อิทธิพลของตัวแปรในการดำเนินงานของเครื่องปฏิกรณ์โคโรนาดิสชาร์จต่อประสิทธิภาพการกำจัดเบนซีน

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Effect of operating variables of corona discharge reactor on benzene removal efficiency

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ธนันท์วุฒิ ธนหิรัญฐิติโชติ : อิทธิพลของตัวแปรในการดำเนินงานของเครื่องปฏิกรณ์โคโรนาดิสชาร์จต่อประสิทธิภาพการกำจัดเบนซีน (Effect of operating variables of corona discharge reactor onbenzene removal efficiency) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร.ธวัชชัย ชรินพาณิชกุล, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: ผศ. ดร.วีรวุฒิ ชัยวัฒน์, 86 หน้า.

สารอินทรีย์ระเหยง่ายเป็นสารมลพิษที่เกิดจากการเจริญเติบโตของอุตสาหกรรมและสังคมที่พัฒนาขึ้น ซึ่งมีสารอินทรีย์หลายชนิดที่ส่งผลกระทบต่อมนุษย์และสิ่งแวดล้อม ทำให้องค์กรที่เกี่ยวข้องออกมารณรงค์เพื่อควบคุมปัญหาเหล่านี้ โดยวิธีที่จะกำจัดสารอินทรีย์ระเหยง่ายเหล่านี้มีด้วยกันหลายวิธี โดยวิธีที่เรียกว่า โคโรนาดิสชาร์จ จะนำมาใช้ในงานนี้เนื่องจากเป็นวิธีที่ให้ประสิทธิภาพสูง และเป็นระบบที่ไม่ซับซ้อน ส่วนของสารเคมีนั้นจะเลือกใช้สารเบนซีนเพื่อนำมาเป็นตัวแทนของสารอินทรีย์ระเหยง่าย โดยการศึกษาประสิทธิภาพของการจำจัดเบนซีนนั้นจะศึกษาผลกระทบต่าง ๆ โดยจะใช้ลวดสแตนเลส ขนาดตั้งแต่ขนาด 0.1, 0.3 และ 0.6 มิลลิเมตร เป็นอิเล็กโทรดในเครื่องปฏิกรณ์, อัตราการไหลของก๊าซในช่วง 1,000 – 4,000 มิลลิลิตรต่อนาที, ความเข้มข้นเริ่มต้นตั้งแต่ 500 – 2,000 ส่วนในล้านส่วน และจำนวนแชนแนลในเครื่องปฏิกรณ์ตั้งแต่ 1, 2 และ 4 แชนแนล ซึ่งจากผลการทดลองพบว่าสามารถกำจัดเบนซีนได้สูงสุดถึง 93 เปอร์เซ็นต์ ภายใต้เงื่อนไขที่ใช้ลวดขนาด 0.6 มิลลิเมตร, อัตราการไหล 1,000 มิลลิลิตรต่อนาที และความเข้มข้นเริ่มต้น 500 ส่วนในล้านส่วน ในเครื่องปฏิกรณ์ที่ใช้รูปแบบ 1 แชนแนล

ภาควิชา	วิศวกรรมเคมี	ลายมือชื่อนิสิต .....
สาขาวิชา	วิศวกรรมเคมี	ลายมือชื่อ อ.ที่ปรึกษาหลัก .....
ปีการศึกษา	2560	ลายมือชื่อ อ.ที่ปรึกษาร่วม .....

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THANUNWUT THANAHIRUNTHITICHOTE: Effect of operating variables of corona discharge reactor onbenzene removal efficiency. ADVISOR: ASSOC. PROF. TAWATCHAI CHARINPANITKUL, D.Eng., CO-ADVISOR: ASST. PROF. WEERAWUT CHAIWAT, Ph.D., 86 pp.

Volatile organic compound (VOC) has been known as one of air pollutants generated by the fast growth of industry and social development. There were many kind of VOC which is harmful for humans and environments. All concerned organization requested controlling of these problems. As a result, there were many technologies developed for handling and degrading such VOC. Among these technologies, corona discharge reactor has been known as a promising means because of its effectiveness and compactness. In this work, benzene was selected as a model VOC pollutant. Performance of multi-channeled corona discharge reactor for removal of benzene was experimentally examined under effect of electrode size, gas flow rate, initial concentration and number of channels on removal of benzene. Stainless wire 0.1, 0.3 and 0.6 mm were employed as electrode for generating plasma within the reactor. The gas flow rate was varied in range 1,000 – 4,000 ml/min. The initial concentration of benzene was varied in a range of 500 – 2,000 ppm and the number of channels within the reactor was 1, 2 and 4 channels. Based on all experimental result, 93 percent of removal efficiency was achieved when the electrode with diameter of 0.6 mm, benzene flow rate of 1,000 ml/min, and concentration of 500 ppm were supplied into the single-channel reactor.

Department:	Chemical Engineering	Student's Signature .....
Field of Study:	Chemical Engineering	Advisor's Signature .....
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Chapter 1
Introduction

Nowadays, the growth of Industry from the social development has affected all sociological aspects, especially the environment and health of people. As a result of industrial manufacturing processes, evaporation of volatile chemicals stored improperly and leakage of chemicals could accidentally occur. If these chemicals contaminated with high volume are accumulated in the atmosphere, it would result in a serious impact on the environment and public health all along.

One of major pollutants mainly found in the air is VOCs (Volatile Organic Compounds) which are chemical substances that have been widely used in the industry. One of the VOCs, mostly found in the environment is “benzene”, which is often released from industrial factories. Generally, benzene is toxic to humans, creatures, and environment. The sources of benzene released to the atmosphere would come from combustion of coal, oil combustion in the engine, volatility of gasoline and smoke of a cigarette. Exposure to low concentration of benzene can cause acute effect such as eye skin and throat irritation, headache. On the other hand, exposure to high concentration can lead to serious impact including internal organs damage and especially cancer. Due to its high toxicity and inevitable, it is a substance that found in daily life. Therefore, organizations involved in health and environment have paid attention to this issue to find out how to prevent and remove benzene before release to the environment. For the pollutions standard of ambient air in Thailand must contain benzene less than 1.7 micrograms per cubic meter of benzene [1, 2].

Currently, there are existing technologies for VOCs removal such as bio-filtration, adsorption, direct combustion and catalytic combustion [3]. These technologies are low cost system and easy to control. Even though these technologies

are able to remove VOCs but there are disadvantages also. For example, the microbial agents of bio-filtration technology take a long time for their growth. Therefore, it is the reason to find an alternative technology for removal of VOCs

1.1 Motivation

Control of volatile organic compounds (VOCs) is a main environmental problem due to their toxicity affect to both human health and environment. Recently, a lot of technologies have been developed to removal of VOCs. Non-thermal plasma technology, especially corona discharge has received more attention in a field of air pollution controls because there are a lot of advantages including, high efficiency for removing target substances at low concentration, simple flow configuration, and low energy consumption [4]. From these advantages, it is interesting for a research issue in this thesis. Some aspects related to the effect of removal efficiency on corona discharge reactor which has been explored by our previous research team.

Previous studies have verified that volatile organic compounds can be efficiently degraded by corona discharge [5-8]. When VOCs was released into the corona reactor and passed through the discharge zone, gas molecules can be excited, ionized and dissociated depending on electron energy. Corona discharges are relatively low power electrical discharges that take place at or near atmospheric pressure. The corona is stably generated by strong electric fields associated with small diameter wires on an electrode. Therefore, corona discharge is a powerful technology to treat organic pollutants in atmosphere. However, it is still rarely practically used in industries because the optimum conditions could be easily changed when parameters and configurations of reactor changed.

