oxygen-

bearing gas. Ozone is generated onsite because it is unstable and decomposes to elemental oxygen in a short amount of time after generation. When ozone decomposes in water, the free radicals hydrogen peroxy (HO_2) and hydroxyl (OH) that are formed have great oxidizing capacity and play an active role in the disinfection process. It is generally believed that the bacteria are destroyed because of protoplasmic oxidation resulting in cell wall disintegration. The key process control parameters are dose, mixing, and contact time. An ozone disinfection system strives for the maximum solubility of ozone in wastewater, as disinfection depends on the transfer of ozone to the wastewater. The amount of ozone that will dissolve in wastewater at a constant temperature is a function of the partial pressure of the gaseous ozone above the water or in the gas feed stream.

Ozone disinfection is generally used at medium to large sized plants after at least secondary treatment. In addition to disinfection, another common use for ozone in wastewater treatment is odor control. Ozone treatment has the ability to achieve higher levels of disinfection than either chlorine or UV, however, the capital costs as well as maintenance expenditures are not competitive with available alternatives. Ozone is therefore used only sparingly, primarily in special cases where alternatives are not effective. The cost of ozone disinfection systems is dependent on the manufacturer, the site, the capacity of the plant, and the characteristics of the wastewater to be disinfected. Ozonation costs are generally high in comparison with other disinfection techniques.

When ozone used to disinfect drinking water reacts with naturally occurring bromide found in source water, it is found bromate. Bromate is an inorganic ion which is tasteless, colorless and has a low volatility. Bromate dissolves easily in water and is fairly stable. Bromate can cause the cancer, in cases of human poisoning from bromate are due to the accidental or intentional ingestion of home permanent wave solutions, which usually contain either 2% potassium bromate or 10% sodium bromate. In children, serious poisonings have been reported following ingestion of 60–120 ml of 2% potassium bromate (WHO, 2005)

Ozone is effectiveness to inactivation many microorganisms. Ozone can participate in electrophilic reactions, particularly with aromatic compounds, and in nucleophilic reactions with many of the components of the microbial cell. Microbs become inactivated through ozone acting on the cytoplasmic membrane, the protein structure of a virus capsid, or nucleic acids of microorganisms.

1.3 Ultraviolet disinfection

Ultraviolet (UV) disinfection system transfers electromagnetic energy from a mercury arc lamp to an organism's genetic material (DNA and RNA). When UV radiation penetrates the cell wall of an organism, it destroys the cell's ability to reproduce. UV radiation, generated by an electrical discharge through mercury vapor, penetrates the genetic material of microorganisms and retards their ability to reproduce. The main components of a UV disinfection system are mercury arc lamps, a reactor, and ballasts. The source of UV radiation is either the low-pressure or Medium-pressure mercury is lamp with low or high intensities.

The optimum wavelength to effectively inactivate microorganisms is in the range of 250 to 270 nm. The intensity of the radiation emitted by the lamp dissipates as the distance from the lamp increases. Low-pressure lamps emit essentially monochromatic light at a wavelength of 253.7 nm. Standard lengths of the low-pressure lamps are 0.75 and 1.5 meters with diameters of 1.5 - 2.0 cm. The ideal lamp wall temperature is between 95 and 122°F.

Medium-pressure lamps are generally used for large facilities. They have approximately 15 to 20 times the germicidal UV intensity of low-pressure lamps. The medium-pressure lamp disinfects faster and has greater penetration capability because of its higher intensity. However, these lamps operate at higher temperatures with higher energy consumption.

The degree of inactivation by ultraviolet radiation is directly related to the UV dose applied to the water. Doses of 35 and 62J/m² were required for a 1-log inactivation of *Escherichia coli* (*E. coli*) in the primary and secondary wastewaters, respectively (Taghipour, 2004).

1.4 Solar disinfection (SODIS)

Solar disinfection is a simple water treatment method using solar radiation to destroy pathogenic bacteria and viruses present in the water. Solar water disinfection can convert the sun energy into heat to increase the water temperature for pasteurization or distillation, or it can use directly the germicide effect of UV radiation or a combination of both. Main solar technologies include solar distillation, solar pasteurization and the SODIS method with plastic bottles. Solar distillation is based on water evaporation and condensation, but the efficiency is very low as it requires higher solar energy doses for longer periods of time to treat the water than those of any of the other solar technologies. If the water is not evaporated but the temperature increase is only to about 70 °C, then it reaches pasteurization temperature (Vivar, Fuentes, García-Pacheco, & de Bustamante, 2013). These systems consist of containers or plastic bottles that are fully black-painted and then exposed to the sun, waiting for the water temperature to reach 70°C. Simple reflectors made with aluminum foils or metallic materials are often used to accelerate the process.

The effects of solar radiation which are believed to contribute to the inactivation of pathogenic organisms are Ultraviolet-A radiation causes damage to DNA and kills living cells, UV-A (wavelength 320-400nm) reacts with oxygen dissolved in the water and produces highly reactive forms of oxygen (oxygen free radicals and hydrogen peroxides), that are believed to also damage pathogens and infrared radiation heats the water and causes pasteurization when the temperature is raised to 70-75 °C. If the water temperatures rise above 50°C, the disinfection process is three times faster.

Waterborne pathogenic bacteria have been found to be readily amenable to solar disinfection following 6 h under suitable field conditions, figure shows inactivation kinetics of microbial populations exposed to real sunlight conditions expressed in units of log reduction. Unless otherwise stated, stationary phase bacterial suspensions were used.

Fecal coliforms have shown much slower inactivation rates in some cases while light-resistant sub-populations of cultured *E. coli* were found to be inactivated considerably more slowly than light-sensitive organisms in other trials.

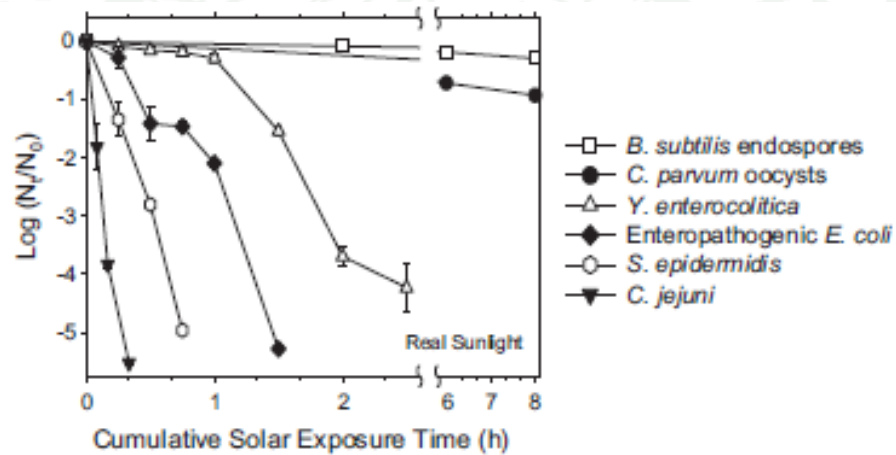


Figure 1 Inactivation kinetics of microbial populations exposed to real sunlight conditions expressed in units of log reduction.

Source : McGuigan *et al* (2012)

1.5 Membrane bioreactors (MBRs) disinfection

Membrane bioreactor (MBR) is the combination of a membrane-based filtration process like microfiltration or ultra-filtration systems with a suspended growth biological reactor. Essentially, the membrane system replaces the solids separation function of the secondary clarifiers in conventional activated sludge systems. The MBR technology combines the unit operations of aeration, secondary

clarification, and filtration into a single process, producing a high quality effluent, suitable for any discharge and most reuse or recycle applications, while greatly reducing space requirements and under stringent norms.

Regarding decontamination, filtration removes very efficiently micro-organism greater than the size of the membrane pores such as bacteria and protozoa, but its efficiency in removing viruses depends on many factors. The pore size of the membranes used, typically ranging from 0.04 to 0.4 μm , means that they are able to remove a wide range of microorganisms by size exclusion (Marti *et al.*, 2011). There are broadly four categories of membrane types, with classification being dependent on the pore size of the membrane. These categories, from smallest to largest pore size, are reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF), figure 2 shows categories of membrane separation processes.

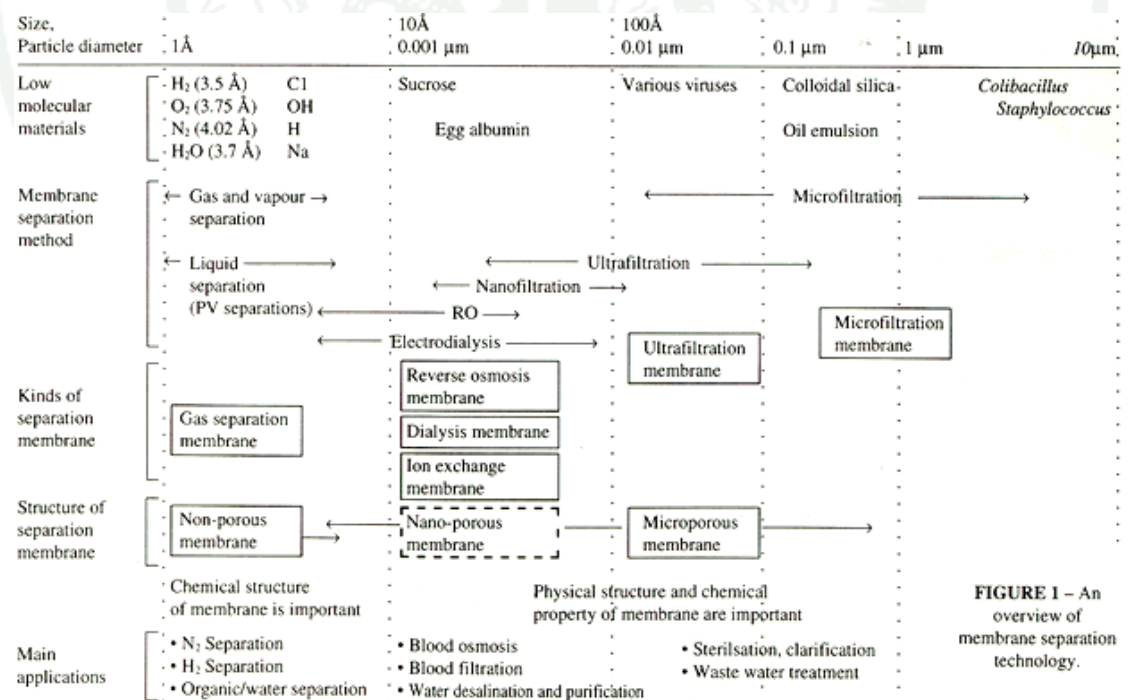


FIGURE 1 – An overview of membrane separation technology.

Figure 2 Categories of membrane separation processes.

The effect of increasing the pore size of the membrane has a marked effect on the performance of the membrane and the quality of the filtered effluent, figure 3 shows Pressure driven separation processes of membrane.

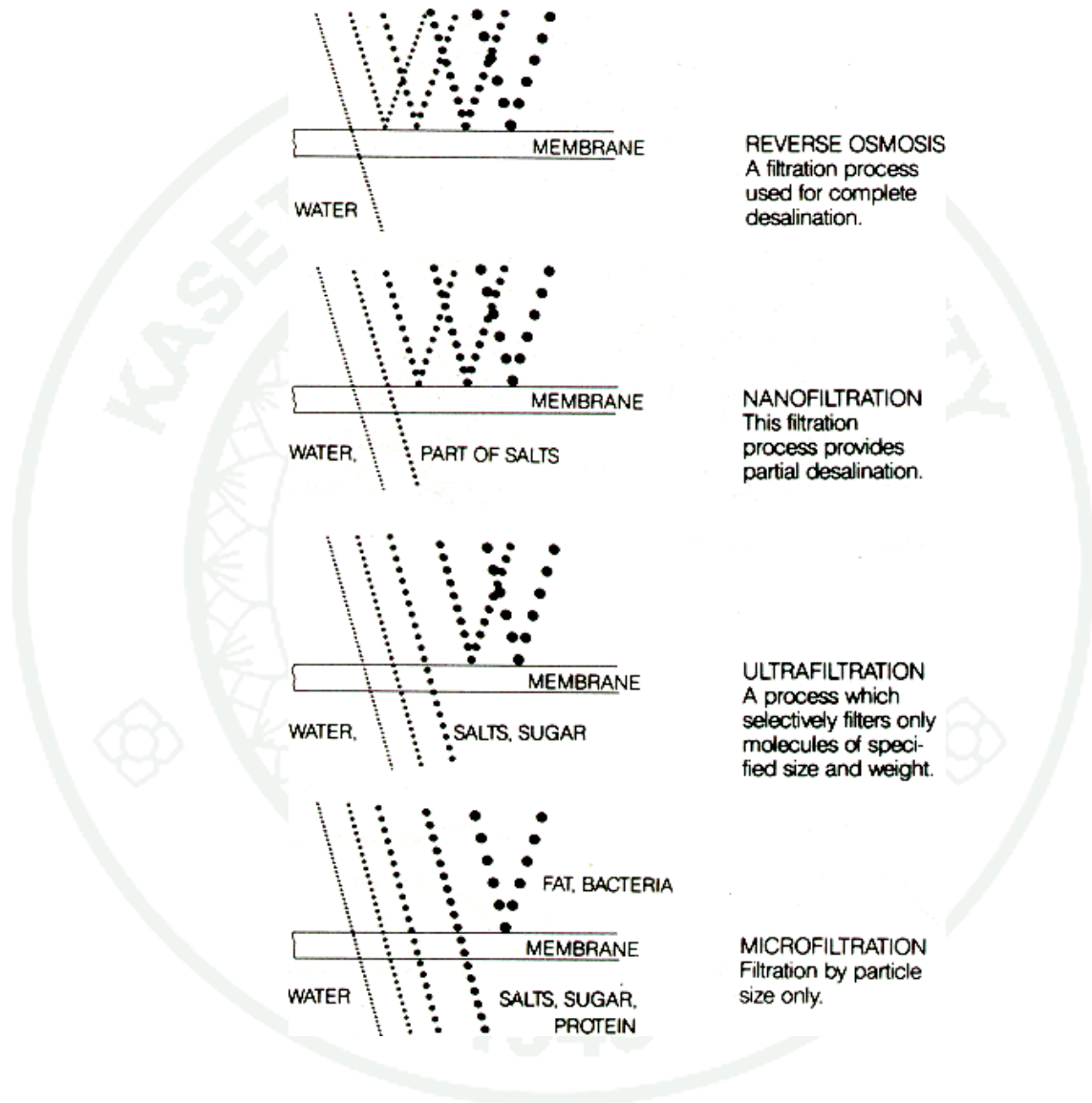


Figure 3 Pressure driven separation processes.

Membranes will essentially reject particulate matter, while RO membranes are capable of rejecting macromolecular fractions, such as dissolved salts. One of the main features of MBR technology is the ability of the membrane to remove pathogenic organisms. The membrane offers a physical barrier to the

organisms that is unaffected by the influent quality. Reductions in bacteria and viruses have been reported (Francy *et al.*, 2012) as show in table 4

Table 4 Reduction in microorganisms using different membrane systems.

Membrane System	Microorganisms	Median log removal
Secondary	<i>E. coli</i> (CFU/L)	3.04
	Fecal coliforms (CFU/L)	2.89
	Enterovirus (gc/L)	1.53
	Norovirus GI (gc/L)	>1.43
MBR	<i>E. coli</i> (CFU/L)	>6.11
	Fecal coliforms (CFU/L)	>6.73
	Enterovirus (gc/L)	3.40
	Norovirus GI (gc/L)	3.02

The method of disinfections has advantage and disadvantage, table 5 shows a advantage and disadvantage of them.

Table 5 Shows the advantage and the disadvantage of chlorination, ozone, UV and membrane disinfection.

Disinfection	Advantage	Disadvantage
Chlorination	<ul style="list-style-type: none"> - Low capital and operating cost - The chlorine residual that remains in the wastewater effluent can prolong disinfection even after initial treatment. - Chlorine has flexible control 	<ul style="list-style-type: none"> - All forms of chlorine are highly corrosive and toxic. - Chlorine oxidizes certain types of organic matter in wastewater, creating hazardous compound (e.g., trihalomethanes.) - Some parasitic species have shown resistance to low doses of chlorine, including oocysts of <i>Cryptosporidium parvum</i>, cysts, of <i>Endamoeba histolytica</i> and <i>Giardia lamblia</i>, and eggs of parasitic worms.
Ozone disinfection	<ul style="list-style-type: none"> - Ozone is more effective than chlorine in destroying viruses and bacteria - The ozonation process utilizes a short contact time (approximately 10 to 30 minutes). 	<ul style="list-style-type: none"> - The cost of treatment can be relatively high in capital and in power intensiveness. - Low dosage may not effectively inactivate some viruses, spores, and cysts.

Table 5 (Continued)

Disinfection	Advantage	Disadvantage
Ozone disinfection (Continued)	<ul style="list-style-type: none"> - Ozone is generated onsite, and thus, there are fewer safety problems associated with shipping and handling. 	<ul style="list-style-type: none"> - Low dosage may not effectively inactivate some viruses, spores, and cysts. - Ozonation is a more complex technology than is chlorine or UV disinfection, requiring complicated equipment and efficient contacting systems.
Ultraviolet disinfection	<ul style="list-style-type: none"> - UV disinfection is effective at inactivating most viruses, spores, and cysts. - There is no residual effect that can be harmful to humans or aquatic life. - UV disinfection is a physical process rather than a chemical disinfectant, which eliminates the need to generate, handle, transport, or store toxic hazardous or corrosive chemicals. 	<ul style="list-style-type: none"> - Low dosage may not effectively inactivate some viruses, spores, and cysts. - Organisms can sometimes repair and reverse the destructive effects of UV through a repair mechanism, known as photoreactivation, or in the absence of light known as dark repair. - UV disinfection is not as cost effective as chlorination, but costs are competitive when chlorination dechlorination is used and fire codes are met.

Table 5 (Continued)

Disinfection	Advantage	Disadvantage
Ultraviolet disinfection (Continued)	<ul style="list-style-type: none"> - UV disinfection has a shorter contact time when compared with other disinfectants (approximately 20 to 30 seconds with low-pressure lamps). 	<ul style="list-style-type: none"> - - Turbidity and total suspended solids (TSS) in the wastewater can render UV disinfection ineffective. - UV disinfection with low-pressure lamps is not as effective for secondary effluent with TSS levels above 30 mg/L
Solar disinfection	<ul style="list-style-type: none"> - Very cheap, no capital costs except plastic bottle, no consumables required - Independent from energy sources other than sunlight. -The technique must not require consumables that are difficult or too expensive to obtain. - The taste of treated water is fresh, not stale or otherwise altered. 	<ul style="list-style-type: none"> - Cannot be used on days with continuous rainfall. - Cannot be used to treat very turbid water (>30 NTU). - Bottles need to be replaced every 4-6 months. - Has a waiting period of 6-12 hours. - Does not remove suspended particles of dissolved compounds

Table 5 (Continued)

Disinfection	Advantage	Disadvantage
Membrane bioreactors disinfection	<ul style="list-style-type: none"> - The effluent from MBRs contains low concentrations of bacteria total suspended solids (TSS), biochemical oxygen demand (BOD), and phosphorus 	<ul style="list-style-type: none"> - higher capital and operating costs - Energy costs are also higher because of the need for air scouring to control bacterial growth on the membranes.

2. Air Composition

Air is a substance, mixture of gases approximately 78%N₂, 21%O₂, 0.03%CO₂ and 0.93% other. Air has weight, takes up space and can be compressed. Air can dissolve in water at different levels. Solution of air in water can be calculated with Henry's law. The solubility of oxygen in water is higher than the solubility of nitrogen but much lower than carbon dioxide. According to the Henry's law, the amount of dissolved gas depends on its partial pressure in the air. Table 6 shows the composition of clean dry air.

Table 6 Composition of clean dry air

Gas	ppm (by volume)
Nitrogen	780,000
Oxygen	209,400
Argon	9,300
Carbon dioxide	313
Neon	18
Heleum	5.2
Methane	1.0-1.2
Crypton	1.0
Nitrous oxide	0.5
Hydrogen	0.5

Source: Boubel et al (1994)

3. Carbon Dioxide Characteristics

3.1 General

Carbon dioxide is formed from the combination of two elements: 1 carbon atom and 2 oxygen atom. The molecular formula is CO_2 . It is present in the atmosphere in small quantities about 370 ppmv (Stefan Bachu *et.,al* n.d.). CO_2 is produced from the combustion of coal or hydrocarbons. In the photosynthesis process plants assimilate CO_2 and release oxygen. CO_2 gas has a slightly irritating odor, is colorless and is denser than air. Although it is a normal, if minor, constituent of air, high concentrations of CO_2 can be dangerous. CO_2 is used in many field e.g., in the chemical industry CO_2 is used for controlling reactor temperatures, in the pharmaceutical field CO_2 is used for chemical synthesis, CO_2 is a food additive used as a propellant and acidity regulator in the food industry, etc.

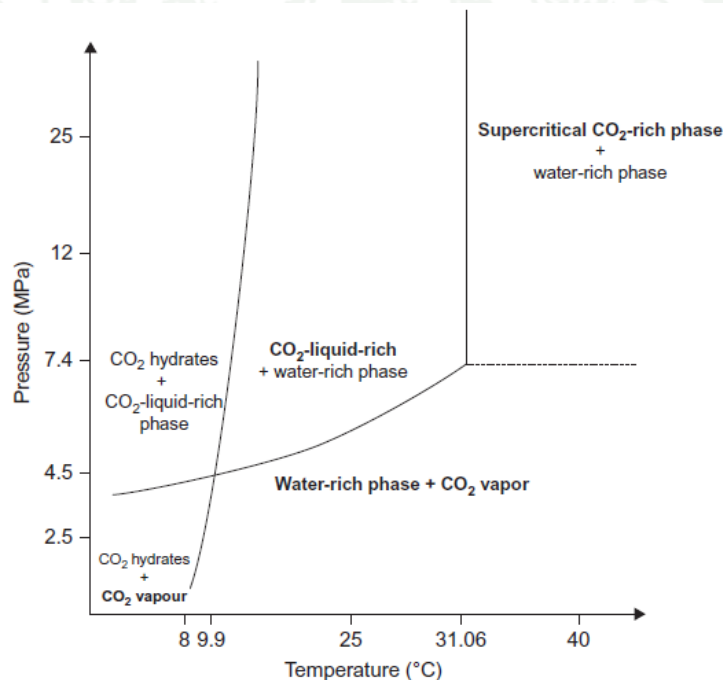


Figure 4 Phase diagram of CO_2 - H_2O system

Source: Ferrentino & Balaban (2012)

3.2 Physical Properties of CO₂

The physical state of CO₂ varies with temperature and pressure as shown in Figure 1. At low pressure CO₂ is vapor, as pressure increase CO₂ goes into the liquid state. At the critical point (Pressure=7.4 MPA, Temperature=31.06 °C) the two phases merge into a single state, as pressure and temperature increase above the critical point CO₂ is supercritical state with high diffusivity, low viscosity and strong solvent power (Ferrentino & Balaban, 2012). Some physical properties of CO₂ are shown in table 7.

Table 7 Physical Properties of CO₂

Property	Value
Molecular weight	44.1
Critical temperature (°C)	31.1
Critical pressure (Bar)	73.9
Critical density (Kg/m ³)	467
Triple point temperature (°C)	-56.5
Triple point pressure (Bar)	5.18
Gas density (1.013 bar at boiling point, Kg/m ³)	2.814
Gas density (@ STP, Kg/m ³)	1.976
Specific volume (@ STP, m ³ /kg)	0.506
Solubility in water (@ STP, vol/vol ⁻¹)	0.5

Source : Stefan Bachu *et.,al* (n.d.)

3.3 Chemical Properties of CO₂

The solubility of CO₂ in water decreases with increasing temperature and increases with increasing pressure as shown in figure 5.

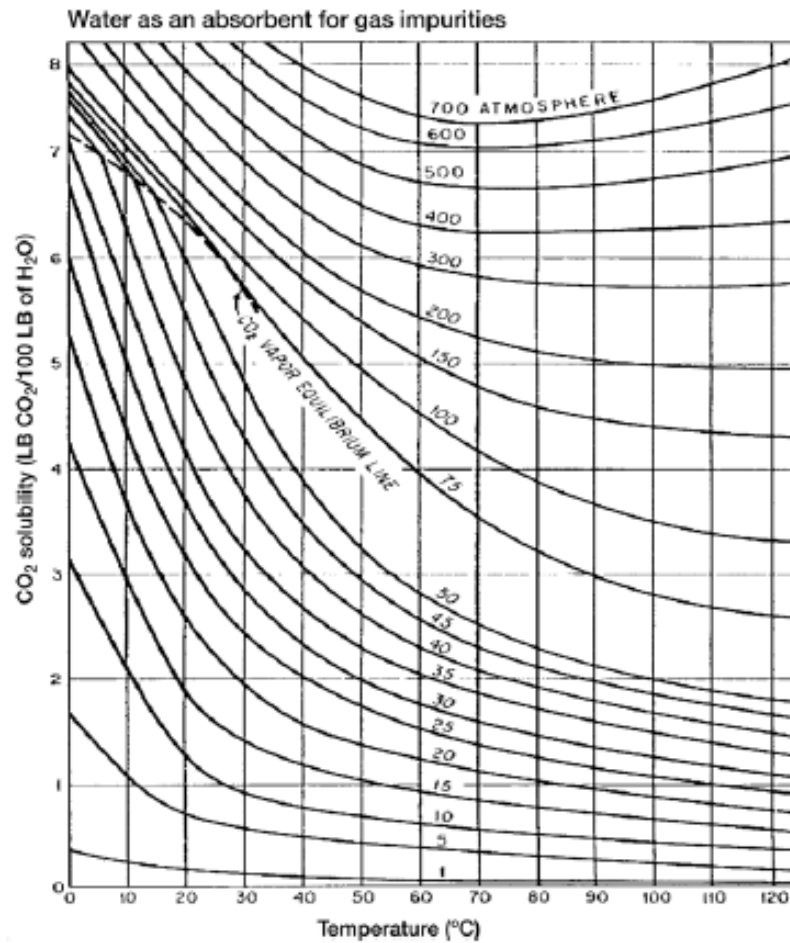
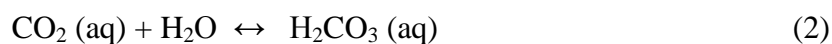


Figure 5 The solubility of CO₂ in water

Source: Stefan Bachu *et.,al* (n.d.)

When CO₂ is dissolve in water, the dissolve CO₂ reacts with water to form carbonic acid (H₂CO₃).Carbonic acid dissociates to form bicarbonate ions (HCO₃⁻), which can further dissociate into carbonate ions (CO₃²⁻). The net effect of dissolving

CO₂ in water is the removal of carbonate ions and production of bicarbonate ions, with a lowering in pH, which can be represented as follows:

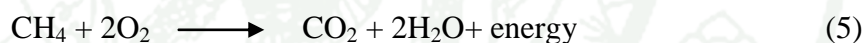


4. Combustion

Combustion is a chemical reaction that occurs between a fuel and an oxidizing agent that produces energy, usually in the form of heat and light. There are 2 types.

4.1 Complete Combustion

In complete combustion is the reactant burns in oxygen (O₂) to form CO₂ and water (H₂O) e.g., the combustion of methane which shown as follow:



4.1 Incomplete Combustion

Incomplete combustion will occur when there is not enough oxygen to allow the fuel to react completely to produce carbon dioxide and water. Some carbon monoxide (CO), Carbon (C) can also form. e.g., the combustion of methane which shown as follow:



Incomplete combustion will occur when there is not enough oxygen to allow the fuel to react completely to produce carbon dioxide and water. Some carbon monoxide (CO), Carbon (C) can also form. e.g., the combustion of methane

5. Mechanism of carbon dioxide bactericidal action

Figure 6 shows schematically how pressurized CO₂ may exert its lethal action on bacteria.

Step 1 CO₂ can dissolve in the water to form carbonic acid (H₂CO₃), which dissociates into bicarbonate (HCO₃⁻), carbonate (CO₃²⁻) and hydrogen (H⁺) ionic. Water in contact with pressurized CO₂ generally becomes acidic due to the formation and dissociation of H₂CO₃, which liberates H⁺ ions. This lowered extracellular pH (pH_{ex}) may inhibit microbial growth and also may diminish microbial resistance to inactivation because of increased energy consumption to maintain pH homeostasis by the proton motive force. However, a reduction in pH is not enough to account for the lethal effect of CO₂ since it shows an inhibitory effect which is greater than that of other acids used to lower medium acidity. These acids do not seem to enter the microbial cells as easily as CO₂ therefore suggested that the lowered pH contributes to an increase in cell permeability, which facilitates the penetration of CO₂ into microbial cells (Garcia-Gonzalez *et al.*, 2007).

Step 2 on the bacteria cell, CO₂ can diffuse in to the membrane and can accumulate in to the phospholipids inner layer, its can cause the effect to the structure and function of the cell membrane due to the loss of the lipid chain, which may increase the fluidity of the membrane. The HCO₃⁻ ion may act on the charged phospholipids and the protein at the surface of membrane, thereby altering the optimal surface charge density of the membrane, and hence altering optimal membrane functions (Garcia-Gonzalez *et al.*, 2007).

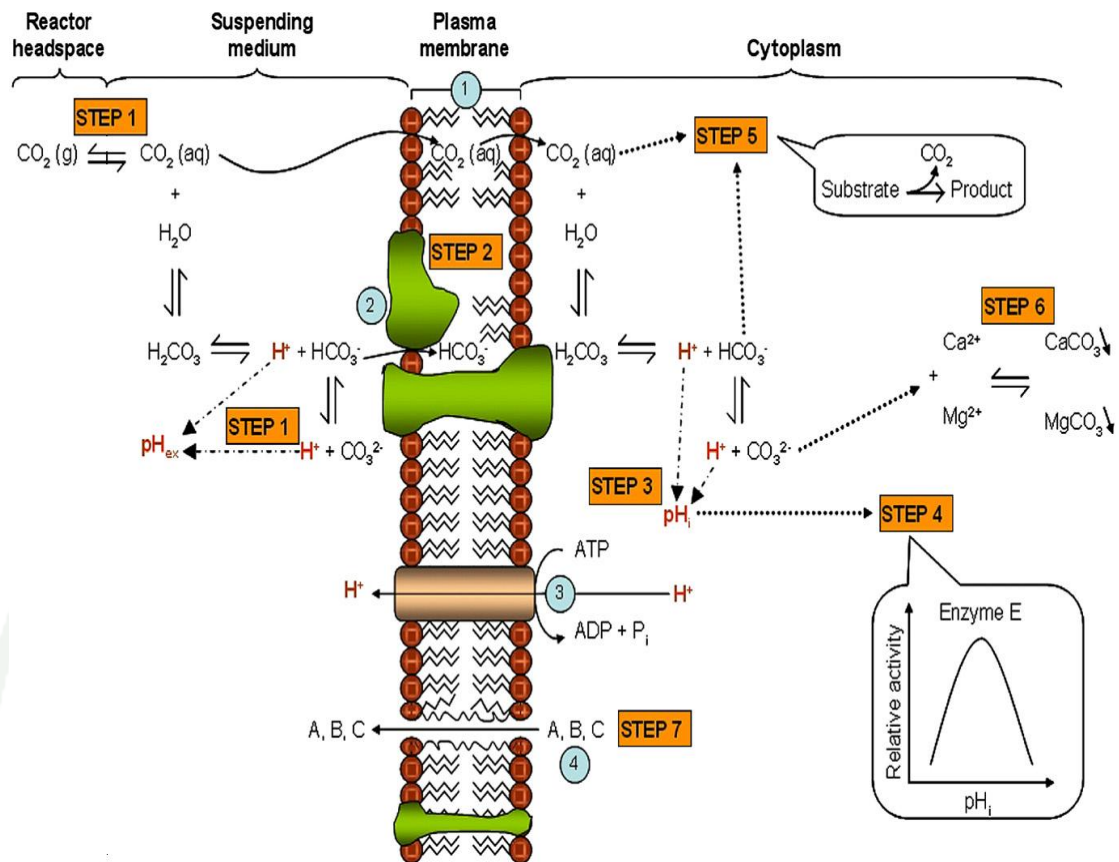


Figure 6 A schematic diagram of how pressurized CO_2 may exert its lethal action on bacteria.

Source: Garcia-Gonzalez *et al.*, (2007)

Step 3 CO_2 can penetrate through the cell membrane and accumulate in the cytoplasm of the cell due to the permeability. The relative concentrations of both aqueous CO_2 and HCO_3^- are controlled by internal pH buffering as a result of pH homeostasis in order to maintain a more or less constant cytoplasmic pH_i . A more important homeostatic system is a membrane-bound H^+ -ATPase which expels protons from the cytoplasm against the prevailing pH gradient and electrochemical gradient proton. If too much dissolved CO_2 enters the cytoplasm, the cells may be unable to expel all the resulting protons and pH_i will start to decrease. If pH_i is lowered too much, cell viability will seriously be impaired (Garcia-Gonzalez *et al.*, 2007).

Step 4 Enzymes have maximal activity at the optimum pH, and their activity declines sharply on either side of the optimum. A loss over biological control of the pH_i of cells may be detrimental in all aspects of intermediary metabolism and cellular function (Garcia-Gonzalez *et al.*, 2007).

Step 5 the effects of HCO₃⁻ and dissolved CO₂ on carboxylation and decarboxylation reactions, CO₂ fulfils the role of either a biosynthetic substrate in carboxylation reactions or a metabolic product from decarboxylation reactions. Carboxylation reactions are particularly important for the gluconeogenesis and the synthesis of particular biosynthetic precursor amino acids and nucleic acids. Because there is no generalized preference for either dissolved CO₂ or HCO₃⁻ as a substrate in carboxylation reactions, the ratio of dissolved CO₂/HCO₃⁻ will, in part, determine the relative rates at which different families of carboxylases function. As far as decarboxylation reactions are concerned, they all appear to produce CO₂ in the dissolved CO₂ form. Although it is clear that dissolved CO₂ can inhibit decarboxylation reactions, the inhibitory effects that CO₂ may have on the decarboxylase enzymes is however not clear and could be due either to product inhibition by CO₂ or to an equilibrium-based mass action effect (Garcia-Gonzalez *et al.*, 2007).

Step 6 the applied CO₂ pressure accumulates in the cytoplasmic of the bacterial cells which damage to the biological system of the cells. This may convert HCO₃⁻ to CO₃²⁻, which could precipitate intracellular inorganic electrolytes, such as Ca²⁺, Mg²⁺ and similar ions, from cells and cell membranes. These inorganic electrolytes aid in maintaining the osmotic relationships between cells and their surrounding media, this could have deleterious effects on the volume of cells (Garcia-Gonzalez *et al.*, 2007).

Step 7 pressurized CO₂ first penetrates into the cells to build up the density to a critical level within the cells after which it removes intracellular

constituents to disturb or alter the structure of the biomembrane and/or the balance of the biological system, thus promoting inactivation. The inactivation rate could be improved by repeating the release and recharge of pressurized CO₂ in the pressure vessel during the treatment to improve transfer of intracellular materials out of the bacterial cells (Garcia-Gonzalez *et al.*, 2007).

6. High dissolved CO₂

6.1 High dissolved CO₂ device

Figure 7 shown high dissolved CO₂ devices, the nozzle with small radius was set up to provide influent at a high rate to improve the contact efficiency between CO₂ and water. When the influent strikes to the device, liquid films were produced, and as a result the CO₂ dissolution rate increases because of the larger gas-liquid contact area.

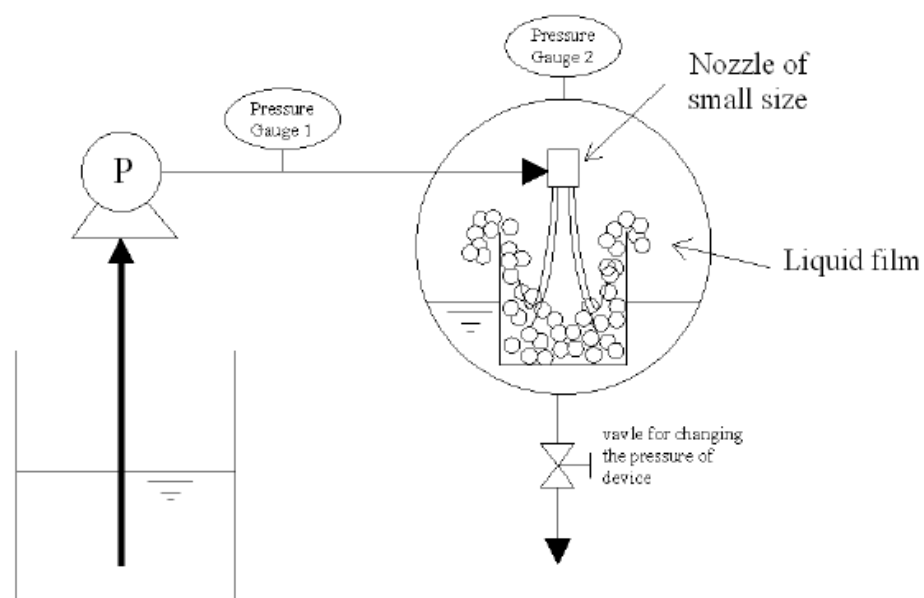


Figure 7 Apparatus to produce high-dissolved CO₂

Source: Chang *et al.* (2011)

6.2 Mechanism of high dissolved CO₂

The microorganisms were able uptake the CO₂ dissolved in the water. When the water was discharged outside the device, the pressure suddenly decrease, while the CO₂ inside the cell appeared and cause a large amount of bubbles to be produce quickly, resulting in the rupture of the microorganism. Figure 8 shows the cell rapture (fig. 8C) and the hole formed at the ends of cell (fig. 8d) indicated the lethal reason was CO₂ expansion from inside the cell.