Therefore, optimization of experimental parameters is still needed to improve the efficiency of corona discharge reactor for benzene removal. Even at the moment benzene removal efficiency which mainly depends on parameters and configuration

of corona reactor has not been clearly understood. This issue has been addressed as a substantial motivation for this thesis.

1.2 Objective of this thesis

The objective of this thesis is to examine performance of corona discharge reactors which have been developed for a specific purpose to remove VOC from exhaust gases of industrial process. In order to figure out clear understanding in phenomena taking place in the corona reactor, benzene has been selected as a representative of VOC. The effect of operating variables which are size of electrode, gas flow rate, initial concentration and configuration of corona reactor on removal efficiency will be discussed and compared with other methods reported in literatures.

1.3 Scope of this research

1.3.1 Operating variables which are expected to exert effects on benzene removal efficiency

- Electrode size will be used stainless steel wire at diameter 0.1, 0.3 and 0.6 mm.
- Gas flow rate will be varied in a range of 1,000 – 4,000 ml/min.
- Initial concentration will be varied at 500, 1000, 1500, and 2000 ppm.
- Number of discharge channels will be varied from 1, 2 and 4 channels.

1.3.2 Microscopic phenomena

Theoretical investigation of microscopic phenomena taking place in both lab-scale and bench-scale reactors would be conducted based on transport phenomena concept. Analogy on mass, momentum, energy and component balance would also be taken into account by comparison with the experimental reults.

1.3.3 Analytical methods to be employed

- GC : Gas Chromatography for analyzing benzene concentration with model CP-3800 Varian®

- GC-MS : Gas chromatography-Mass spectrometry for analyzing solid deposition on the internal wall of corona wall reactor.

- SEM : Scanning electron microscopy for analyzing surface of electrode with model Jeol JSM-6400 scanning electron microscopy (SEM) 5.0 kV at Scientific and Technological Research Equipment Centre Foundation (STREC), Chulalongkorn University.

1.4 Expected benefits

- Knowledge of installation of corona reactor.

- Optimal conditions for removal efficiency.

- Understanding in effect of each parameters on removal efficiency.

- Understanding in phenomenon of benzene removal via corona discharge within tubular reactor.

1.5 Procedure of the research

No.	Plan	Month							
		2016	May'17	Jun'17	Jul'17	Aug'17	Sep'17	Oct'17	Nov'17
1	Survey and review literature								
2	Set up corona discharge system								
3	Proposal examination								
4	Investigating effects of design and configuration of reactor on benzene removal efficiency by varying regulated variables (electrode size, gas flow rate, initial concentration and configuration)								
5	Investigating theory of microscopic phenomena taking place in corona reactors.								
6	Discussing all experimental results								
7	Making final conclusions								
8	Defending thesis examination								

Chapter 2

Theory and Literature reviews

According to introduction, the purpose in this work is to study effect of operating variables of corona discharge reactors on benzene removal efficiency. Therefore, some basic knowledge and selected literatures related to benzene, and corona technology have been review and described in this chapter.

2.1 Benzene

Benzene (C_6H_6) is one type of volatile organic compounds, it is an aromatic hydrocarbon with molecular weight 78.1 (at 1 atmosphere pressure and 25 °C, 1 ppm benzene is equivalent to 3.26 mg m^{-3}). Benzene exists as colorless or light-yellow liquid with gasoline odor. Melting point of benzene is 5.5 °C with a density of 0.87 g cm^{-3} at 20 °C. It has a relatively low boiling point (80.1 °C) and a high vapor pressure (9.95 kPa at 20 °C), which causes it to evaporate rapidly at room temperature. Residence times in air (vapor phase) varying between a few hours and a few days, depend on the environment, climate, and the concentration of other pollutants [1].

We can expose to benzene, both indoor and outdoor. Benzene concentration is high within areas of heavy motor vehicle traffic and around gas stations, Indoor benzene is also released from human activities such as cleaning, painting, the use of consumer products, mosquito repellents, photocopying, printing ink, the storage and use of solvents, and smoking [2]. Smoking is a major source of indoor benzene exposure, with increasing of benzene concentrations up to 50% compared with homes of nonsmokers.

Benzene can enter to human body through lungs, gastrointestinal tract, and skin. When humans expose to high concentration of benzene in the air, about half of the benzene will enter bloodstream. Once in the bloodstream, benzene travels throughout the body and can be temporarily stored in the bone marrow, and fat. Benzene is converted to products called metabolites in the liver, and bone marrow.

Some of the harmful effects of benzene exposure are caused by these metabolites [9]. Most of the metabolites of benzene exit the body by urine within 48 hours after exposure. Benzene is mainly metabolized in the liver but also in other tissues, such as the bone marrow [10]. A diagram of benzene metabolism is presented in **Figure 2.1.**

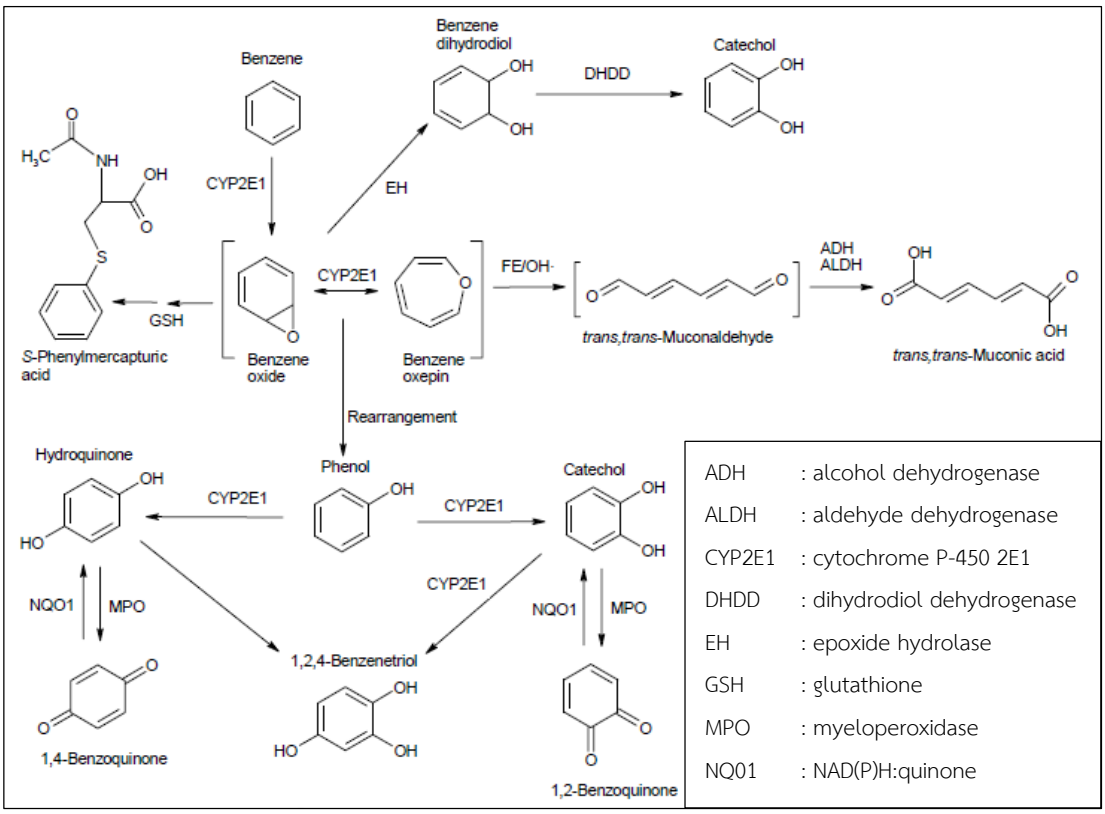


Fig 2.1 Metabolic Pathways of Benzene [4].