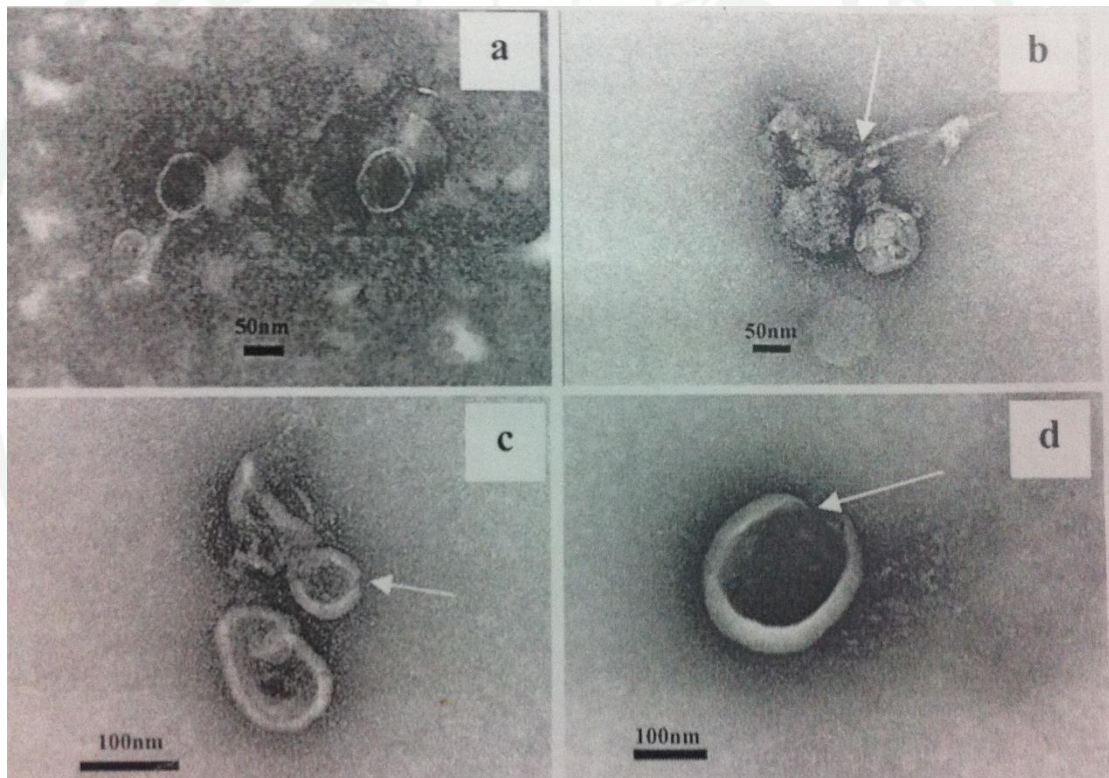


Figure 8 TEM images of bacteriophage T4 (a) untreated (b),(c),(d) after inactivation treatment for 20 min

Source: Chang et al. (2011)

7. Coliform Bacteria

Coliform Bacteria include total coliform bacteria, fecal coliform bacteria, *Escherichia coli* (*E. coli*). Figure 8 shown classification of coliforms; the smaller the subset, the more accurate the microorganism of choice.

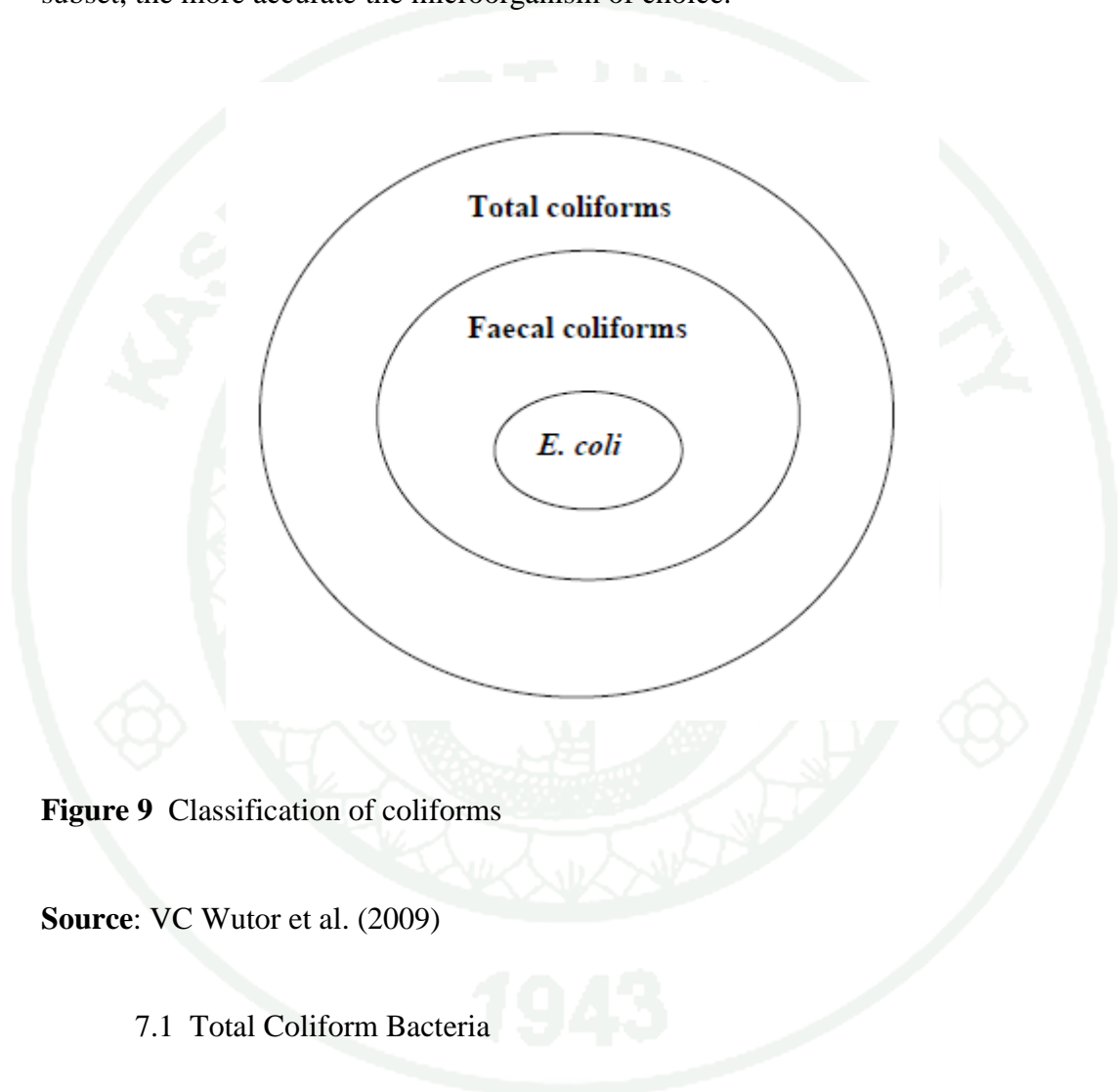


Figure 9 Classification of coliforms

Source: VC Wutor et al. (2009)

7.1 Total Coliform Bacteria

Coliform are a large group of gram-negative, non-spore forming, rod-shaped bacteria that all belong to a single taxonomic family Enterobacteriaceae. Coliform bacteria can ferment lactose with the production of acid and gas when incubated at 35–37°C (APHA *et al.*, 2012). They can be isolated from polluted and non-polluted waters, soils and plants, as well as from the feces of humans and warm-blooded animals.

7.2 Fecal Coliform Bacteria

Fecal coliform bacteria are a sub-group of total coliform bacteria. A fecal coliform is a facultatively anaerobic, rod-shaped, gram-negative, non-sporulating bacterium. Fecal coliform are found in the fecal material of humans and other warm-blooded animals and produce acid and gas from lactose within 48 hours at $44 \pm 0.5^{\circ}\text{C}$. In practice, some organisms with these characteristics may not be of fecal origin and the term thermotolerant coliform is more correct and is becoming more commonly used (Jamie Bartram and Richard Balance, 1996). More than 95 per cent of thermotolerant coliforms isolated from water are the gut organism *Escherichia coli* (*E. coli*), the presence of which is definitive proof of fecal contamination. As a result, it is often unnecessary to undertake further testing to confirm the specific presence of *E. coli*.

Fecal coliform enter surface waters with agricultural and storm water runoff. Sewage connections that are connected to storm drain pipes can also allow human sewage into surface waters. Some country use a combine sewer, a combined sewer carries both domestic sewage and storm water. During high rainfall periods, a combined sewer can become overloaded and overflow to a nearby stream or river. Animal can contribute to fecal contamination of surface waters. Birds can be a significant source of fecal coliform bacteria

7.3 *E. Coli*

E. coli is a rod-shaped bacteria is a sub-group of the fecal coliform group. *E. coli* are found in great quantities in the intestinal of people and warm-blooded animals. Most *E. coli* strains remain harmless. However, there are also pathogenic strains associated with human and animal diseases.

MATERIALS AND METHODS

Materials

1. Autoclave: required for sterilizing the culture media.
2. Incubator or water-baths: must each be fitted with a temperature control and should be capable of maintaining a uniform temperature correct to 35 or 37 \pm 0.5°C and/or 44 or 44.5 \pm 0.25°C.
3. Balance: needed for weighing powdered culture medium. It should have an accuracy of 0.05 g.
4. Pipettes: 1ml and 10ml, with cotton plugs at the mouthpiece, are required.
5. Test-tubes and racks: tubes can be 20x 150mm in size for 10-ml sample volumes plus 10 ml of culture medium (screw caps are not recommended for fermentation media).
6. Bottles: used for the larger volumes consisting of 50ml of sample and 50ml of culture medium. They should have loose-fitting caps and ideally be calibrated with 50-ml and 100-ml marks.
7. Media preparation: equipment: glass or stainless-steel containers
8. Culture tubes containing inverted vials (Durham tubes)
9. Inoculation loop and holder
10. Petri dish
11. Evaporating dish
12. Filter paper
13. Refrigerator for the storage of prepared culture media.
14. Hot air sterilizer for sterilizing pipettes.
15. Hot air oven
16. Water bath
17. Vacuum pump
18. Analytical balance

Methods

1. Experimental setup

An air compressor is used to store exhaust gas from a car with pressure up to 4 kg/cm² (0.4 MPA). The outlet of the compressor is connected to the experiment unit as shown in Figure 2. The study is conducted in a batch system. In the experiment, 7 liters of effluent from the central wastewater treatment plant of Kasetsart University is fed into in the 14-liter experimental unit. Then, exhaust gas from the compressor is fed into water through fine bubble nozzles. The experiment was set up under room temperature which is about 30 °C. The total pressure in the experiment unit is controlled by the pressure control valve at the inlet of the experimental unit. After some detention period, water in the experimental unit is drained out and the pressure decreases to atmospheric pressure, resulting in fine bubble formation in water. The CO₂ content in the exhaust gas is measured using Gas Analyzer. Water sample from the container is withdrawn at 5-minute interval to analyze for fecal coliform and heterotrophic bacteria according to APHA, AWWA & WEF (2012) . The study is then repeated for other pressures in the range of 0.1-0.4 Mpa and detention periods in the range of 5-25 minutes. Also, similar study is conducted using ambient air instead of the exhaust gas so as to compare the inactivation results. The log survival ratio ($\log N_t/N_0$) (in which N_0 is MPN value at time 0 and N_t is MPN value at time t), is calculated to determine the inactivation rate.

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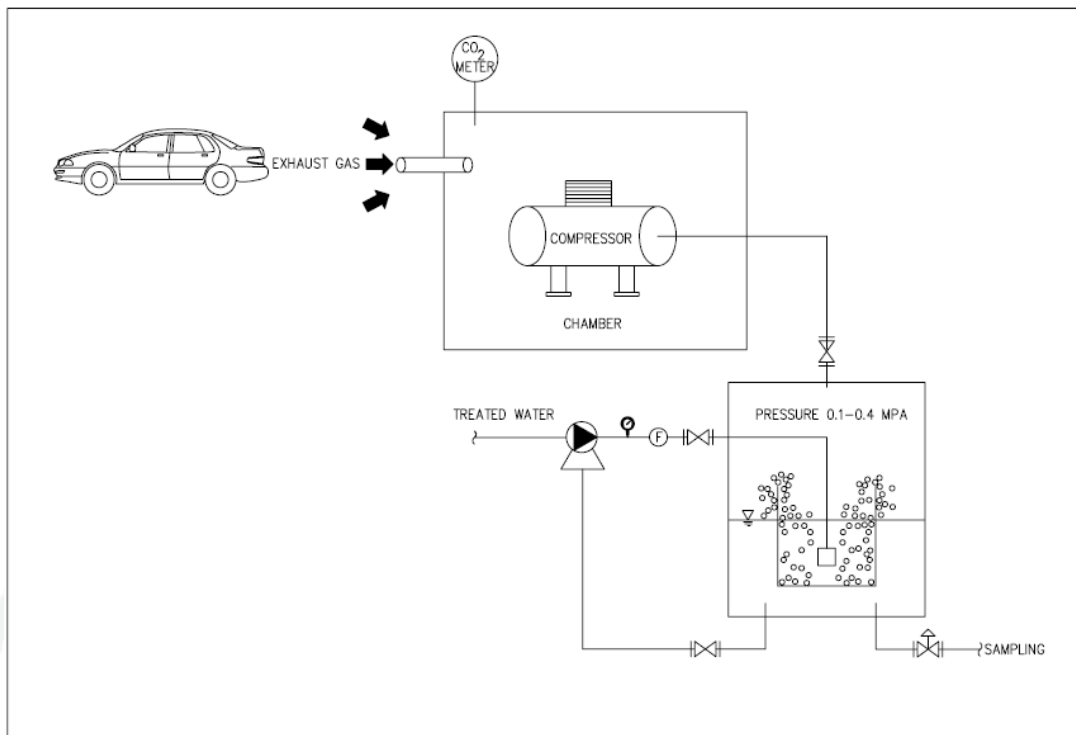


Figure 10 Schematic of experiment

Figure 10 shows the step of the experiment can be summarized as follows

Step 1 the exhaust pipe of the car was connected to the chamber to ensure that the exhaust gas is not contaminated from the ambient air ; the exhaust gas was stored in the chamber and penetrated to the compressor by automatic pressure switch.

Step 2 7 L of effluent water was fed to the high-dissolved CO₂ device by pump than circulated the water for 5-25 minute treatment time by the pump

Step 3 compressor was connected to the high-dissolved CO₂ device, the exhaust gas was penetrated to the device varying pressure 0.1, 0.2, 0.3, 0.4 MPa and 5, 10, 15, 20, 25 minutes treatment time.

Step 4 the water sample was taken at pressure 0.1, 0.2, 0.3, 0.4 MPa and 5, 10, 15, 20, 25 minutes treatment time

Step 5 the water sample was measured fecal coliform by MPN method and heterotrophic bacteria by standard plate count.

Step 6 the experiment was repeat follow step 1-step 5 without circulation

Step 7 the CO₂ concentration in the exhaust gas was measure by gas analyzer.

2. Enumeration of microorganism

2.1 Fecal coliform bacteria

Enumeration of fecal coliform bacteria was done by multiple-tube method according to APHA, AWWA & WEF (2012). The 5-tube system was used to measure fecal coliform in this study.

2.2 Fecal coliform bacteria

Enumeration of fecal heterotrophic bacteria was done by stand plate count according to APHA, AWWA & WEF (2012). The pour plate was used to measure fecal heterotrophic in this study.

RESULT AND DISCUSSION

1. The inactivation rate with circulation

The central wastewater treatment plant of Kasetsart University prior to chlorination process is treated under various pressure and detention period. The water was fed to the experiment than cycled inside the device by a circulate pump for all of the treatment time. The obtained results of the inactivation rate under circulate condition are analyzed and describe as:

1.1 The inactivation against fecal coliform bacteria with circulation

The inactivation rate of air and exhaust are summarized in Table 8 and the log survival ratios are plotted as shown in Figure 11, 12

From Table 8 and Figure 11,12, it is found that when using high-pressure air, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are only 21%, 25%, 39% and 46%, respectively, which correspond to the log survival ratios of -0.10, -0.12, -0.22 and -0.27, respectively. When the high-pressure exhaust gas is used, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period increase to 50%, 61%, 75% and 78%, respectively, which correspond to the log survival ratios of -0.30, -0.41, -0.60 and -0.65, respectively.

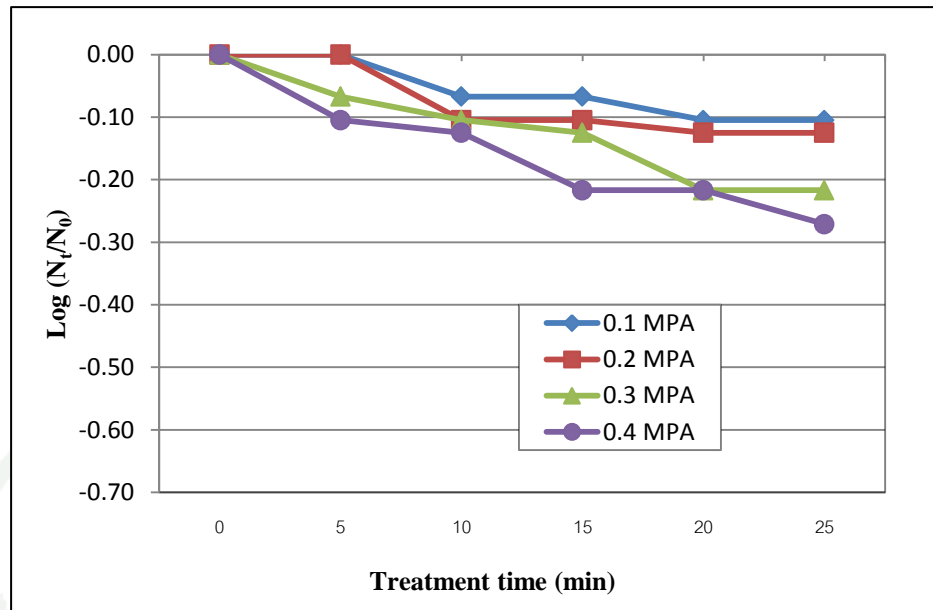


Figure 11 Inactivation performance of ambient air against fecal coliform under 0.1-0.4 MPA of pressure with circulation.