The toxicity of benzene was divided into two main types included acute effects when inhaling benzene into the body, it will cause drowsiness, dizziness, nausea, vomiting, headache, rapid heartbeat, convulsions and if gave in very high doses for a long time, it may lead to death. For chronic effects, if there was benzene in the body for a long period, it could affect the blood system. The benzene will damage the bone marrow and decrease a number of blood cells. Therefore, it can decrease platelets and destroy the body's immune system. In addition, benzene is toxic to the nervous

system, the dysfunction of the cranial nerves is toxic to the liver, and it is also a carcinogen causing leukemia.

In Thailand, USA, Australia, and Europe the concentration of benzene in gasoline has been reduced to 1% by volume but in other regions like Russia, India, Malaysia, UAE, Bangladesh, Saudi Arabia, Egypt, Libya and some African countries, concentration of benzene in gasoline is estimated to be in the range of 3–7% volume. Pakistan, Iran, Iraq, Turkmenistan, Uzbekistan, Syria, and Sudan are the countries where are no monitoring activities which related to over benzene contents and any standard for benzene concentration in gasoline has not also been set yet follow as **Figure 2.2** and **Table 2.1** [11].

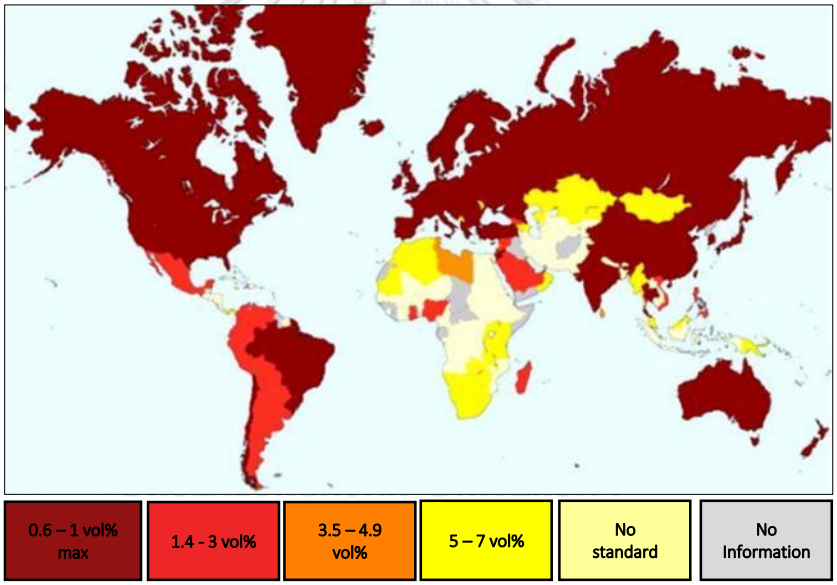


Fig 2.2 International limits on benzene contents in gasoline.

Table 2.1 Benzene gasoline ratio in different countries of the world.

Countries	**Concentration of Benzene**
Thailand, USA, China, European Countries, Australia	Less than 2 vol %
Russia, India, Malaysia, UAE, Bangladesh, Saudi Arabia, Egypt, Libya and South Africa	Benzene in gasoline 3–7 vol %
Pakistan, Iran, Iraq, Turkmenistan, Uzbekistan, Syria, Sudan	No standard defined yet

From all of mentioned basic information above, benzene is recognized as a very dangerous chemical. Therefore, benzene was selected to VOCs model for removal investigating in this work.

2.2 Corona discharge phenomenon

Corona discharge has been used as an ionizer in a wide range of research and industrial fields such as environment. The corona discharges observed at the surface of a conductor were formed by the formation of electron avalanches which occurred when the intensity of the electric field at the conductor surface exceeded a certain critical value. Corona discharges are relatively low power electrical discharges which take place at or near atmospheric pressure. The corona was generated by strong electric fields associated with small diameter wires, needles and appeared as a faint filamentary discharge radiating outward from the discharge electrode. When applying high-voltage to the electrodes, it can produces a corona discharge on the wires or needles. Then a corona discharge occurs and the air that surrounds the electrode needles is broken down, and ions are produced. Using these ions, reverse-polarity static electricity is neutralized, and static is eliminated.

Corona discharges exist in several forms, depending on the polarity of the field and the electrode geometrical configurations. For example positive corona in the

needle-plate electrode configuration, discharges will start with burst pulse corona and proceed to the streamer corona, glow corona, and spark discharge as the applied voltage increases as **Figure 2.3** For negative corona in the same geometry, the initial form will be the Trichel pulse corona, followed by pulseless corona and spark discharge as the applied voltage increased as **Figure 2.4** [12].

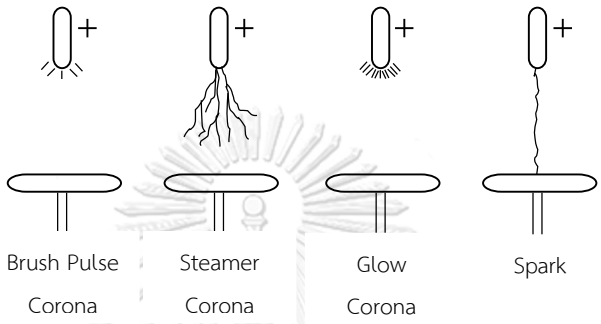


Fig 2.3 Schematic of type of positive corona discharges

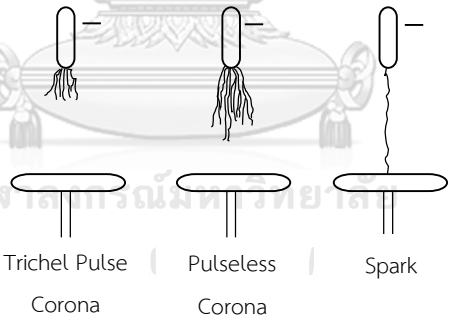


Fig 2.4 Schematic of type of negative corona discharges

Corona discharge is an advanced oxidation process with potential applications in purification of environmental contaminants. It has received great attention in pollution control field because it is appropriate for simultaneous treatment of various refractory pollutants by a lot of oxidative species even if under complex atmosphere. Therefore, it is suggested that corona discharge plasma may be powerful enough to treat organic pollutants in atmosphere. When pollutant in an atmosphere containing

VOCs (Benzene) passes through the discharge zone, the gas molecules can be excited, ionized and dissociated by high energy electrons, producing chemically active species to react with VOCs [13, 14]. Typical and possible reactions taking place in a corona reactor are listed in **Table 2.2**.

Table 2.2 Main reactions in corona reactor [15].

Reaction	Stoichiometry
Excitation	$e + A_2 \rightarrow A_2^* + e$
Dissociation	$e + A_2 \rightarrow 2A + e$
Attachment	$e + A_2 \rightarrow A_2^-$
Dissociative attachment	$e + A_2 \rightarrow A^- + A$
Ionization	$e + A_2 \rightarrow A_2^+ + 2e$
Dissociative ionization	$e + A_2 \rightarrow A^- + A + e$
Recombination	$e + A_2^+ \rightarrow A_2$
Detachment	$e + A_2^- \rightarrow A_2 + 2e$

In addition, ozone will be generated by corona discharge process and ozone is used in electrostatic precipitator indoor air cleaner and also used for removal pollutants in industrial [16]. Moreover, ozone is the strongest oxidant and disinfectant available for the treatment of aqueous solutions, gaseous mixtures, and after ozone oxidizes, it decomposes into oxygen. Therefore, ozone reacts with a large variety of organic compounds resulting in oxygen-containing organic by-products.

In this work, corona discharge technology will be chosen for removal of benzene because it is a high performance process. In addition, this process can be further developed for practical usage in industrial in near future.

2.3 Literature review

Nowadays, controlling the amount of VOCs in the atmosphere is a big problem. It is not only the toxicity but it can also form a photochemical oxidants [17]. This causes eye irritation, irritation to the respiratory system and carcinogen. A lot of technologies have been developed to remove volatile organic compounds. In particular, corona discharge relates to non-thermal plasma technology. By the way, this technology is being researched to remove volatile organic compounds and factors which affect to the removal efficiency compared to other technologies. The research which related to the use of this technology will be described as follows.

Tamon et al, (1995) presented ideas about gas cleaning react with the addition of electron [18] that called gas discharge or corona discharge. This method has been used in ozonizers and electrostatic precipitators. It was also well known that high-energy electrons generated by gas discharge which ionized gas and induced plasma. When low-energy electrons collide with gas molecules, some of them are captured by gas molecules, and negative ions are produced. This phenomenon is called electron attachment which depends on electron energy, the structure of the gas molecule, and its electron affinity. Therefore, it is possible to use this method to remove pollutant gas. Next, Yamamoto et al, (1997) [19] studied about removal of VOCs by using non-thermal plasma process. Influence of the collision of electrons is a transfer of molecules of VOCs during decomposition which involves time. VOCs are degraded when they get enough energy to overcome the potential energy area, and to be radical. This method is very useful because it can use without large plasma source.

Higher removal efficiency depends on several parameters. Many researchers have designed their experiments to find out the optimum conditions for getting higher removal efficiency. Therefore, Davidson and McKinney (1998) [20] reported that chemical vapor deposition on a wire in air cleaning machine affected corona steam to

decrease 95% on the same voltage after using for 180 hours. According to the comparison between clean wire and deposit wire by fixed voltage at 7.5 kV, it was found that current decreased from 0.09 of clean wire to 0.004 mA of contaminated wire. In addition, voltage required up from 5.6 kV of clean wire to 7.5 kV of contaminated wire. Therefore, Davidson and McKinney concluded that in 48 hours under dry condition, there were no effect on corona steam and chemical vapor deposition. On the other hand, if the usage of time is more than 48 hours, corona steam and chemical vapor deposition would be affected. After that Ogata el al, (1999) [21] studied the current frequency, initial concentration of benzene, and the oxygen concentration in the gas that was used to remove benzene in the air with ferroelectric packed bed reactor. The first result was, low frequency was better than high frequency. The next result was, low initial concentration of benzene was better because byproducts were not formed. Finally, selectivity of CO_2 would be increased if O_2 concentration was more than 5%. While Cal and Schluep, (2001) [22] studied about removal of benzene using dielectric barrier discharge reactor with humidity (RH) addition. The result showed that when water vapor was added into gas steam, removal rate would decrease. On the other hand, removal rate in dry air would rapidly increases. However, humidity only affected the removal rate, removal efficiency was achieved in both wet and dry gas steams.

The configuration of electrode was also studied. Oda, (2003) [23] tried to remove VOCs using non-thermal plasma process. In this experiment different types of electrode in plasma reactor were used. The electrodes which were used, consisted of three types coil type, rod type, and bolt type respectively. Then there was removal of trichloroethylene, the results showed that coil type electrode had the lowest removal efficiency. On the other hand bolt and rod type electrodes had similar removal efficiency but bolt type used lower voltage. Therefore, the bolt type electrode was

the best performance. Generally, increase of temperature in non-thermal plasma process was very small. Sano et al, (2004) [24] studied the influence of temperature in the room temperature up to 400 °C that affected removal efficiency of both gas types. DC corona discharge reactor was applied for sulfur dioxide and benzene removal. The results showed that the removal efficiency of sulfur dioxide would decrease by increasing of temperature. On the other hand, it had no effect with benzene in the same condition.

Satoh et al, (2008) [25] investigated the decomposition characteristics of benzene in a positive DC corona discharge under gas mixture of nitrogen and oxygen. The results found that benzene is primarily converted into CO_2 via CO at low oxygen concentrations and also found C_2H_2, HCN, HCOOH, CO as benzene fragments and by-products in the corona discharge. The energy required for the removal of benzene increased by the oxygen concentration because the energy used for producing HCOOH and O_3 to decompose benzene. At the same time, Ye et al, (2008) [26] studied about removal of benzene with dielectric barrier discharge. Effects of gas flow rate, benzene concentration, energy yield and electrical power were studied in this research. The first result showed that increase of gas flow rate removal efficiency of benzene would decrease rapidly. Secondly, when increasing initial concentration of benzene removal efficiency, it also decreased and required more energy yield. Finally, using more electric power to achieve better removal efficiency.

To apply this technology with another system, Chen et al, (2004) [27] studied the removal of phenol in aqueous solution using pulsed high-voltage discharge plasma. Effect of electrode size was studied in this research. Diameters of electrode were 0.6, 0.9 and 1.6 mm respectively. The result showed that the removal efficiency would decrease when increasing electrode diameter. Even though most of this technology

was applied for gas system but in this research the researcher adapted for liquid system.

There are a lot of researches in this technology which studied a lot of parameters on removal efficiency. These researches use different experimental methods but the same purpose of each experimental, which is to remove VOCs with optimum conditions. Most researches as described above were applied single-channel of corona discharge reactor but in my work multi-channels corona discharge reactor is applied (detail of reactor will be described in next chapter) because the VOC can be removed in more quantity and higher efficiency. In addition, study of optimum conditions for multi-channels corona discharge reactor have been examined.

Chapter 3

Experiments

According to literature reviews which related to the removal of volatile organic compounds, including studies of various factors which affect removal efficiency. This chapter will describe the experimental methodology and configuration of corona reactor.

3.1 Materials and configurations of corona reactor.

Corona reactor was fabricated by Global R&D Company. It is consist of 4 channels in the main reactor and there is one electrode in each channel as shown in **Figure 3.1**. A stainless steel cylinder was used as an anode whose inner diameter and length were 74±2 and 744 mm, respectively. Three different sizes of stainless steel wire with diameters of 0.1, 0.3 and 0.6 mm were used as a cathode. DC type voltage was used as a power source. AR grade liquid benzene was purchased from QRëC® and used to generate benzene vapor by VOCs generator GasMix™ LiqMix. Nitrogen gas was purchased from Linde to use as a carrier gas for adjusting a concentration of benzene. Water was used for making liquid film in each channels of corona reactor.