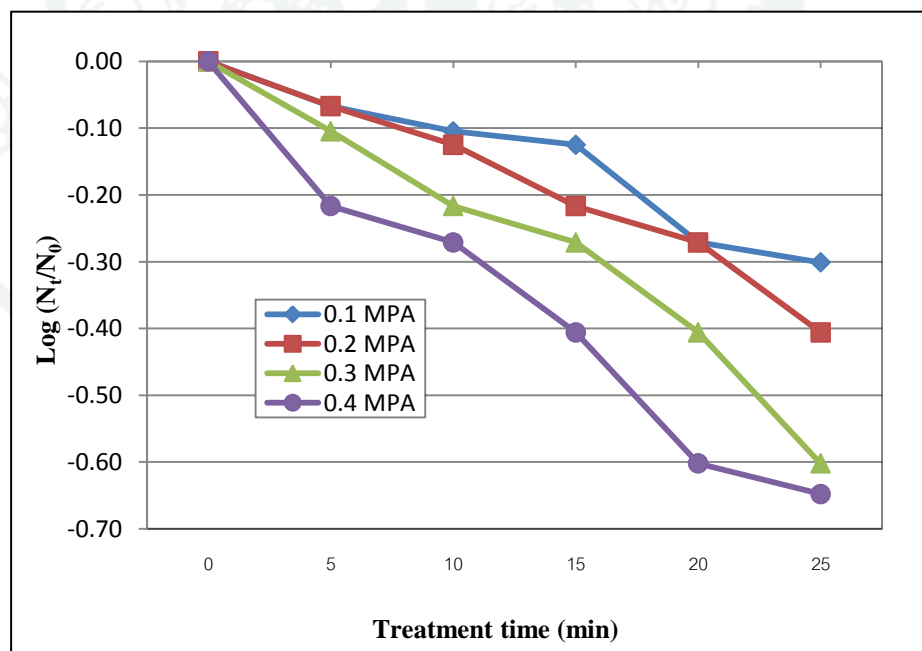


Figure 12 Inactivation performance of exhaust gas against fecal coliform under 0.1-0.4 MPA of pressure with circulation

Table 8 Inactivation percentages and log survival ratio using air and exhaust gas against fecal coliform with circulation

Air				Exhaust Gas			
Pressure (MPa)	Time (min)	% In activation	log (N_t/N_0)	Pressure (MPa)	Time (min)	% In activation	log (N_t/N_0)
0.1	0	0	0.00	0.1	0	0	0.00
	5	0	0.00		5	14	-0.07
	10	14	-0.07		10	21	-0.10
	15	14	-0.07		15	25	-0.12
	20	21	-0.10		20	46	-0.27
	25	21	-0.10		25	50	-0.30
0.2	0	0	0.00	0.2	0	0	0.00
	5	0	0.00		5	14	-0.07
	10	21	-0.10		10	25	-0.12
	15	21	-0.10		15	39	-0.22
	20	25	-0.12		20	46	-0.27
	25	25	-0.12		25	61	-0.41
0.3	0	0	0.00	0.3	0	0	0.00
	5	14	-0.07		5	21	-0.10
	10	21	-0.10		10	39	-0.22
	15	25	-0.12		15	46	-0.27
	20	39	-0.22		20	61	-0.41
	25	39	-0.22		25	75	-0.60
0.4	0	0	0.00	0.4	0	0	0.00
	5	21	-0.10		5	39	-0.22
	10	25	-0.12		10	46	-0.27
	15	39	-0.22		15	61	-0.41
	20	39	-0.22		20	75	-0.60
	25	46	-0.27		25	78	-0.65

1.2 The inactivation against heterotrophic bacteria with circulation

In order to ensure the inactivation rate of air and exhaust gas, the heterotrophic bacteria were analyzed as well. The inactivation rate of air and exhaust against heterotrophic bacteria with circulate condition are summarized in Table 9 and the log survival ratios are plotted as shown in Figure 13, 14

From Table 9 and Figure 13,14, it is found that when using high-pressure air, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are only 13%, 21%, 31% and 44%, respectively, which correspond to the log survival ratios of -0.06, -0.10, -0.16 and -0.25, respectively. When the high-pressure exhaust gas is used, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period increase to 30%, 42%, 60% and 70%, respectively, which correspond to the log survival ratios of -0.15, -0.23, -0.40 and -0.53, respectively.

From the obtained results, it is found that the inactivation of fecal coliform bacteria and heterotrophic bacteria caused by high pressure ambient air with circulate condition is significantly lower than that of the exhaust gas at every operating pressure with circulate condition. This is due to the difference in CO₂ partial pressure which causes different concentrations of dissolved gas in water. The inactivation rates of exhaust gas and ambient air increase as the pressure increases, which are similar to other studies (Garcia-Gonzalez *et al.*, 2007; Ishikawa *et al.*, 1995; Kobayashi *et al.*, 2007; Cheng *et al.*, 2011)

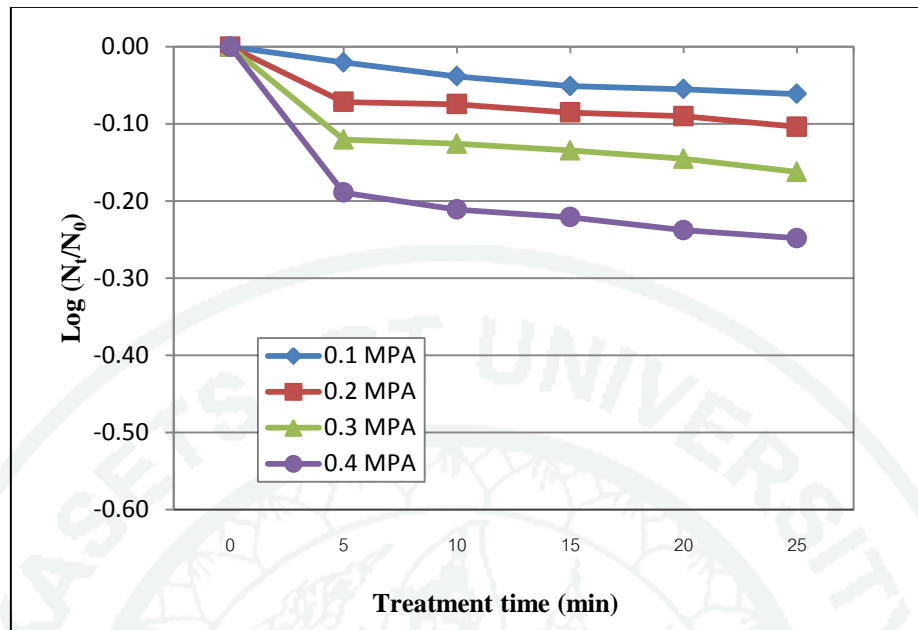


Figure 13 Inactivation Performance of air against heterotrophic bacteria under 0.1-0.4 MPA of pressure with circulation

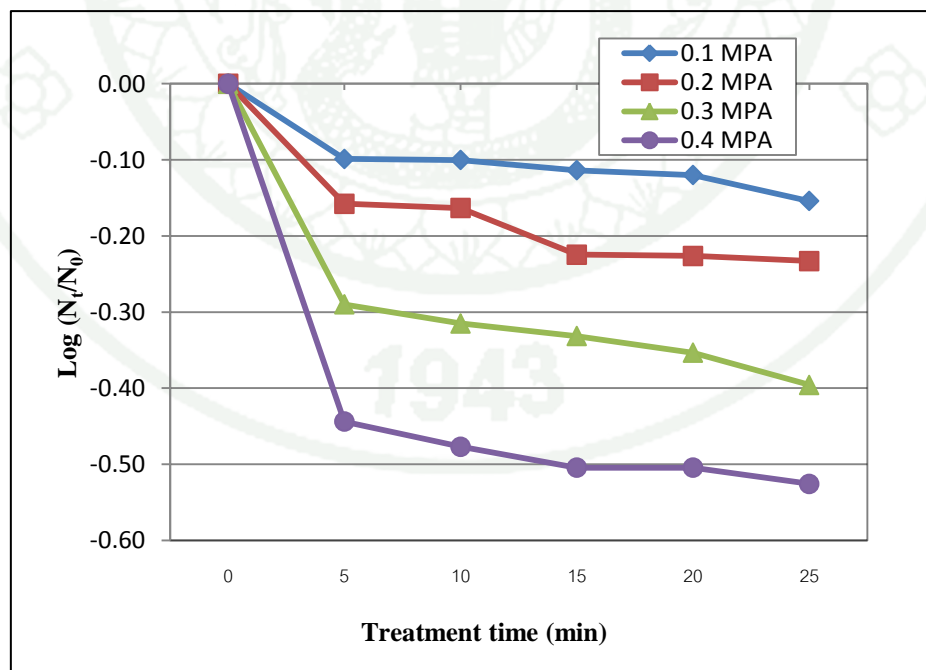


Figure 14 Inactivation Performance of exhaust gas against heterotrophic bacteria under 0.1-0.4 MPA of pressure with circulation

Table 9 Inactivation percentages and log survival ratio using air and exhaust gas against heterotrophic bacteria with circulation

Air				Exhaust Gas			
Pressure (MPa)	Time (min)	% In activation	log (N_t/N_0)	Pressure (MPa)	Time (min)	% In activation	log (N_t/N_0)
0.1	0	0	0.00	0.1	0	0	0.00
	5	5	-0.02		5	20	-0.10
	10	8	-0.04		10	21	-0.10
	15	11	-0.05		15	23	-0.11
	20	12	-0.05		20	24	-0.12
	25	13	-0.06		25	30	-0.15
0.2	0	0	0.00	0.2	0	0	0.00
	5	15	-0.07		5	30	-0.16
	10	16	-0.07		10	31	-0.16
	15	18	-0.09		15	40	-0.22
	20	19	-0.09		20	41	-0.23
	25	21	-0.10		25	42	-0.23
0.3	0	0	0.00	0.3	0	0	0.00
	5	24	-0.12		5	49	-0.29
	10	25	-0.13		10	52	-0.31
	15	27	-0.13		15	53	-0.33
	20	28	-0.15		20	56	-0.35
	25	31	-0.16		25	60	-0.40
0.4	0	0	0.00	0.4	0	0	0.00
	5	35	-0.19		5	64	-0.44
	10	38	-0.21		10	67	-0.48
	15	40	-0.22		15	69	-0.50
	20	42	-0.24		20	69	-0.50
	25	44	-0.25		25	70	-0.53

1.3 The inactivation against heterotrophic bacteria with circulation when increasing treatment time.

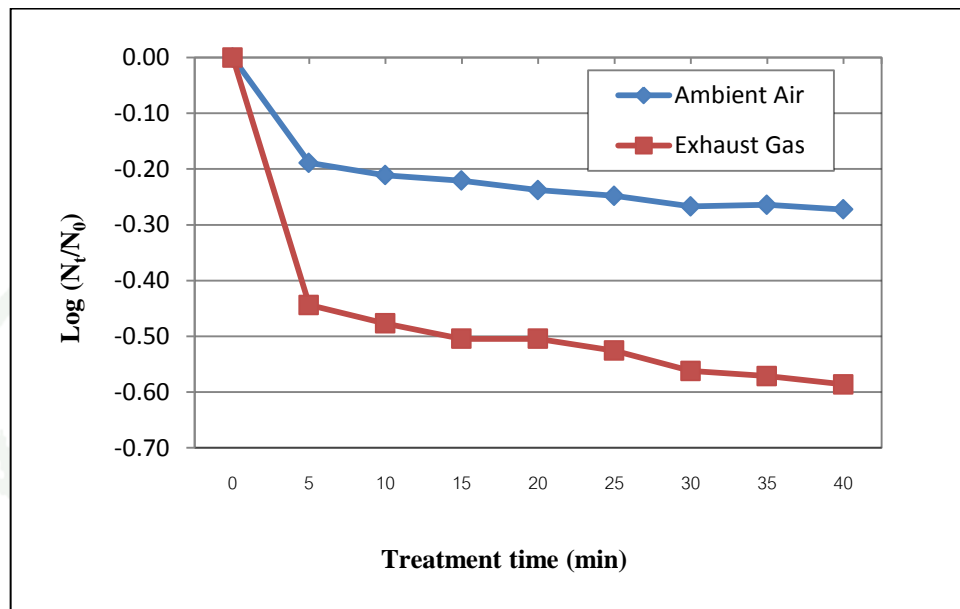


Figure 15 Inactivation performance of ambient air and exhaust gas against heterotrophic bacteria under 0.4 MPA of pressure when increase the treatment to 40 minute with circulation

Figure 15 shown the inactivation rate of ambient air and exhaust gas against heterotrophic bacteria under 0.4 MPA, when using ambient air and increasing treatment time to 30,35,40 minute, the log survival ratios are -0.27,-0.26,-0.27 respectively, When using exhaust gas and increasing treatment time to 30,35,40 minute, the log survival ratios are -0.56,-0.57,-0.59 respectively,

2. The inactivation rate without circulation

Without circulate of water is the assumed factor affecting inactivation rate, therefore inactivation of ambient air and exhaust without circulate was investigated.

2.1 The inactivation against fecal coliform bacteria without circulation

The inactivation rate of air and exhaust against fecal coliform bacteria without circulate condition are summarized in Table 10 and the log survival ratios are plotted as shown in Figure 16, 17

From Table 10 and Figure 16,17, it is found that when using high-pressure air, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are only 21%, 25%, 30% and 40%, respectively, which correspond to the log survival ratios of -0.10, -0.12, -0.15 and -0.22, respectively.

When the high-pressure exhaust gas is used, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period increase to 25%, 39%, 46% and 72%, respectively, which correspond to the log survival ratios of -0.12, -0.22, -0.27 and -0.55, respectively.

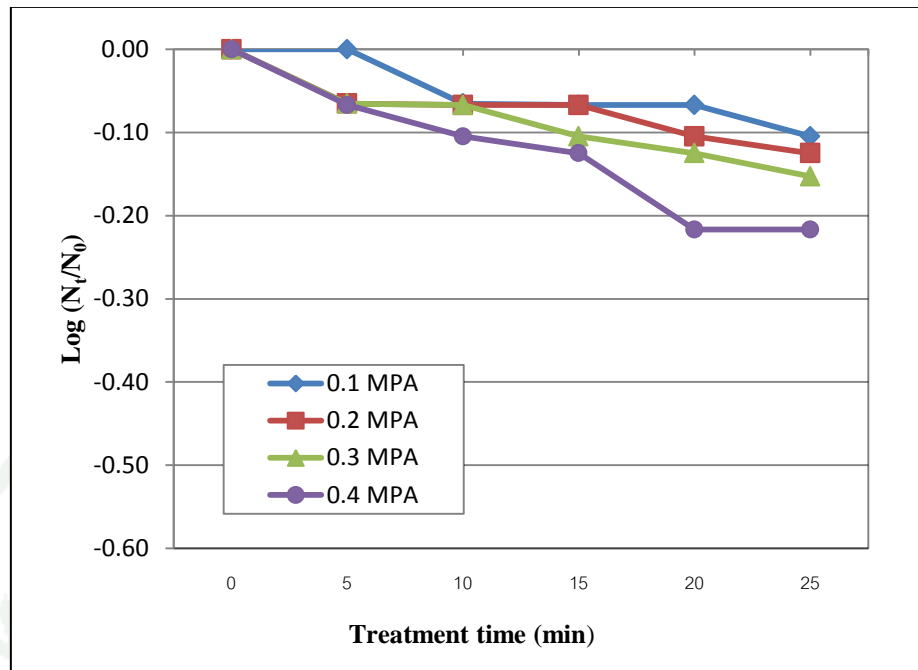


Figure 16 Inactivation performance of air against fecal coliform bacteria under 0.1-0.4 MPA of pressure without circulation

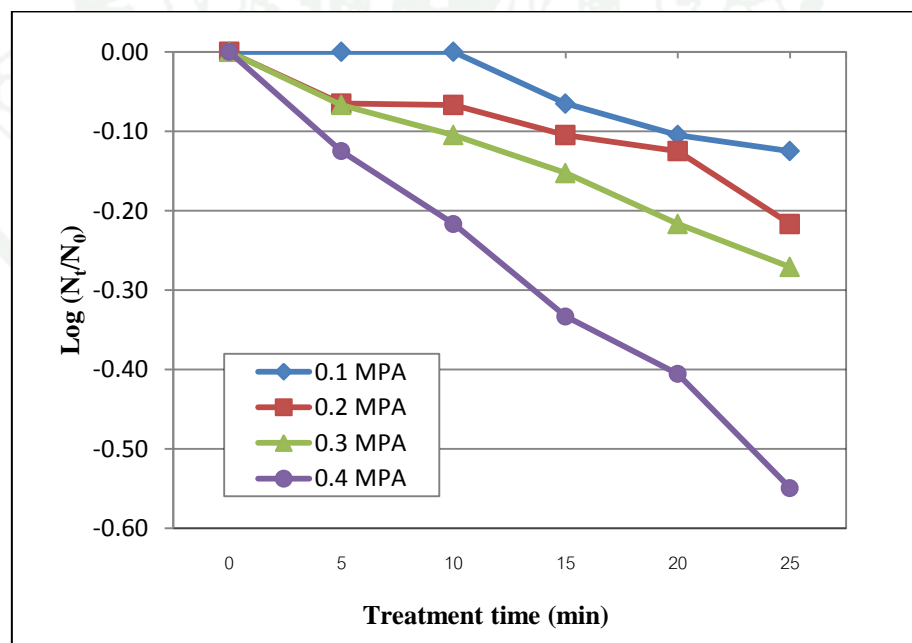


Figure 17 Inactivation performance of exhaust gas against fecal coliform bacteria under 0.1-0.4 MPA of pressure without circulation

Table 10 Inactivation percentages and log survival ratio using air and exhaust gas against fecal coliform bacteria without circulation

Air				Exhaust Gas			
Pressure (MPa)	Time (min)	% In activation	log (N_t/N_0)	Pressure (MPa)	Time (min)	% In activation	log (N_t/N_0)
0.1	0	0	0.00	0.1	0	0	0.00
	5	0	0.00		5	0	0.00
	10	0	0.00		10	0	0.00
	15	14	-0.07		15	14	-0.07
	20	14	-0.07		20	21	-0.10
	25	21	-0.10		25	25	-0.12
0.2	0	0	0.00	0.2	0	0	0.00
	5	0	0.00		5	14	-0.07
	10	14	-0.07		10	14	-0.07
	15	14	-0.07		15	21	-0.10
	20	21	-0.10		20	25	-0.12
	25	25	-0.12		25	39	-0.22
0.3	0	0	0.00	0.3	0	0	0.00
	5	14	-0.07		5	14	-0.07
	10	14	-0.07		10	21	-0.10
	15	21	-0.12		15	30	-0.15
	20	25	-0.12		20	39	-0.22
	25	30	-0.15		25	46	-0.27
0.4	0	0	0.00	0.4	0	0	0.00
	5	14	-0.07		5	25	-0.12
	10	21	-0.10		10	39	-0.22
	15	25	-0.12		15	53	-0.33
	20	40	-0.22		20	61	-0.41
	25	40	-0.22		25	72	-0.55

2.2 The inactivation against heterotrophic bacteria without circulate condition

The inactivation rate of air and exhaust against heterotrophic bacteria without circulate condition are summarized in Table 6 and the log survival ratios are plotted as shown in Figure 18, 19.