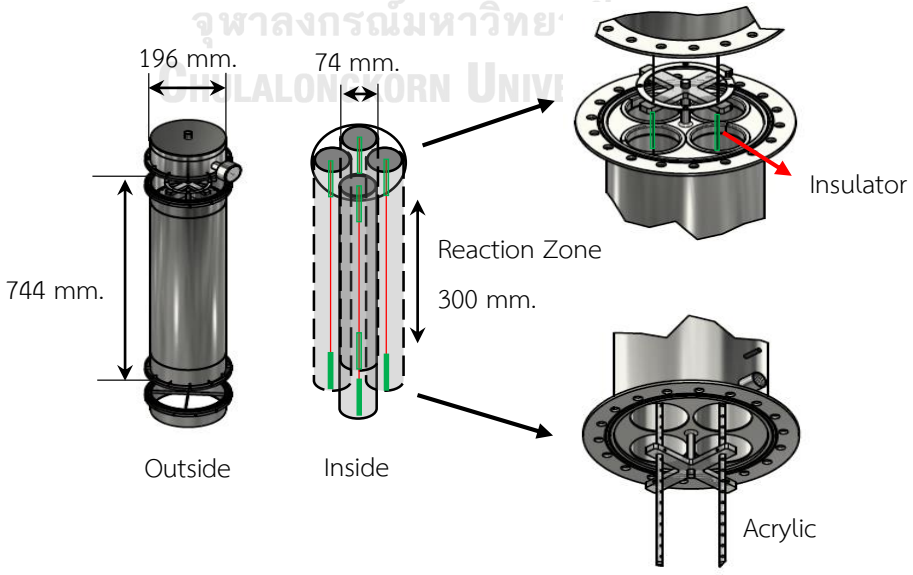


Fig 3.1 Configuration of multi-channeled corona discharge reactor.

3.2 Experimental method

The experimental setup for the corona discharge system is schematically showed in **Figure 3.2** Liquid of benzene will generate to vapor by VOCs generator. The concentration of benzene vapor was adjusted by diluting with nitrogen gas (N_2). To obtain target concentration and flow rate, the flows of benzene and N_2 were controlled by flow meter before being mix together in a mixing chamber. The mix gas was released into each channel of the corona reactor afterwards AC voltage was applied respectively. The gas sample for analysis will take every 5 minutes after corona discharge started. Gas samples before and after discharge reaction will be taken from the corona reactor and analyze by an on-line gas chromatography (CP-3800 Varian®) afterwards removal efficiency of benzene was calculated. Details of each condition which use in these experiments will be describe in the next content and shows in **Figure 3.3.**

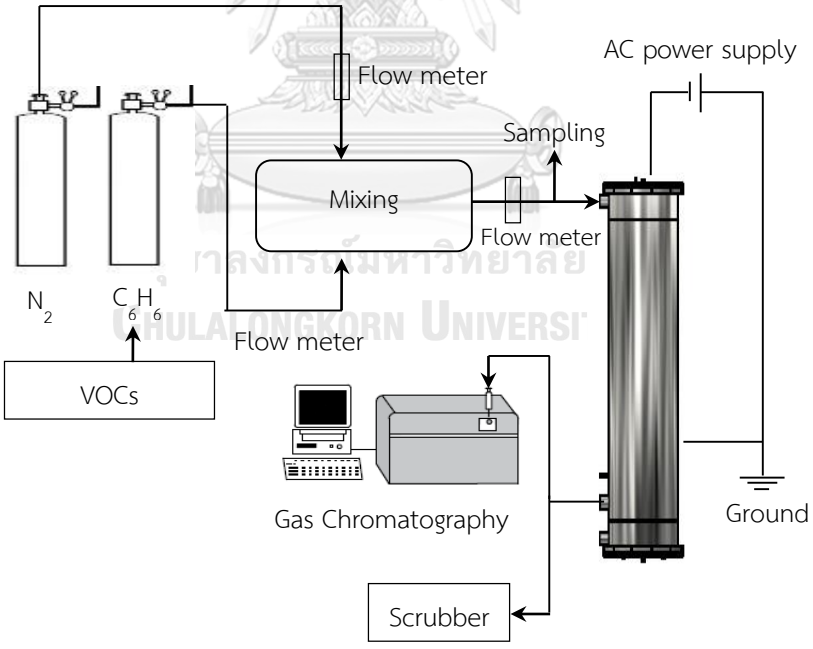


Fig 3.2 Schematic diagram of corona discharge system

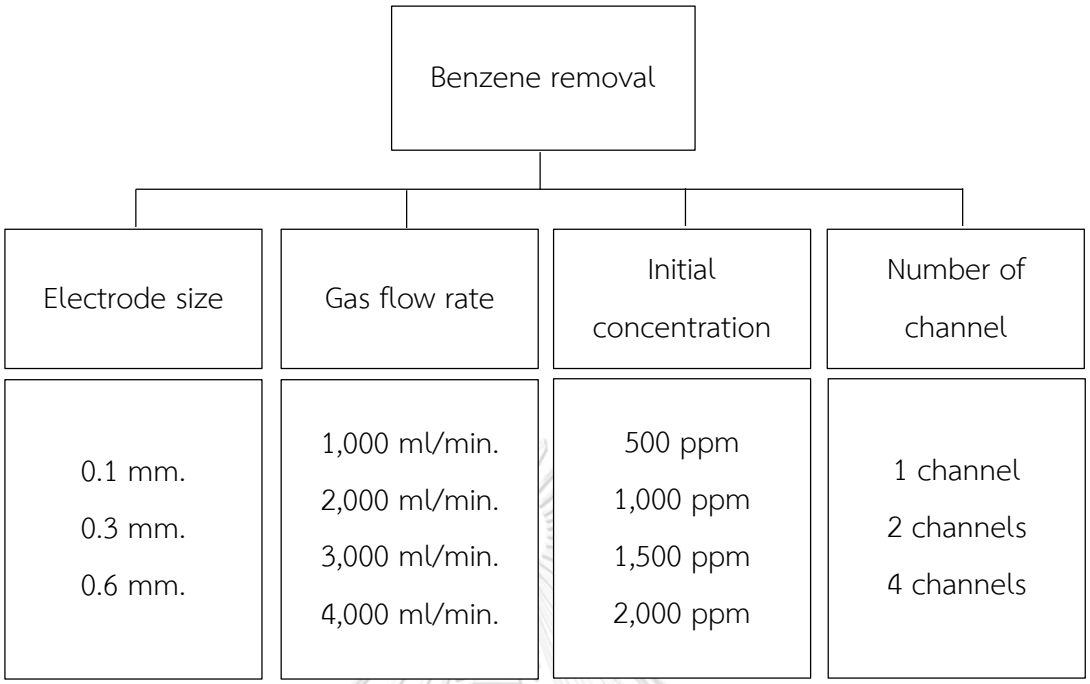


Fig 3.3 Condition of benzene removal experiment

3.2.1 Procedure of electrode size effect

The detail of this experiment was included 9 steps as follows.

1) Stainless wire type 304-SL was used an electrode including 0.1, 0.3 and 0.6 mm. as show in **Figure 3.4**.

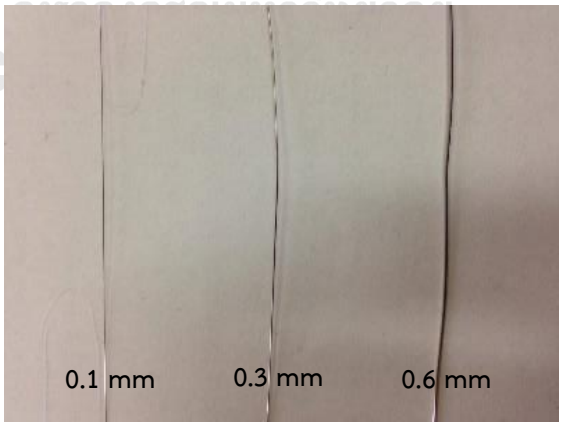


Fig 3.4 Different size of stainless wire 0.1, 0.3 and 0.6 mm.

2) 0.1 mm of electrode size was applied into 4 channels of corona reactor.

3) Reaction zone or discharge zone was adjusted to 300 mm.

4) Input power was measured before the experiment.

5) Benzene gas was fed downward into the reactor with flow rate 1,000 ml/min.

6) Target concentration of benzene was adjusted to 500 ppm.

7) AC voltage was applied to the electrode with the maximum power at 140 watt for 0.1 mm of electrode size.

8) Benzene gas samples after pass through discharge zone was taken from the corona reactor and analyze by an on-line gas chromatography (CP-3800 Varian®). Afterward, GC peak area was obtained.

9) The removal efficiency of benzene was calculated from GC peak area. Repeat step 1-9, afterward go to step 10.

10) Change the electrode to 0.3 and 0.6 mm, respectively and do step 1-9 again. All parameters were set up as followed **Table 3.1.**

Table 3.1 Parameters set up with condition of electrode size.

Parameter		Unit
Electrode size	0.1, 0.3 and 0.6	mm.
Gas flow rate	1,000	ml/min
Benzene concentration	500	ppm
Distance of reaction zone	300	mm.
Number of channel	4	channel

3.2.2 Procedure of gas flow rate effect

The detail of this experiment was included 9 steps as follows.

1) 0.6 mm. of Stainless wire type 304-SL was used an electrode.

2) 0.6 mm of electrode size was applied into 4 channels of corona reactor.

3) Reaction zone or discharge zone was adjusted to 300 mm.

4) Input power was measured before the experiment.

5) Benzene gas was fed downward into the reactor with flow rate 1,000 ml/min.

6) Target concentration of benzene was adjusted to 500 ppm.

7) AC voltage was applied to the electrode with the maximum power at 180 watt for 1,000 ml/min of gas flow rate.

8) Benzene gas samples after pass through discharge zone was taken from the corona reactor and analyze by an on-line gas chromatography (CP-3800 Varian®) same machine as first experiment. Afterward, GC peak area was obtained.

9) The removal efficiency of benzene was calculated from GC peak area. Repeat step 1-9, afterward go to step 10.

10) Adjust flow rate to 2000, 3000 and 4000 ml/min, respectively and do step 1-9 again. All parameters were set up as followed **Table 3.2.**

Table 3.2 Parameters set up with condition of gas flow rate.

Parameter		Unit
Electrode size	0.6	mm.
Gas flow rate	1000, 2000, 3000 and 4000	ml/min
Benzene concentration	500	ppm
Distance of reaction zone	300	mm.
Number of channel	4	channel

3.2.3 Procedure of initial concentration effect

The detail of this experiment was included 9 steps as follows.

1) 0.6 mm. of Stainless wire type 304-SL was used an electrode.

2) 0.6 mm of electrode size was applied into 4 channels of corona reactor.

3) Reaction zone or discharge zone was adjusted to 300 mm.

4) Input power was measured before the experiment.

5) Benzene gas was fed downward into the reactor with flow rate 1,000 ml/min.

6) Target concentration of benzene was adjusted to 500 ppm.

7) AC voltage was applied to the electrode with the maximum power at 160 watt for 500 ppm of initial concentration.

8) Benzene gas samples after pass through discharge zone was taken from the corona reactor and analyze by an on-line gas chromatography (CP-3800 Varian®) same machine as first experiment. Afterward, GC peak area was obtained.

9) The removal efficiency of benzene was calculated from GC peak area. Repeat step 1-9, afterward go to step 10.

10) Adjust initial concentration to 1000, 1500 and 2000 ppm, respectively do step 1-9 again. All parameters were set up as followed **Table 3.3.**

Table 3.3 Parameter set up with condition of initial concentration.

Parameter		Unit
Electrode size	0.6	mm.
Gas flow rate	1,000	ml/min
Benzene concentration	500, 1000, 1500 and 2000	ppm
Distance of reaction zone	300	mm.
Number of channel	4	channel

3.2.4 Procedure of number of channels effect

In this work corona reactor was developed from single-channel to multi-channeled column of electrode. Different point between single-channel and multi-channeled corona reactor is aerodynamics in the reactor. In case of single-channel reactor, gas will be passed directly from the top to the bottom or the bottom to the top of reactor depends on each design but in multi-channeled reactor, gas will be separated to each channel (4 channels) of reactor. Flow pattern in the reactor should be laminar flow because it is easier to control.

The detail of this experiment was included 9 steps as follows.

1) 0.6 mm. of Stainless wire type 304-SL was used an electrode.

2) 0.6 mm of electrode size was applied into 1 channel of corona reactor as shows in **Figure 3.5** However, 2 and 4 channels of corona reactor were applied after complete the condition of 1 channel of corona reactor respectively.

3) Reaction zone or discharge zone was adjusted to 300 mm.

4) Input power was measured before the experiment.

5) Benzene gas was fed downward into the reactor with flow rate 1,000 ml/min.

6) Target concentration of benzene was adjusted to 500 ppm.

7) AC voltage was applied to the electrode with the maximum power at 140 watt.

8) Benzene gas samples after pass through discharge zone was taken from the corona reactor and analyze by an on-line gas chromatography (CP-3800 Varian®) same machine as first experiment. Afterward, GC peak area was obtained.

9) The removal efficiency of benzene was calculated from GC peak area. Repeat step 1-9, afterward go to step 10.

10) Fix number of channel to 2 and 4 channels, respectively do step 1-9 again. All parameters were set up as followed **Table 3.4.**