From Table 11 and Figure 18,19, it is found that when using high-pressure air without circulate, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are 12%, 17%, 23% and 36%, respectively, which correspond to the log survival ratios of -0.05, -0.08, -0.12 and -0.19, respectively.

When the high-pressure exhaust gas is used, the inactivation percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period increase to 24%, 36%, 50% and 60%, respectively, which correspond to the log survival ratios of -0.12, -0.19, -0.30 and -0.40, respectively.

From the obtained results, it is found that the inactivation of heterotrophic bacteria caused by high pressure without circulate condition is significantly lower than that of the circulate when using ambient and exhaust gas at every operating pressure without circulate condition. This is due to the circulate condition can enhance the solubilization of CO₂ and the CO₂ dissolved easy to contact bacteria cell (Garcia-Gonzalez *et al.*, 2007) The inactivation rates of exhaust gas and ambient air increase as the pressure increases, which are similar to other studies (Garcia-Gonzalez *et al.*, 2007; Ishikawa *et al.*, 1995; Kobayashi *et al.*, 2007; Cheng *et al.*, 2011)

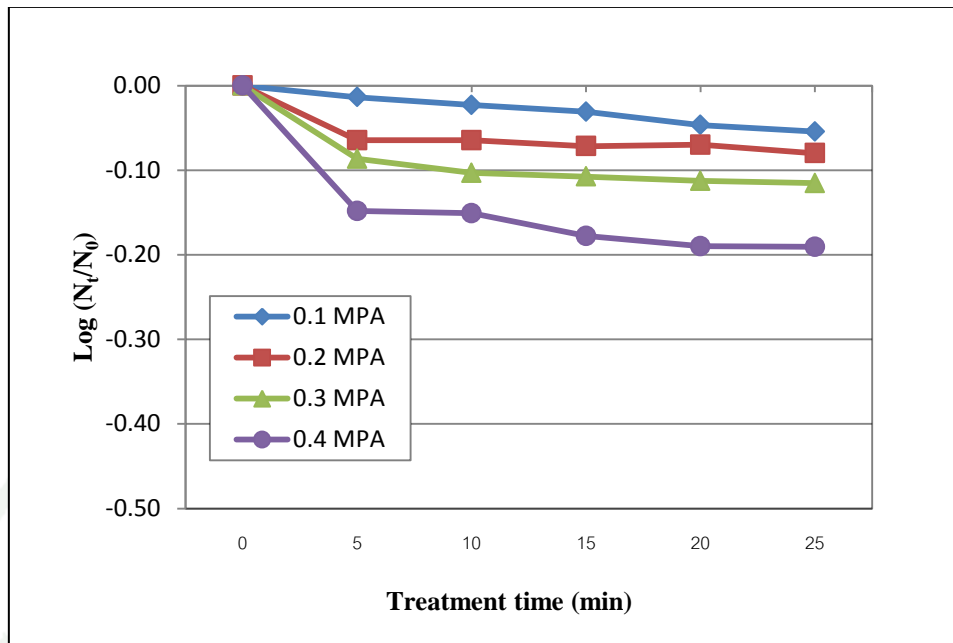


Figure 18 Inactivation performance of ambient air against heterotrophic bacteria under 0.1-0.4 MPA of Pressure without circulation

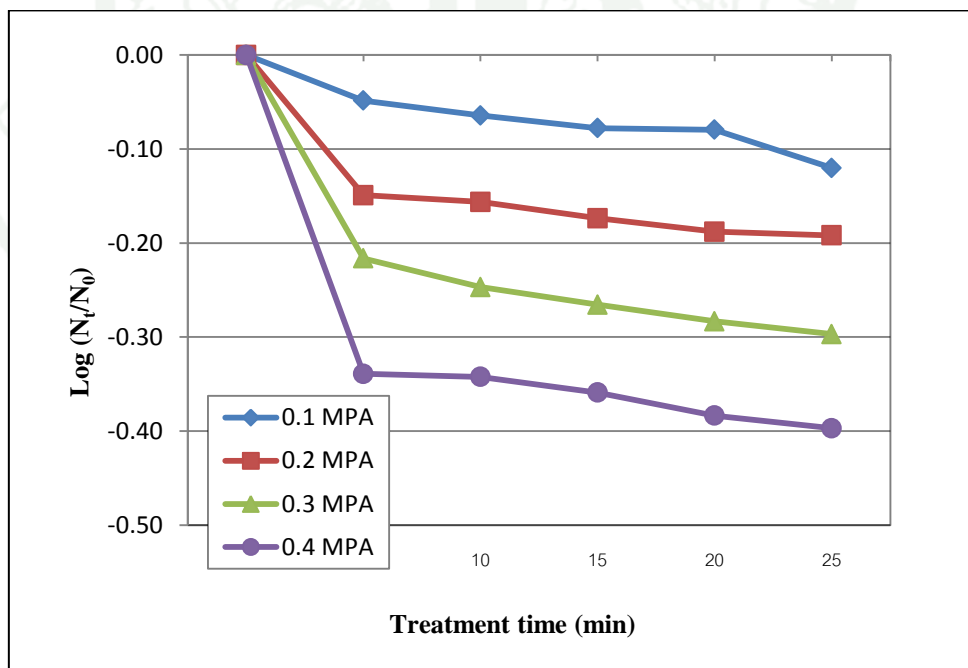


Figure 19 Inactivation Performance of Exhaust Gas against heterotrophic bacteria under 0.1-0.4 MPA of Pressure without circulation

Table 11 Inactivation percentages and log survival ratio using air and exhaust gas heterotrophic bacteria without circulation

Air				Exhaust Gas			
Pressure (MPa)	Time (min)	% In activation	Log (N_t/N_0)	Pressure (MPa)	Time (min)	% In activation	Log (N_t/N_0)
0.1	0	0	0.00	0.1	0	0	0.00
	5	3	-0.01		5	11	-0.05
	10	5	-0.02		10	14	-0.06
	15	7	-0.03		15	16	-0.08
	20	10	-0.05		20	17	-0.08
	25	12	-0.05		25	24	-0.12
0.2	0	0	0.00	0.2	0	0	0.00
	5	12	-0.06		5	29	-0.15
	10	14	-0.06		10	30	-0.16
	15	15	-0.07		15	33	-0.17
	20	15	-0.07		20	35	-0.19
	25	17	-0.08		25	36	-0.19
0.3	0	0	0.00	0.3	0	0	0.00
	5	28	-0.09		5	39	-0.22
	10	21	-0.10		10	43	-0.25
	15	22	-0.11		15	46	-0.27
	20	23	-0.11		20	48	-0.28
	25	23	-0.12		25	50	-0.30
0.4	0	0	0.00	0.4	0	0	0.00
	5	29	-0.15		5	54	-0.34
	10	29	-0.15		10	55	-0.34
	15	34	-0.18		15	56	-0.36
	20	35	-0.19		20	59	-0.38
	25	36	-0.19		25	60	-0.40

2.2 The inactivation against heterotrophic bacteria without circulation when increasing treatment time.

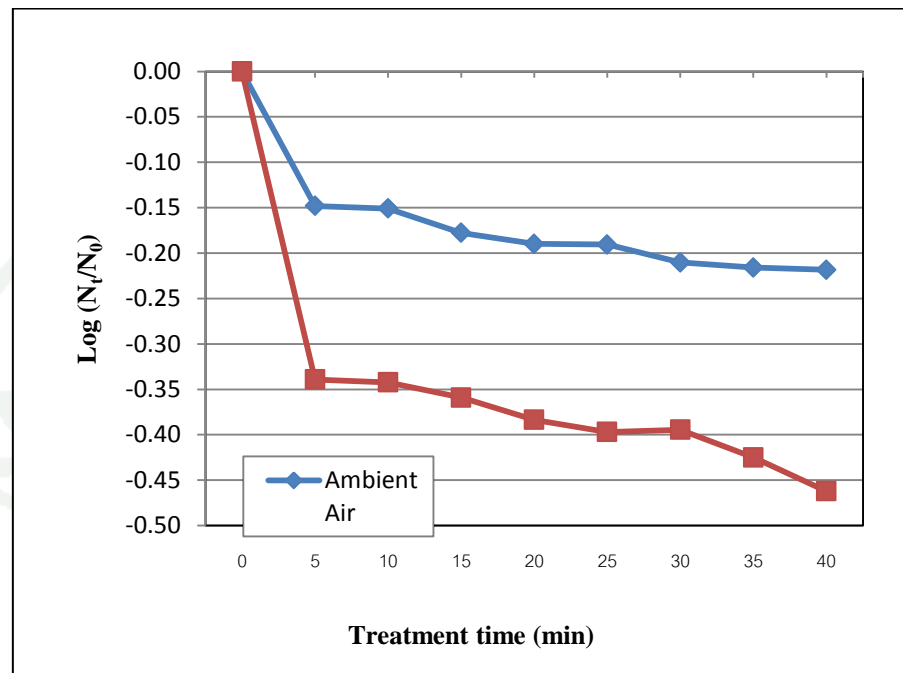


Figure 20 Inactivation performance of ambient air and exhaust gas against heterotrophic bacteria under 0.4 MPA of pressure when increase the treatment to 40 minute without circulation

Figure 20 shown the inactivation rate of ambient air and exhaust gas against heterotrophic bacteria under 0.4 MPA, when using ambient air and increasing treatment time to 30, 35, 40 minute, the log survival ratios are -0.21,-0.22,-0.22 respectively, When using exhaust gas and increasing treatment time to 30,35,40 minute, the log survival ratios are -0.39,-0.43,-0.46 respectively,

The inactivation of ambient air and exhaust gas against fecal coliform bacteria and heterotrophic bacteria with both circulate condition and without circulate was increased with increasing treatment time. This because when to CO_2 dissolve in the water, its need the time to dissolve. The long duration time can enhances the solubility of CO_2 .

3. The effect of air and exhaust gas to Total Solid (TS) and Suspended Solid (SS) at 0.4 MPA pressure.

Feeding the air and exhaust gas to water may effect water quality, therefore the water quality was measured total solid and suspended solid and pH at 0.4 MPA. The results are shown figure 21. From Figure 21, it is found that when feeding the air to the water, the SS increase percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are 10%, 13%, 23% and 25%, respectively and the TS increase percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are 2%, 8%, 20% and 23%, respectively.

From figure 22, it is found that when feeding the air to the water, the SS increase percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are 10%, 24%, 28% and 31%, respectively and the TS increase percentages under 0.1, 0.2, 0.3 and 0.4 MPA in 25-minute detention period are 3%, 10%, 15% and 20%, respectively

From the obtained result, it is found that when the air and exhaust gas is fed, SS and TS increases at every operating pressure. The reason for this result is the ambient and exhaust gas contain many solids particles, when it was fed to the water will increase the solids in water.

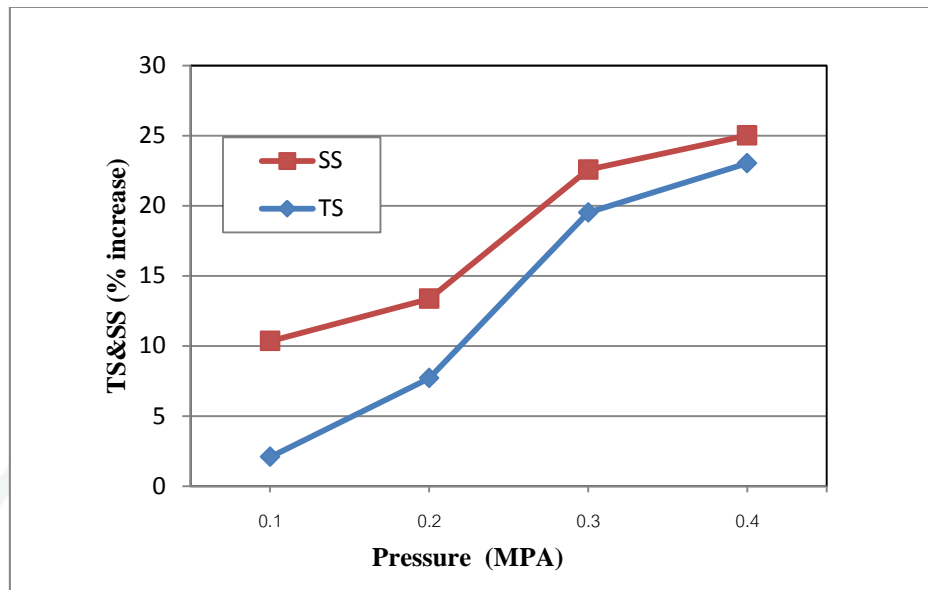


Figure 21 Percentages increase of SS&TS when using air gas in 25 minute treatment time

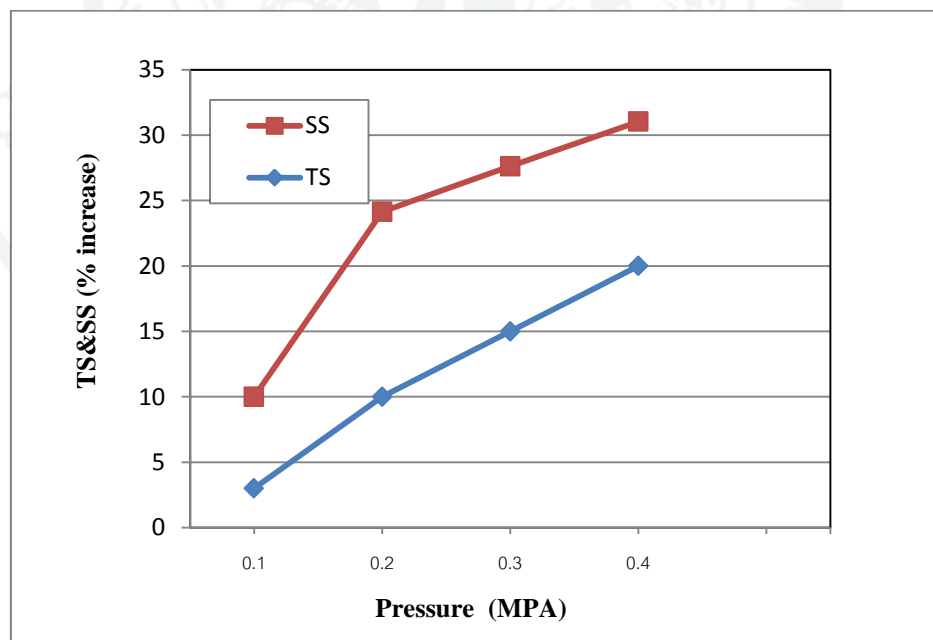


Figure 22 Percentages increase of SS&TS when using exhaust gas in 25 minute treatment time

4. The effect of air and exhaust gas to pH.

Figure 23 shows the pH change when air and exhaust was fed to the experiment which 25 minutes of treatment time, when using air ph decrease from 8.12 to 7.50. When using exhaust gas ph decrease from 8.12 to 6.04.

The decreasing of ph when using air was lower than when using exhaust gas. This is due to the difference in CO₂ partial pressure which causes different concentrations of dissolved gas in water, when the CO₂ solute in water, the effect of dissolving CO₂ in water is the removal of carbonate ions and production of bicarbonate ions, with a lowering in pH.

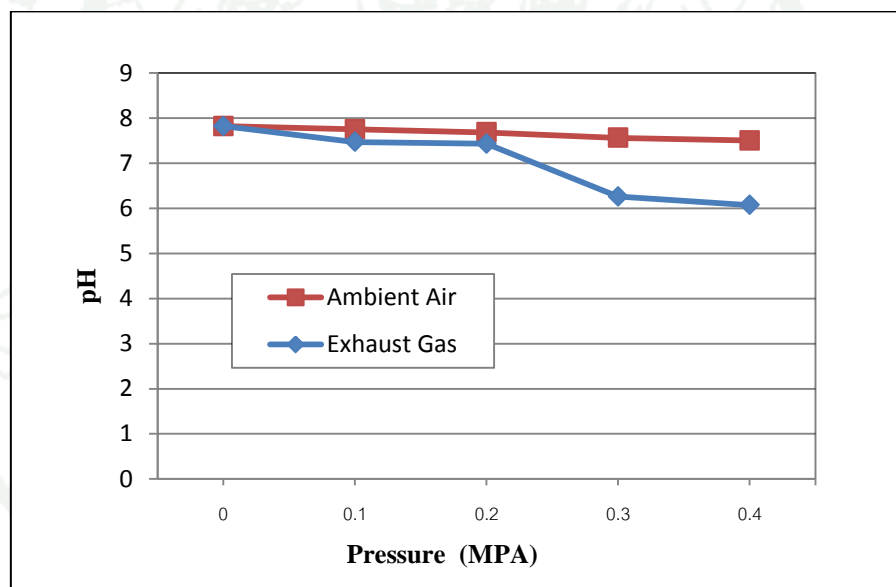


Figure 23 Percentages increase of SS&TS when using air in 25 minute treatment time

5. Composition of exhaust gas

The exhaust gas was measured by gas analyzer, the result shows in table 12

Table 12 Composition of exhaust gas

Time	HC	CO	CO ₂	O ₂	NO _x
	ppm	% Volume	% Volume	% Volume	ppm
5 min	10	0	6.99	10.00	547
10 min	12	0	6.73	10.75	1047
15 min	10	0	6.67	10.16	845
20 min	8	0	5.98	11.44	387
25 min	8	0	6.09	11.63	823
30 min	8	0	5.99	12.11	597
35 min	8	0	5.52	12.12	910
40 min	10	0	5.99	11.74	455

CONCLUSION AND RECOMMENDATIONS

1. Conclusion

Based on the high level dissolve CO₂ at low pressure effectiveness to inactivation many microorganism, the major objective in this study were to investigate the inactivation rate of fecal coliform and heterotrophic bacteria by using CO₂ produced from fuel combustion the range of 0.1-0.4 MPa with contact time 5-25 minutes under circulation and without circulation compared to the inactivation rate of fecal coliform and heterotrophic bacteria by using CO₂ from the ambient air at the range of 0.1-0.4 MPa with contact time 5-25 minutes under circulation and without circulation

The results obtained from this study reveal, when using CO₂ produced from fuel combustion the inactivation rate of fecal coliform with circulation was higher than the inactivation rate of fecal coliform without circulation at every pressure and treatment time as the same way the inactivation rate of heterotrophic bacteria with circulation was higher than the inactivation rate of heterotrophic bacteria without circulation at every pressure and treatment time.