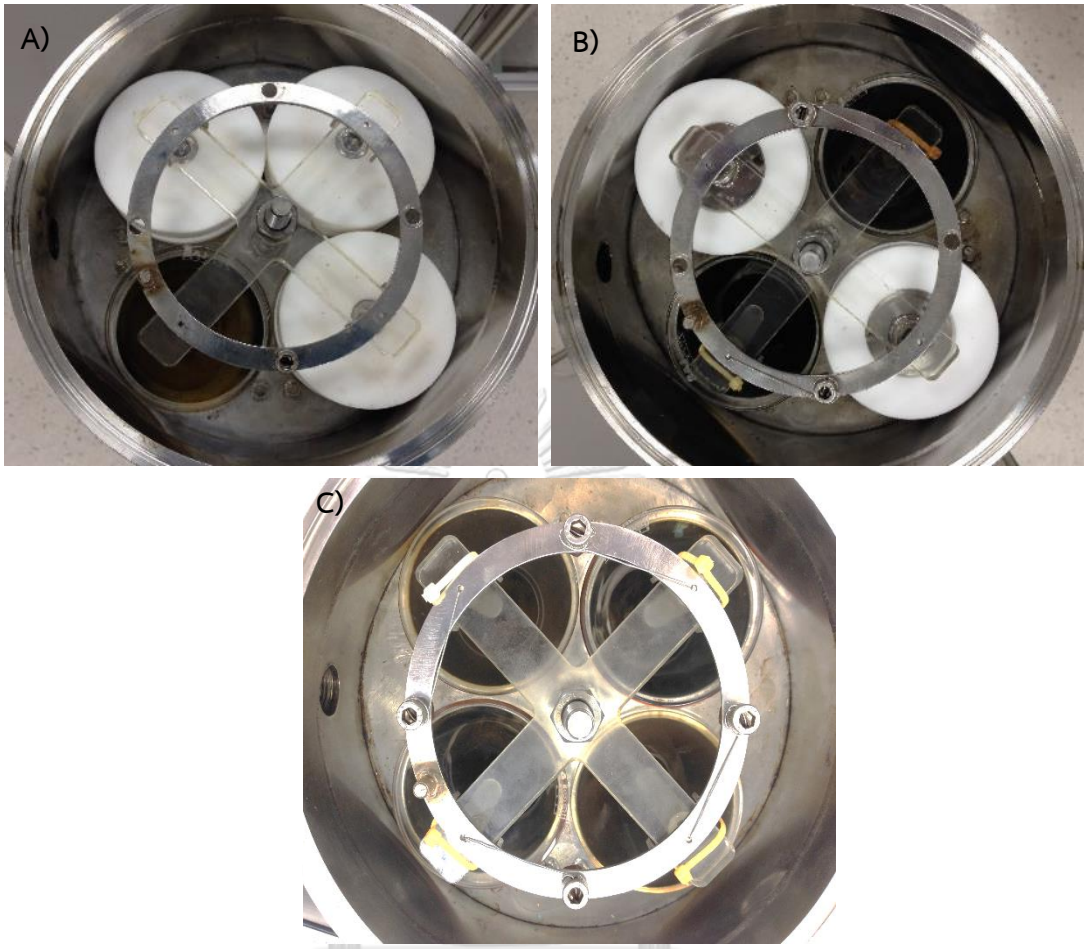


Fig 3.5 Various number of channel for corona reactor
A) 1 Channel B) 2 Channels and C) 4 Channels

Table 3.4 Parameters set up with condition number of channels.

Parameter		Unit
Electrode size	0.6	mm.
Gas flow rate	1,000	ml/min
Benzene concentration	500	ppm
Distance of reaction zone	300	mm.
Number of channel	1, 2 and 4	channel

3.3 Scope of operating variables to be investigated

- Size of stainless steel wire electrode will be varied at diameter of 0.1, 0.3 and 0.6 mm.

- Gas flow rate will be varied in a range 1,000 – 4,000 ml/min.

- Initial concentration will be varied at 500, 1000, 1500, 2000 ppm.

- Number of discharge channels will be varied from 1, 2 and 4 channels.

3.4 Characterization

3.4.1 Gas Chromatography (GC)

Chromatography is a technique for separating chemical substances that relies on differences in partitioning behavior between a flowing mobile phase and a stationary phase to separate the components in a mixture. The sample was injected into the instrument enters a gas stream which transports the sample into a separation tube known as the "column." (Helium or nitrogen is used as the carrier gas.) The various components are separated inside the column. The detector measures the quantity of the components that exit the column. To measure a sample with an unknown concentration, a standard sample with known concentration is injected into the instrument. The standard sample peak retention time and area are compared to the test sample to calculate the concentration. Therefore, benzene concentration was

analyzed by gas chromatography with model model CP-3800 Varian® **(Figure 3.6)** flame ionization detector (FID). Under machine condition column temperature of 30 °C, injection temperature of 150 °C, detector temperature of 150 °C, and retention time of 1.1 minute.

Fig 3.6 Gas Chromatography (GC) model CP-3800 Varian®

3.4.2 Gas chromatography- Mass spectrometry (GC-MS)

GC-MS is an instrument that combines the features of gas-chromatography (GC) and mass spectrometry (MS) techniques to analyze organic compounds in a mixture. The mixture will be separated into individual compounds when heated by the GC system and can be identified and quantified by the MS detector which provide detailed structural information. In order for a compound to be analyzed by GC-MS it must be sufficiently volatile and thermally stable. Samples are usually analyzed as organic solutions. Therefore, the solid deposition on the internal wall of corona reactor was analyzed with GC-MS model Bruker as shows in **Figure 3.7.**

Fig 3.7 Gas-chromatography (GC) and Mass spectrometry (MS) model Bruker.

3.4.3 Scanning electron microscopy (SEM)

SEM is a microscope which uses electrons to illuminate a sample, instead of visible light used in optical microscope. When an electron beam strikes the sample, a variety of signals are generated that provide the sample's surface information and elemental composition. Secondary electron (SE) image displays fine structure topographical feature of sample surface and backscattered electron (BE) image shows the distribution of different elements based on atomic number in the sample. The composition of wire contamination was analyzed with scanning electron microscopy (SEM) Jeol JSM-6400 at Scientific and Technological Research Equipment Centre Foundation (STREC), Chulalongkorn University as shows in **Figure 3.8.**

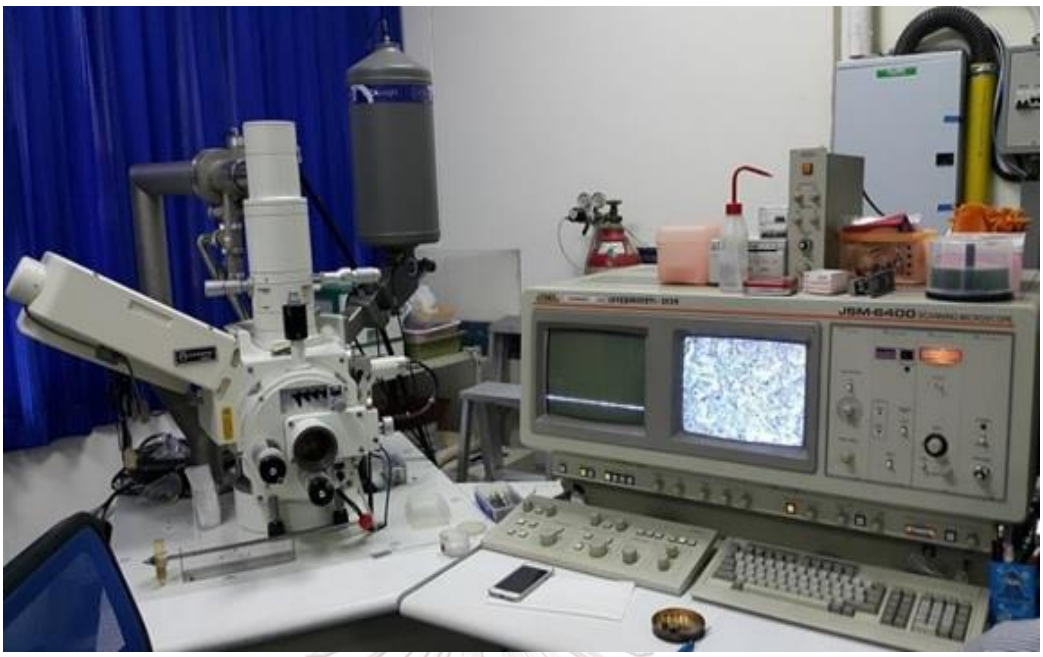


Fig 3.8 Scanning electron microscopy (SEM) model Jeol JSM-6400.

3.5 Evaluation of benzene removal efficiency

Removal efficiency of benzene was calculated from the GC peak areas before and after discharge. The results in peak areas form will be get from gas chromatography, then convert peak areas to concentration of both inlet and outlet peak areas by compare with standard curve. Afterward calculate removal efficiency as below formula.

$$\eta_{benzene} = \frac{C_i - C_0}{C_i} \times 100\%$$

Where, C_i is Initial concentration and

C_0 is Final concentration

Chapter 4

Results and Discussion

This chapter describes all experimental and analytical results included of 1). Experiment on effect of electrode size on benzene removal efficiency 2). Experiment on effect of gas flow rate on benzene removal efficiency 3). Experiment on effect of initial concentration on benzene removal efficiency and 4). Experiment on effect of number of channels on benzene removal efficiency

4.1 Result of electrode size on benzene removal efficiency

Stainless steel wire type 304-SL was used an electrode varied by 0.1, 0.3 and 0.6 mm. The removal process was operate as follows **Table 4.1.**

Table 4.1 Experimental conditions with effect of electrode size**.**

Parameter		Unit
Electrode size	0.1, 0.3 and 0.6	mm.
Gas flow rate	1,000	ml/min
Benzene concentration	500	ppm
Distance of reaction zone	300	mm.
Number of channel	4	channel

Benzene concentration before and after discharge were analyzed by using gas chromatography (GC) and removal efficiency of benzene was calculate from GC peak area. It was found that 0.1, 0.3 and 0.6 mm of electrode size could reached maximum power at 140, 160 and 180 watt respectively. For the removal efficiency of benzene reached 16.5, 31.5 and 62.6 % for the 0.1, 0.3 and 0.6 mm of electrode size, respectively as shows in **Figure 4.1**.