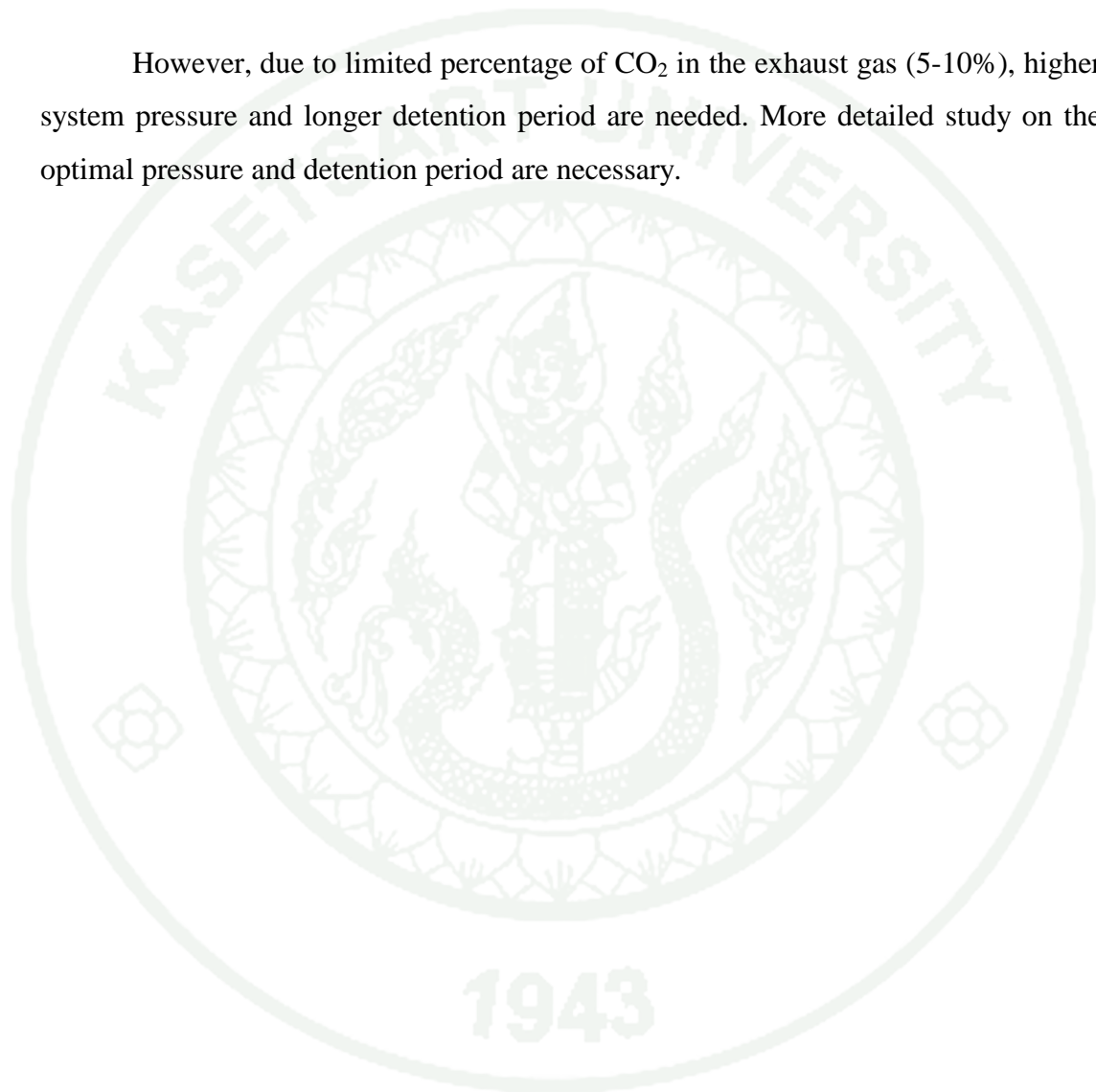
When using CO₂ from ambient air the inactivation rate of fecal coliform with circulation was higher than the inactivation rate of fecal coliform without circulation at every pressure and treatment time as the same way the inactivation rate of heterotrophic bacteria with circulation was higher than the inactivation rate of heterotrophic bacteria without circulation at every pressure and treatment time.

The inactivation rate when using CO₂ produced from fuel combustion was higher the inactivation rate when using CO₂ from ambient air. The CO₂ in the exhaust gas can be used to inactivate microorganisms in wastewater effluent. This can help reduce the chemical cost for disinfection and can avoid formation of disinfection byproducts.

2. Recommendation

The feeding of the exhaust gas to the water will increase the suspended solid and total solid. The removal of suspended solid and total solid are needed.

However, due to limited percentage of CO₂ in the exhaust gas (5-10%), higher system pressure and longer detention period are needed. More detailed study on the optimal pressure and detention period are necessary.



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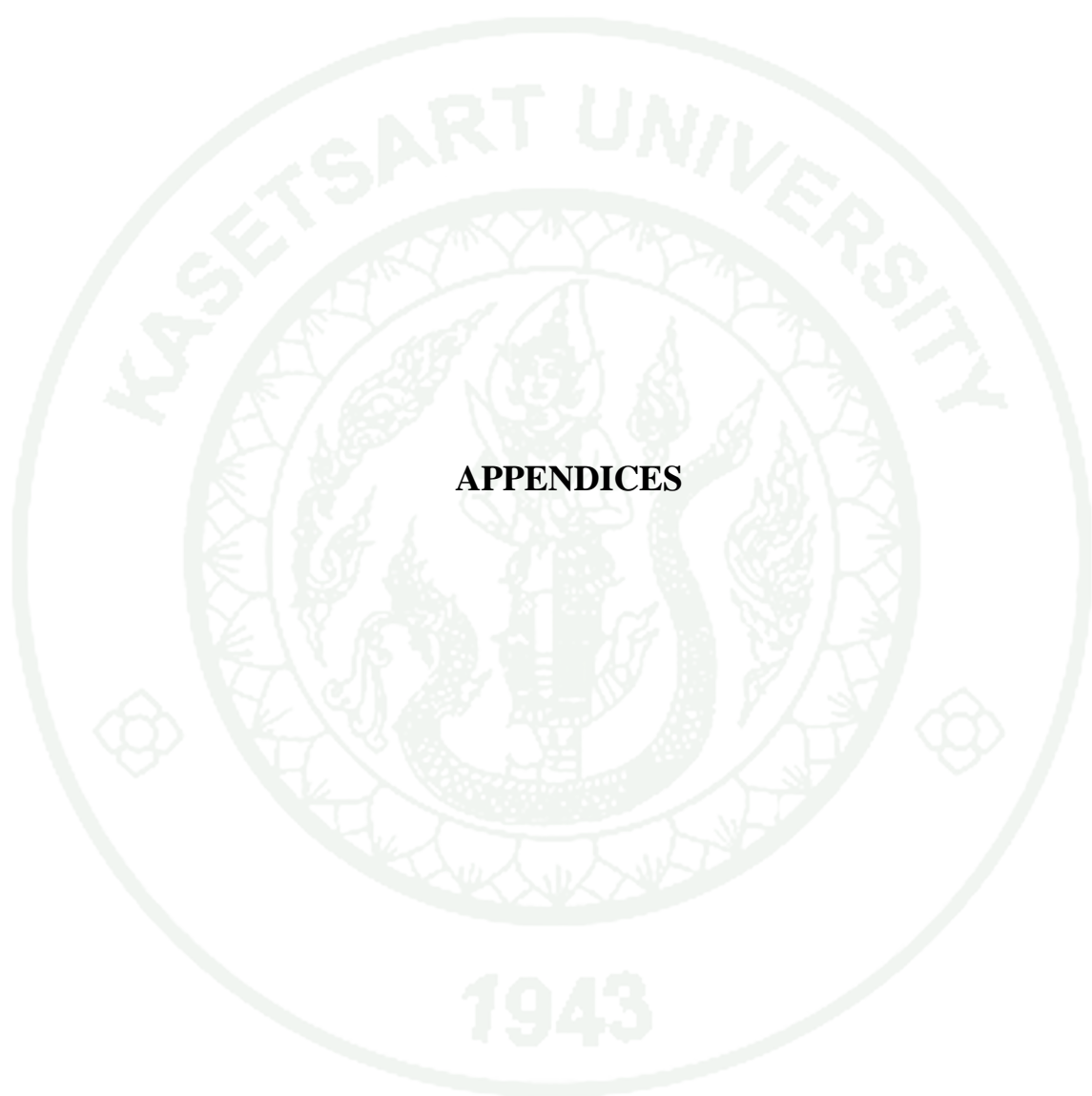
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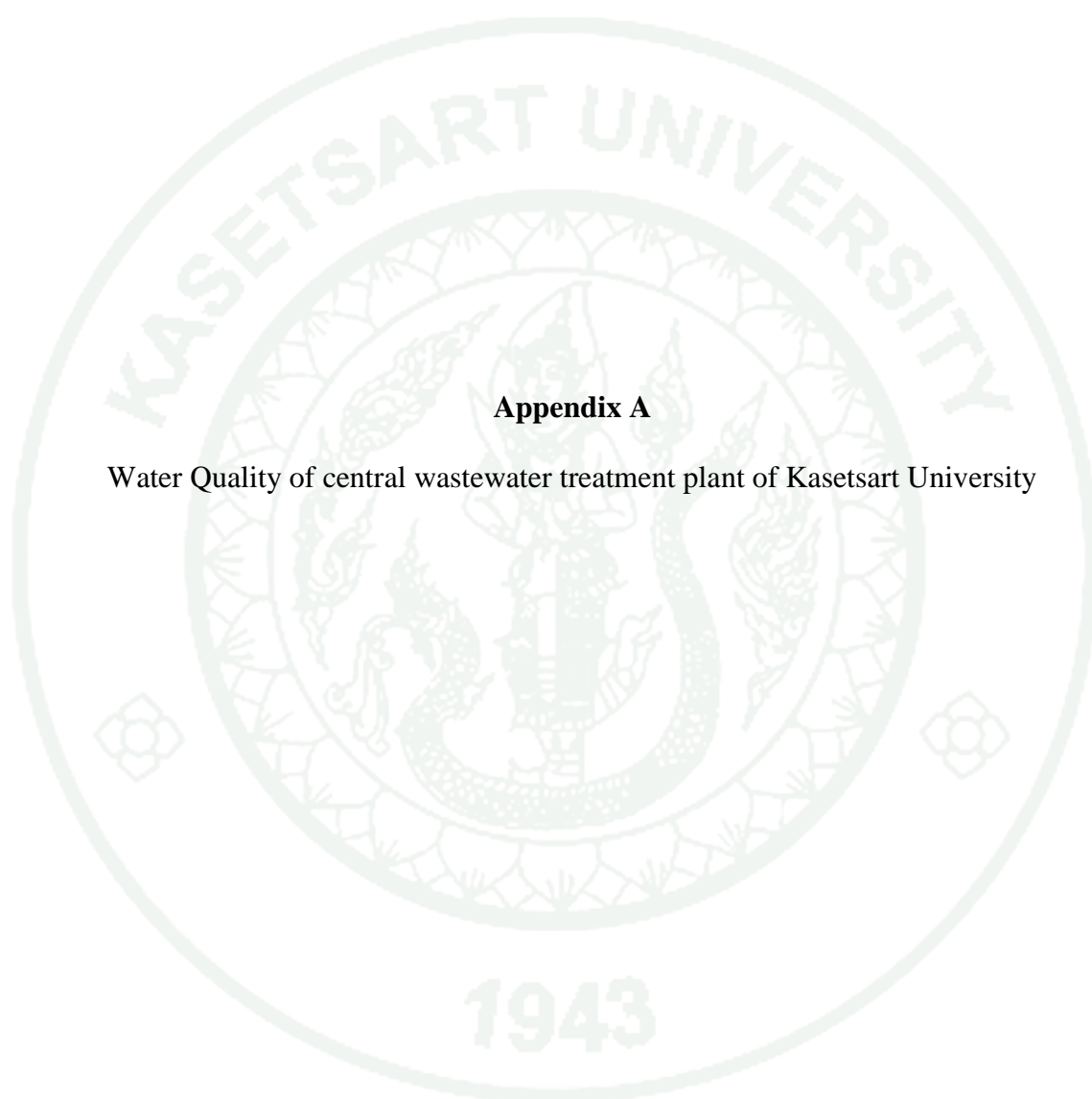
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APPENDICES

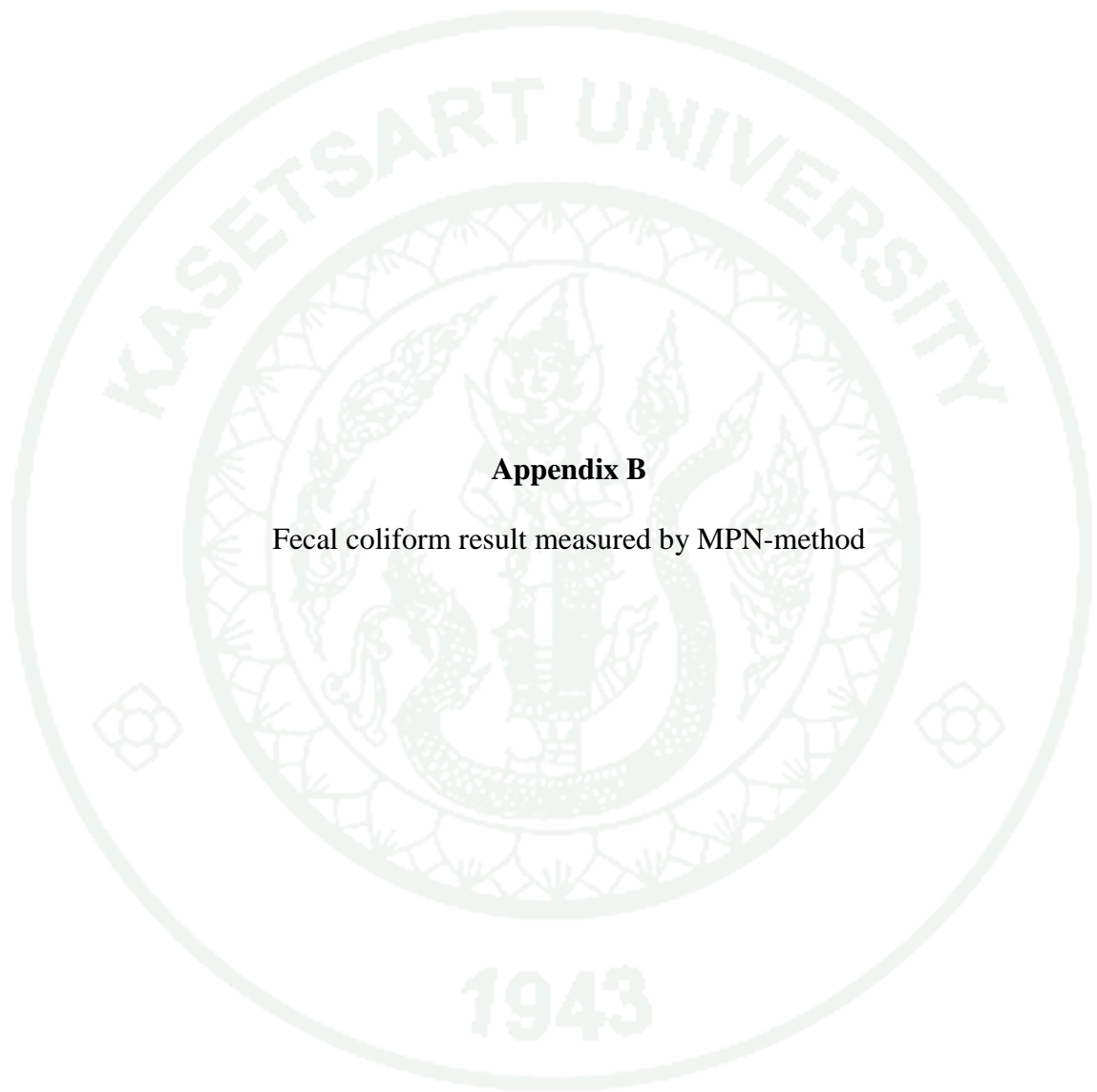


Appendix A

Water Quality of central wastewater treatment plant of Kasetsart University

Appendix Table A1 Water Quality of central wastewater treatment plant of Kasetsart University

Parameter	Value
Fecal Coliform (MPN/100 ml)	28000
Heterotrophic bacteria	29183+-8.74
Total Solid	480.67+-17.01
Suspended Solid	16.11+-1.92
pH	7.82+-0.43



Appendix B

Fecal coliform result measured by MPN-method

Appendix Table B1 MPN index of fecal coliform when using ambient air with circulation

Pressure (MPa)	Treatment Time (min)	Number of Positive Tube	Dilution Series	MPN Index/100 ml
0.1	5	5-4-3	0.1/0.01/0.001	28000
	10	5-5-0	0.1/0.01/0.001	24000
	15	5-5-0	0.1/0.01/0.001	24000
	20	5-4-2	0.1/0.01/0.001	22000
	25	5-4-2	0.1/0.01/0.001	22000
0.2	5	5-4-3	0.1/0.01/0.001	28000
	10	5-5-0	0.1/0.01/0.001	28000
	15	5-5-0	0.1/0.01/0.001	22000
	20	5-4-2	0.1/0.01/0.001	22000
	25	5-4-2	0.1/0.01/0.001	21000
0.3	5	5-4-3	0.1/0.01/0.001	28000
	10	5-5-0	0.1/0.01/0.001	22000
	15	5-5-0	0.1/0.01/0.001	21000
	20	5-4-2	0.1/0.01/0.001	17000
	25	5-4-2	0.1/0.01/0.001	17000
0.4	5	5-4-3	0.1/0.01/0.001	22000
	10	5-5-0	0.1/0.01/0.001	21000
	15	5-5-0	0.1/0.01/0.001	17000
	20	5-4-2	0.1/0.01/0.001	17000
	25	5-4-2	0.1/0.01/0.001	15000

Appendix Table B2 MPN index of fecal coliform when using exhaust gas with circulation

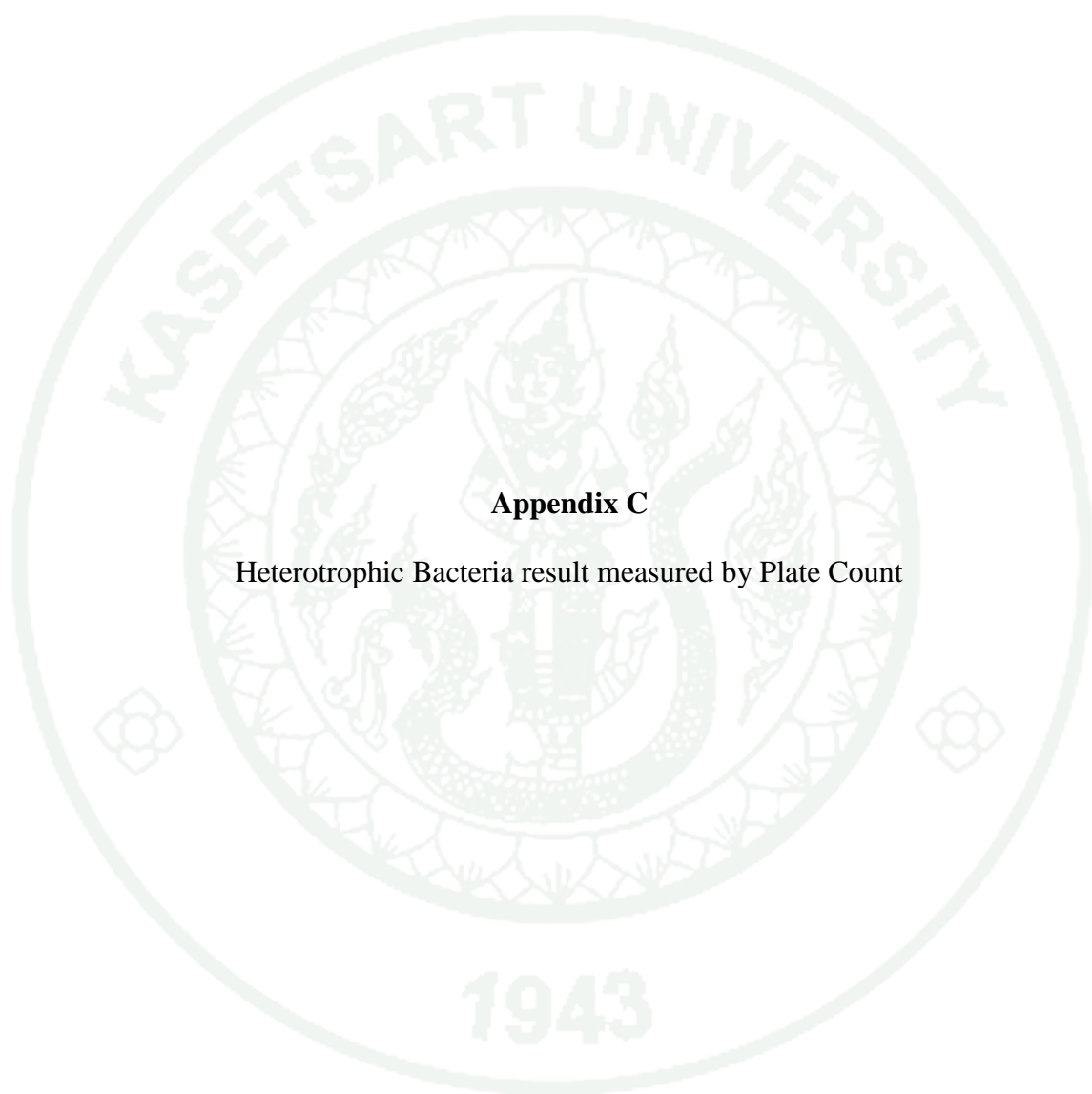
Pressure (MPa)	Treatment Time (min)	Number of Positive Tube	Dilution Series	MPN Index/100 ml
0.1	5	5-4-3	0.1/0.01/0.001	24000
	10	5-4-2	0.1/0.01/0.001	24000
	15	5-3-4	0.1/0.01/0.001	21000
	20	5-2-4	0.1/0.01/0.001	15000
	25	5-3-2	0.1/0.01/0.001	14000
0.2	5	5-5-0	0.1/0.01/0.001	24000
	10	5-3-4	0.1/0.01/0.001	21000
	15	5-3-3	0.1/0.01/0.001	17000
	20	5-2-4	0.1/0.01/0.001	15000
	25	5-3-1	0.1/0.01/0.001	11000
0.3	5	5-4-3	0.1/0.01/0.001	22000
	10	5-5-0	0.1/0.01/0.001	17000
	15	5-5-0	0.1/0.01/0.001	15000
	20	5-4-2	0.1/0.01/0.001	11000
	25	5-4-2	0.1/0.01/0.001	7000
0.4	5	5-4-3	0.1/0.01/0.001	17000
	10	5-5-0	0.1/0.01/0.001	15000
	15	5-5-0	0.1/0.01/0.001	11000
	20	5-4-2	0.1/0.01/0.001	7000
	25	5-4-2	0.1/0.01/0.001	6300

Appendix Table B3 MPN index of fecal coliform when using ambient air without circulation

Pressure (MPa)	Treatment Time (min)	Number of Positive Tube	Dilution Series	MPN Index/100 ml
0.1	5	5-4-3	0.1/0.01/0.001	28,000
	10	5-4-3	0.1/0.01/0.001	28,000
	15	5-4-3	0.1/0.01/0.001	28,000
	20	5-3-5	0.1/0.01/0.001	24,100
	25	5-5-0	0.1/0.01/0.001	24,000
0.2	5	5-4-2	0.1/0.01/0.001	22,000
	10	5-4-3	0.1/0.01/0.001	28,000
	15	5-4-3	0.1/0.01/0.001	28,000
	20	5-5-0	0.1/0.01/0.001	24,000
	25	5-5-1	0.1/0.01/0.001	24,000
0.3	5	5-4-2	0.1/0.01/0.001	22,000
	10	5-3-4	0.1/0.01/0.001	21,000
	15	5-4-3	0.1/0.01/0.001	28,000
	20	5-3-5	0.1/0.01/0.001	24,100
	25	5-5-0	0.1/0.01/0.001	24,000
0.4	5	5-4-2	0.1/0.01/0.001	22,000
	10	5-3-4	0.1/0.01/0.001	21,000
	15	5-2-5	0.1/0.01/0.001	19,700
	20	5-4-3	0.1/0.01/0.001	28,000
	25	5-5-0	0.1/0.01/0.001	24,000

Appendix Table B4 MPN index of fecal coliform when using exhaust gas without circulation

Pressure (MPa)	Treatment Time (min)	Number of Positive Tube	MPN Index/100 ml
0.1	5	5-4-3	28,000
	10	5-4-3	28,000
	15	5-4-3	28,000
	20	5-3-5	24,100
	25	5-4-2	22,000
0.2	5	5-3-4	21,000
	10	5-4-3	28,000
	15	5-3-5	24,100
	20	5-5-0	24,000
	25	5-4-2	22,000
0.3	5	5-3-4	21,000
	10	5-3-3	17,000
	15	5-4-3	28,000
	20	5-5-0	24,000
	25	5-4-2	22,000
0.4	5	5-2-5	19,700
	10	5-4-1	17,000
	15	5-2-4	15,000
	20	5-4-3	28,000
	25	5-3-4	21,000



Appendix C

Heterotrophic Bacteria result measured by Plate Count

Appendix Table C1 CFU/ml+-SD of heterotrophic bacteria when using air ambient

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.1	5	10 ⁻¹	270	350	372			
		10 ⁻²	281	289	267	279.00	11.14	27850
		10 ⁻³	65	33	67			
	10	10 ⁻¹	288	312	321			
		10 ⁻²	256	258	289	267.67	18.50	26717
		10 ⁻³	13	20	13			
	15	10 ⁻¹	312	321	298			
		10 ⁻²	265	254	261	260.00	5.57	25950
		10 ⁻³	100	20	87			
	20	10 ⁻¹	298	256	313			
		10 ⁻²	241	265	267	257.67	14.47	25717
		10 ⁻³	98	21	36			
25	10 ⁻¹	353	342	398				
	10 ⁻²	254	265	243	254.00	11.00	25350	
	10 ⁻³	45	108	90				
0.2	5	10 ⁻¹	311	319	340			
		10 ⁻²	231	254	259	248.00	14.93	24750
		10 ⁻³	34	14	56			
	10	10 ⁻¹	291	342	301			
		10 ⁻²	254	231	254	246.33	13.28	24583
		10 ⁻³	11	21	32			
	15	10 ⁻¹	312	342	301			
		10 ⁻²	222	234	265	240.33	22.19	23983
		10 ⁻³	15	34	76			
	20	10 ⁻¹	345	321	318			
		10 ⁻²	251	231	231	237.67	11.55	23717
		10 ⁻³	120	43	64			
25	10 ⁻¹	343	255	318				
	10 ⁻²	245	222	224	230.33	12.74	22983	
	10 ⁻³	23	43	33				

Appendix Table C1 (Continued)

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.3	5	10 ⁻¹	321	343	312			
		10 ⁻²	209	213	243	221.67	18.58	22117
		10 ⁻³	59	59	80			
	10	10 ⁻¹	323	299	309			
		10 ⁻²	232	193	232	219.00	22.52	21850
		10 ⁻³	19	18	21			
	15	10 ⁻¹	322	312	343			
		10 ⁻²	212	200	232	214.67	16.17	21417
		10 ⁻³	23	25	33			
	20	10 ⁻¹	309	321	288			
		10 ⁻²	199	231	198	209.33	18.77	20883
		10 ⁻³	19	43	64			
25	10 ⁻¹	306	313	340				
	10 ⁻²	216	212	176	201.33	22.03	20083	
	10 ⁻³	28	67	44				
0.4	5	10 ⁻¹	305	321	311			
		10 ⁻²	183	197	188	189.33	7.09	18883
		10 ⁻³	45	78	35			
	10	10 ⁻¹	311	301	342			
		10 ⁻²	199	165	176	180.00	17.35	17950
		10 ⁻³	21	28	29			
	15	10 ⁻¹	317	309	312			
		10 ⁻²	165	176	187	176.00	11.00	17550
		10 ⁻³	34	12	32			
	20	10 ⁻¹	321	343	312			
		10 ⁻²	145	189	174	169.33	22.37	16883
		10 ⁻³	65	20	31			
25	10 ⁻¹	325	342	213				
	10 ⁻²	167	189	140	165.33	24.54	16483	
	10 ⁻³	21	20	30				

Appendic Table C1 (Continued)

Pressure (MPa)	treatment time (min)	Dilution	Colonies Plate			Average	SD	CFU/m ^l
			1	2	3			
0.4	30	10 ⁻¹	300	234	298			
		10 ⁻²	145	154	176	158.33	15.95	15783
		10 ⁻³	21	20	20			
	35	10 ⁻¹	276	277	288			
		10 ⁻²	144	169	165	159.33	13.43	15883
		10 ⁻³	20	10	15			
	40	10 ⁻¹	288	271	289			
		10 ⁻²	161	165	143	156.33	11.72	15583
		10 ⁻³	31	15	20			

Appendix Table C2 CFU/ml+-SD of heterotrophic bacteria when using exhaust gas

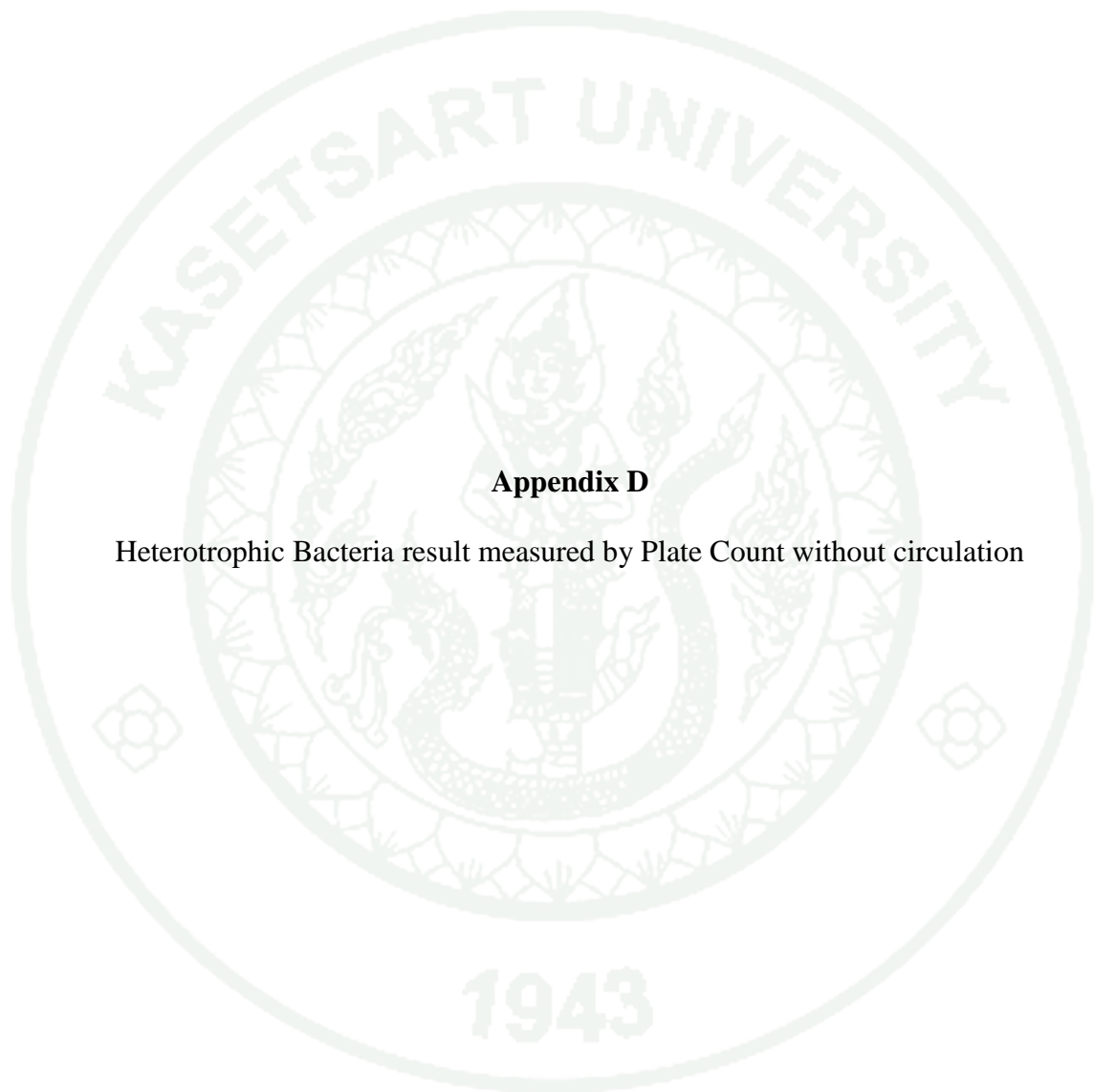
Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.1	5	10 ⁻¹	312	331	312			
		10 ⁻²	232	222	245	233.00	11.53	23250
		10 ⁻³	40	62	60			
	10	10 ⁻¹	299	245	287			
		10 ⁻²	256	213	226	231.67	22.05	23167
		10 ⁻³	65	43	33			
	15	10 ⁻¹	214	324	314			
		10 ⁻²	231	212	231	224.67	10.97	22467
		10 ⁻³	24	30	34			
	20	10 ⁻¹	345	312	312			
		10 ⁻²	234	230	200	221.33	18.58	22133
		10 ⁻³	22	32	33			
25	10 ⁻¹	331	287	319				
	10 ⁻²	200	214	200	204.67	8.08	20467	
	10 ⁻³	40	45	33				
0.2	5	10 ⁻¹	245	311	312			
		10 ⁻²	189	197	223	203.00	17.78	20300
		10 ⁻³	40	43	33			
	10	10 ⁻¹	318	320	321			
		10 ⁻²	214	199	188	200.33	13.05	20033
		10 ⁻³	29	45	19			
	15	10 ⁻¹	388	333	321			
		10 ⁻²	145	189	188	174.00	25.12	17400
		10 ⁻³	34	44	21			
	20	10 ⁻¹	318	365	319			
		10 ⁻²	177	167	176	173.33	5.51	17333
		10 ⁻³	30	33	10			
25	10 ⁻¹	344	343	31				
	10 ⁻²	132	211	169	170.67	39.53	17067	
	10 ⁻³	29	21	14				

Appendix Table C2 (Continued)

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.3	5	10 ⁻¹	345	312	331			
		10 ⁻²	145	140	164	149.67	12.66	14967
		10 ⁻³	43	14	25			
	10	10 ⁻¹	312	301	288			
		10 ⁻²	134	156	134	141.33	12.70	14133
		10 ⁻³	15	32	20			
	15	10 ⁻¹	317	365	299			
		10 ⁻²	144	155	109	136.00	24.02	13600
		10 ⁻³	13	43	20			
	20	10 ⁻¹	299	267	301			
		10 ⁻²	134	140	114	129.33	13.61	12933
		10 ⁻³	19	13	20			
25	10 ⁻¹	213	324	345				
	10 ⁻²	132	101	119	117.33	15.57	11733	
	10 ⁻³	18	10	4				
0.4	5	10 ⁻¹	288	256	291			
		10 ⁻²	116	98	101	105.00	9.64	10500
		10 ⁻³	12	90	30			
	10	10 ⁻¹	231	241	345			
		10 ⁻²	98	91	103	97.33	6.03	9733
		10 ⁻³	13	12	32			
	15	10 ⁻¹	312	298	288			
		10 ⁻²	91	95	88	91.33	3.51	9133
		10 ⁻³	21	12	23			
	20	10 ⁻¹	321	214	265			
		10 ⁻²	89	94	91	91.33	2.52	9133
		10 ⁻³	6	4	2			
25	10 ⁻¹	256	298	312				
	10 ⁻²	98	87	76	87.00	11.00	8700	
	10 ⁻³	2	3	8				

Appendix Table C2 (Continued)

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.4	30	10 ⁻¹	298	217	256			
		10 ⁻²	87	77	76	80.00	6.08	8000
		10 ⁻³	2	4	3			
	35	10 ⁻¹	224	214	212			
		10 ⁻²	78	80	77	78.33	1.53	7833
		10 ⁻³	5	6	7			
	40	10 ⁻¹	217	223	212			
		10 ⁻²	71	75	81	75.67	5.03	7567
		10 ⁻³	5	4	10			



Appendix D

Heterotrophic Bacteria result measured by Plate Count without circulation

Appendix Table D1 CFU/ml+-SD of heterotrophic bacteria when using air ambient without circulation

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.1	5	10 ⁻¹	311	342	231			
		10 ⁻²	265	298	287	283.33	16.80	28283
		10 ⁻³	20	30	12			
	10	10 ⁻¹	309	304	311			
		10 ⁻²	278	287	267	277.33	10.02	27683
		10 ⁻³	50	20	30			
	15	10 ⁻¹	312	343	298			
		10 ⁻²	265	276	276	272.33	6.35	27183
		10 ⁻³	25	45	44			
	20	10 ⁻¹	311	322	301			
		10 ⁻²	265	245	278	262.67	16.62	26217
		10 ⁻³	34	30	16			
25	10 ⁻¹	313	321	301				
	10 ⁻²	233	254	287	258.00	27.22	25750	
	10 ⁻³	30	34	25				
0.2	5	10 ⁻¹	298	295	306			
		10 ⁻²	265	243	265	257.67	12.70	25717
		10 ⁻³	28	40	53			
	10	10 ⁻¹	312	354	310			
		10 ⁻²	232	254	270	252.00	19.08	25150
		10 ⁻³	43	20	30			
	15	10 ⁻¹	321	297	331			
		10 ⁻²	234	245	265	248.00	15.72	24750
		10 ⁻³	38	26	31			
	20	10 ⁻¹	338	354	354			
		10 ⁻²	268	224	255	249.00	22.61	24850
		10 ⁻³	30	30	28			
25	10 ⁻¹	318	321	344				
	10 ⁻²	245	234	251	243.33	8.62	24283	
	10 ⁻³	20	29	33				

Appendix Table D1 (Continued)

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.3	5	10 ⁻¹	321	324	354			
		10 ⁻²	221	222	276	239.67	31.47	23917
		10 ⁻³	20	34	23			
	10	10 ⁻¹	319	345	288			
		10 ⁻²	219	212	261	230.67	26.50	23017
		10 ⁻³	32	26	32			
	15	10 ⁻¹	297	308	323			
		10 ⁻²	232	231	222	228.33	5.51	22783
		10 ⁻³	12	20	23			
	20	10 ⁻¹	321	334	356			
		10 ⁻²	234	211	232	225.67	12.74	22517
		10 ⁻³	29	33	21			
25	10 ⁻¹	319	288	298				
	10 ⁻²	231	213	229	224.33	9.87	22383	
	10 ⁻³	54	26	32				
0.4	5	10 ⁻¹	322	345	321			
		10 ⁻²	204	211	209	208.00	3.61	20750
		10 ⁻³	31	22	18			
	10	10 ⁻¹	303	299	301			
		10 ⁻²	213	199	208	206.67	7.09	20617
		10 ⁻³	29	23	89			
	15	10 ⁻¹	312	312	323			
		10 ⁻²	183	222	178	194.33	24.09	19383
		10 ⁻³	20	12	24			
	20	10 ⁻¹	288	298	301			
		10 ⁻²	222	189	156	189.00	33.00	18850
		10 ⁻³	20	34	21			
25	10 ⁻¹	300	301	317				
	10 ⁻²	205	195	166	188.67	20.26	18817	
	10 ⁻³	29	23	28				

Appendix Table D1 (Continued)

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.4	30	10 ⁻¹	269	289	291			
		10 ⁻²	178	198	165	180.33	16.62	17983
		10 ⁻³	15	20	13			
	35	10 ⁻¹	287	289	245			
		10 ⁻²	180	165	189	178.00	12.12	17750
		10 ⁻³	13	20	22			
	40	10 ⁻¹	287	245	234			
		10 ⁻²	165	188	178	177.00	11.53	17650
		10 ⁻³	13	12	13			

Appendix Table D2 CFU/ml+-SD of heterotrophic bacteria when using exhaust
without circulation

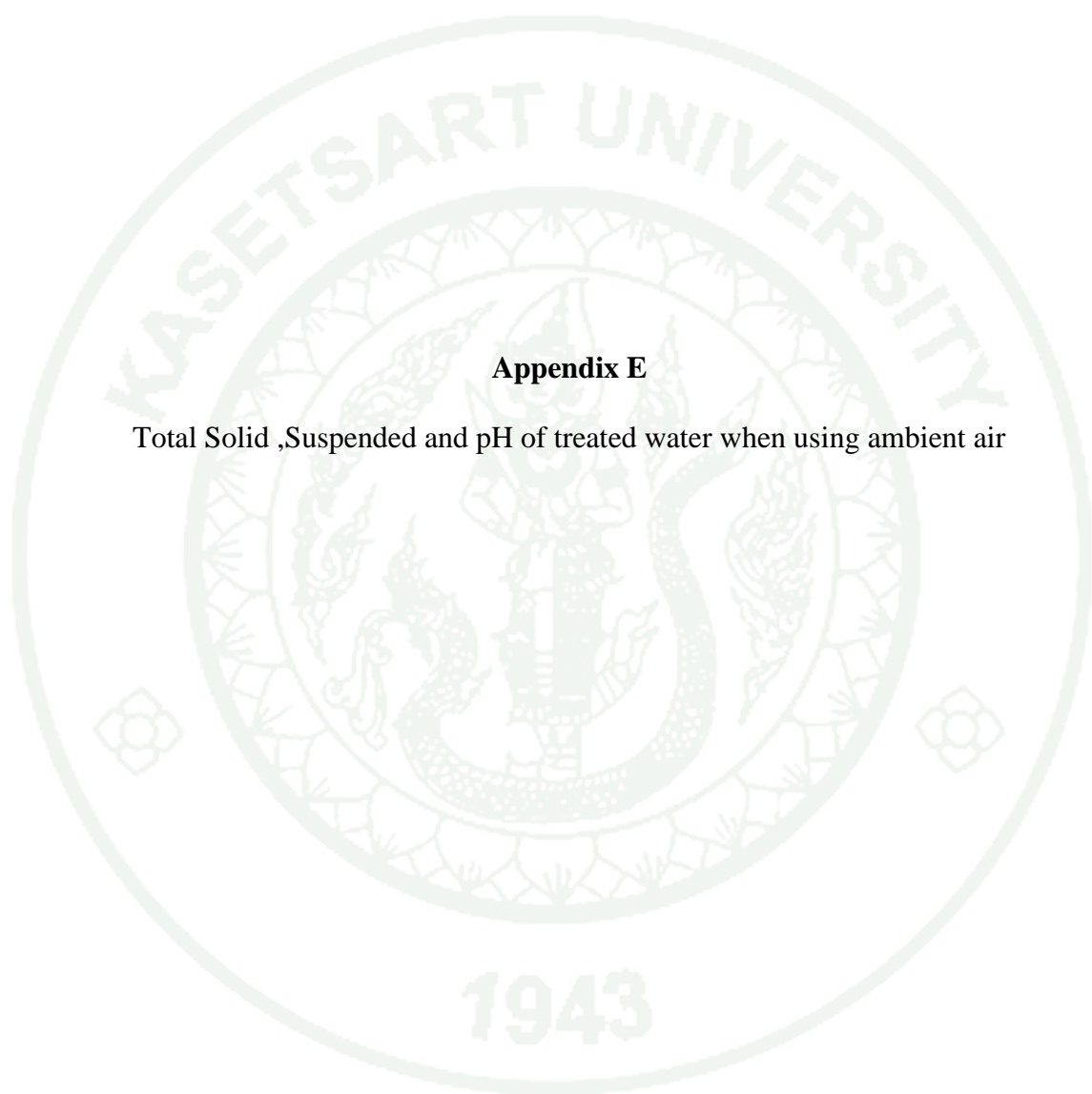
Pressure (MPa)	Time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.1	5	10 ⁻¹	300	321	311			
		10 ⁻²	256	261	266	261.00	5.00	26100
		10 ⁻³	44	34	26			
	10	10 ⁻¹	316	322	321			
		10 ⁻²	267	254	234	251.67	16.62	25167
		10 ⁻³	34	20	21			
	15	10 ⁻¹	311	323	299			
		10 ⁻²	216	265	251	244.00	25.24	24400
		10 ⁻³	55	20	44			
	20	10 ⁻¹	301	313	321			
		10 ⁻²	231	242	256	243.00	12.53	24300
		10 ⁻³	43	22	32			
25	10 ⁻¹	345	321	321				
	10 ⁻²	231	211	222	221.33	10.02	22133	
	10 ⁻³	33	45	32				
0.2	5	10 ⁻¹	306	333	351			
		10 ⁻²	212	200	209	207.00	6.24	20700
		10 ⁻³	43	34	33			
	10	10 ⁻¹	318	316	343			
		10 ⁻²	201	212	198	203.67	7.37	20367
		10 ⁻³	30	45	34			
	15	10 ⁻¹	339	343	321			
		10 ⁻²	209	187	191	195.67	11.72	19567
		10 ⁻³	18	16	32			
	20	10 ⁻¹	343	343	332			
		10 ⁻²	195	184	189	189.33	5.51	18933
		10 ⁻³	22	23	34			
25	10 ⁻¹	331	343	319				
	10 ⁻²	181	189	193	187.67	6.11	18767	
	10 ⁻³	45	20	34				

Appendix Table D2 (Continued)

Pressure (MPa)	Time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.3	5	10 ⁻¹	309	312	318			
		10 ⁻²	165	165	166	165.33	0.58	16533
		10 ⁻³	31	34	43			
	10	10 ⁻¹	298	288	308			
		10 ⁻²	176	143	156	158.33	16.62	15833
		10 ⁻³	29	45	32			
	15	10 ⁻¹	300	312	305			
		10 ⁻²	156	155	145	152.00	6.08	15200
		10 ⁻³	27	29	20			
	20	10 ⁻¹	304	298	281			
		10 ⁻²	150	148	144	147.33	3.06	14733
		10 ⁻³	25	43	21			
25	10 ⁻¹	287	278	305				
	10 ⁻²	143	124	134	133.67	9.50	13367	
	10 ⁻³	34	12	34				
0.4	5	10 ⁻¹	294	298	289			
		10 ⁻²	121	145	132	132.67	12.01	13267
		10 ⁻³	30	33	21			
	10	10 ⁻¹	298	287	288			
		10 ⁻²	129	122	132	127.67	5.13	12767
		10 ⁻³	30	40	21			
	15	10 ⁻¹	289	278	287			
		10 ⁻²	121	113	128	120.67	7.51	12067
		10 ⁻³	22	20	15			
	20	10 ⁻¹	310	304	287			
		10 ⁻²	99	129	123	117.00	15.87	11700
		10 ⁻³	14	20	22			
25	10 ⁻¹	309	312	318				
	10 ⁻²	165	165	166	165.33	0.58	16533	
	10 ⁻³	31	34	43				

Appendix Table D2 (Continued)

Pressure (MPa)	time (min)	Dilution	Colonies Plate			Average	SD	CFU/ml
			1	2	3			
0.4	30	10 ⁻¹	321	329	365			
		10 ⁻²	118	131	104	117.67	13.50	11767
		10 ⁻³	17	18	11			
	35	10 ⁻¹	321	389	343			
		10 ⁻²	105	103	121	109.67	9.87	10967
		10 ⁻³	16	19	11			
	40	10 ⁻¹	291	267	287			
		10 ⁻²	90	101	111	100.67	10.50	10067
		10 ⁻³	18	9	5			



Appendix E

Total Solid ,Suspended and pH of treated water when using ambient air

Appendix Table E1 Suspended Solid of treated water when using air ambient

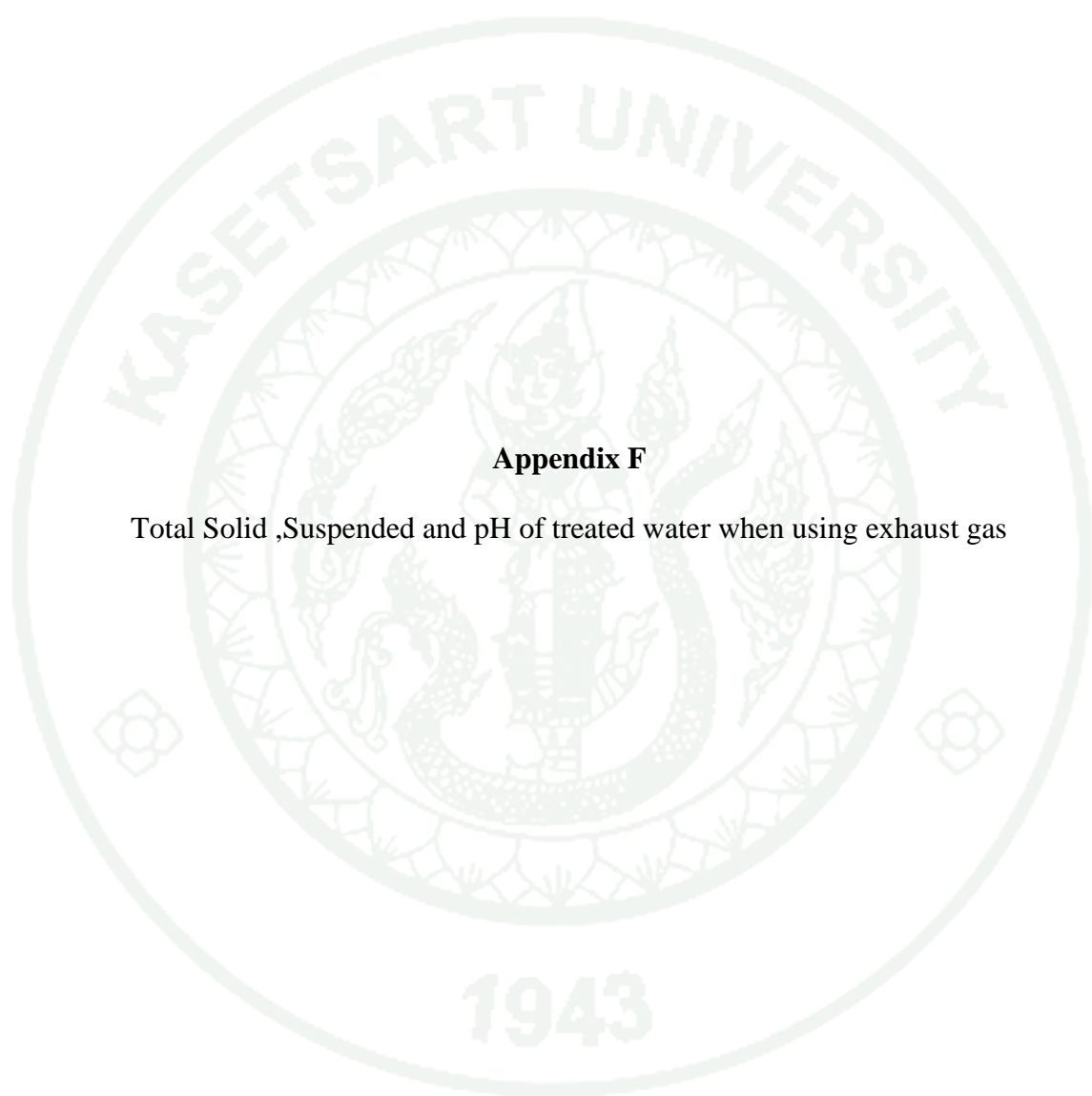
Pressure (MPa)	Sample	Volume (ml)	X (g)	Y (g)	SS (mg/l)	SS (mg/l)+-SD
0.1	1	60	3.4521	3.4531	16.6667	16.11+-0.96
	2	60	4.5321	4.5330	15.0000	
	3	60	2.9879	2.9889	16.6667	
0.2	5	60	4.3219	4.3230	18.3333	16.67+-2.89
	10	60	4.1287	4.1295	13.3333	
	15	60	3.2132	3.2143	18.3333	
0.3	5	60	4.6543	4.6553	16.6667	17.22+-0.96
	10	60	2.9891	2.9901	16.6667	
	15	60	2.8743	2.8754	18.3333	
0.4	5	60	3.4211	3.4218	11.6667	17.78+-5.85
	10	60	4.1198	4.1209	18.3333	
	15	60	3.2123	3.2137	23.3333	

Appendix Table E2 Total Solid of treated water when using air ambient

Pressure (MPa)	Sample	Volume (ml)	A (g)	B (g)	TS (mg/l)	TS (mg/l)+-SD
0.1	1	50	54.9841	55.007	450.0000	481.33+-27.59
	2	50	51.8765	51.902	502.0000	
	3	50	52.7659	52.791	492.0000	
0.2	1	50	49.8091	49.832	450.0000	485.33+-56.08
	2	50	54.5421	54.57	550.0000	
	3	50	56.9871	57.0099	456.0000	
0.3	1	50	49.8654	49.89	484.0000	488.67+-21.39
	2	50	54.8763	54.9	470.0000	
	3	50	52.6541	52.6797	512.0000	
0.4	1	50	51.6531	51.679	512.000	489.33+-44.56
	2	50	49.6530	49.679	518.000	
	3	50	39.8876	39.91	438.000	

Appendix Table E3 pH of treated water when using air ambient

Pressure (MPa)	Sample	pH	pH+-SD
0.1	1	8.03	7.75+-0.25
	2	7.56	
	3	7.67	
0.2	1	7.45	7.68+-0.25
	2	7.95	
	3	7.65	
0.3	1	7.60	7.56+-0.05
	2	7.56	
	3	7.51	
0.4	1	7.55	7.5+-0.18
	2	7.65	
	3	7.30	



Appendix F

Total Solid ,Suspended and pH of treated water when using exhaust gas

Appendix Table F1 Suspended Solid of treated water when using exhaust gas

Pressure (MPa)	Sample	Volume (ml)	X (g)	Y (g)	SS (mg/l)	SS (mg/l)+-SD
0.1	1	60	3.4521	2.8772	18.3333	16.11+-0.96
	2	60	3.1154	3.1166	20.0000	
	3	60	3.7641	3.7651	16.6667	
0.2	5	60	4.3219	4.6139	18.3333	20.00+-3.33
	10	60	2.7843	2.7855	13.3333	
	15	60	3.0912	3.0926	18.3333	
0.3	5	60	3.8876	3.8892	26.6667	20.56+-6.74
	10	60	3.9081	3.9089	13.3333	
	15	60	4.5675	4.5688	21.6667	
0.4	5	60	2.9981	2.9989	13.3333	21.11+-12.06
	10	60	3.8650	3.8659	15.0000	
	15	60	2.9657	2.9678	35.0000	

Appendix Table F2 Total Solid of treated water when using exhaust gas

Pressure (MPa)	Sample	Volume (ml)	A (g)	B (g)	TS (mg/l)	TS (mg/l)+-SD
0.1	1	50	54.8216	53.9335	432.0000	511.00+-27.59
	2	50	49.5298	49.5565	534.0000	
	3	50	53.9123	84.8498	564.0000	
0.2	1	50	51.9854	52.0141	450.0000	520.67+-199.42
	2	50	49.9081	53.2478	550.0000	
	3	50	49.9081	49.9231	456.0000	
0.3	1	50	51.7632	51.7898	574.0000	523.33+-67.42
	2	50	50.9861	51.0154	688.0000	
	3	50	49.8765	49.8991	300.0000	
0.4	1	50	49.9870	50.0201	662.000	530.00+-120.47
	2	50	51.9876	52.0089	426.000	
	3	50	43.9861	44.0112	502.000	

Appendix Table F3 pH of treated water when using exhaust

Pressure (MPa)	Sample	pH	pH+-SD
0.1	1	10 ⁻¹	7.47+-0.53
	2	10 ⁻²	
	3	10 ⁻³	
0.2	1	7.45	7.13+-0.29
	2	6.91	
	3	7.02	
0.3	1	6.65	6.26+-0.34
	2	6.11	
	3	6.01	
0.4	1	6.19	6.07+-0.11
	2	5.98	
	3	6.04	

CURRICULUM VITAE

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BIRTH DATE : July 18, 1987

BIRTH PLACE : Mueng, Nakhonsrithammarat

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