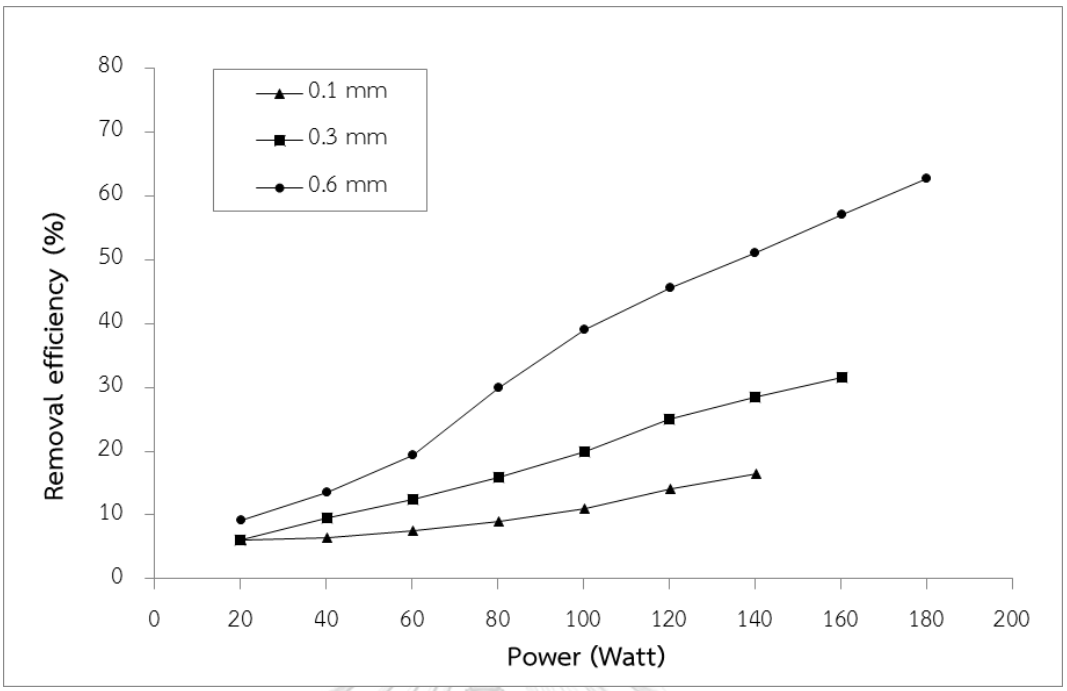


Fig 4.1 Comparison of benzene removal efficiency of each electrode size

As the results shows, the electrode size was increase from 0.1 to 0.6 mm the maximum power was also increased. It could be described by Ohm's law [28], in an electrical circuit the current passing through a resistor is related to the voltage and inversely related to the electrical resistance. The resistance of each electrode size was calculated using as below formula.

$$R = \rho L/A$$

Where, ρ is resistivity of material (stainless steel = 6.9×10^{-7} Ωm)

L is length

A is cross sectional area

It was found that the resistance of 0.1, 0.3 and 0.6 mm electrode would be 26.37, 2.93 and 0.73 ohm respectively [29] (Calculation in Appendix A1). Therefore, high input power could be greatly supplied in a larger electrode.

Next, benzene removal efficiency of 0.1, 0.3 and 0.6 mm electrode reached 16.5, 31.5 and 62.6 percent respectively which can be explained that corona discharge was generated when the strength of the electric field around the surface of an electrode (conductor) is high enough to form a conductive region. According to specific surface area calculation (Appendix A2) of 0.1, 0.3 and 0.6 mm electrode would be 40.01, 13.34 and 6.67 mm^{-1} respectively. Hence, this result showed that 0.1 mm electrode has the most specific surface area, and it could supply more current than other electrode sizes as following **Table 4.2.**

Table 4.2 Measurement of voltage and current supplied with different electrode size

0.1 mm electrode			0.3 mm electrode			0.6 mm electrode		
Voltage (kV)	Current (mA)	Power (Watt)	Voltage (kV)	Current (mA)	Power (Watt)	Voltage (kV)	Current (mA)	Power (Watt)
10.5	1.94	20	12.5	1.62	20	15.6	1.32	20
13.2	3.07	40	14.7	2.69	40	16.8	2.41	40
14.5	4.17	60	16.0	3.69	60	18.3	3.31	60
16.0	5.03	80	17.3	4.55	80	20.2	3.99	80
17.4	5.77	100	18.7	5.28	100	21.9	4.60	100
18.4	6.56	120	19.7	6.00	120	22.9	5.27	120
19.0	7.41	140	20.9	6.70	140	23.8	5.90	140
			21.6	7.39	160	24.5	6.56	160
						25.6	7.05	180

According to table 4.2 it showed that 0.1 mm electrode had the most quantity of electrons, when consider about voltage of 0.1 mm electrode, it had the lowest voltage comparing with other electrode sizes. Although 0.1 mm electrode would provide more electrons because of more specific surface area. But electron energy of 0.1 mm electrode was lower than other electrode sizes, resulted in benzene could not be decomposed. On the other hand, 0.6 mm electrode which had the lowest

quantity of electrons, but electrons had sufficient energy to decompose benzene. As a result, large electrode had the efficiency more than small electrode.

The surface appearance of electrode was observed by SEM. All electrodes size were smooth surface before discharge as shows in **Figure 4.2.** After benzene gas pass through the discharge zone the surface appearance of electrode was covered with contamination. In case of high removal efficiency the electrode is completely covered as shows in **Figure 4.3.**

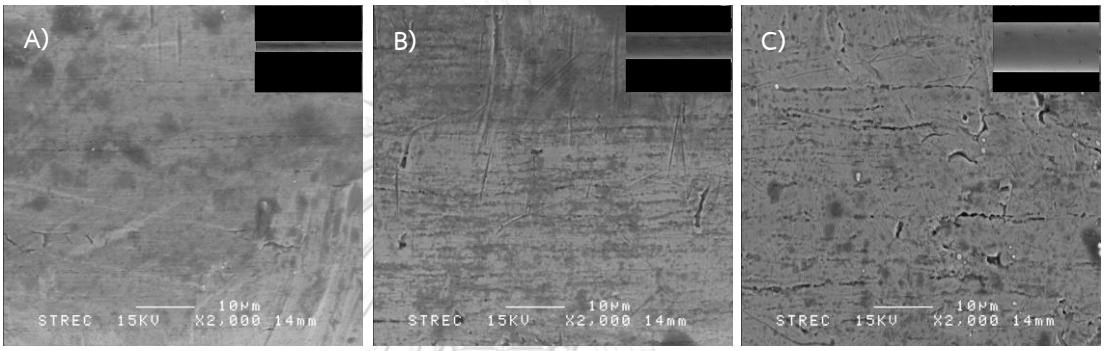


Fig 4.2 Surface appearance before discharge A) 0.1 mm, B) 0.3 mm and C) 0.6 mm.

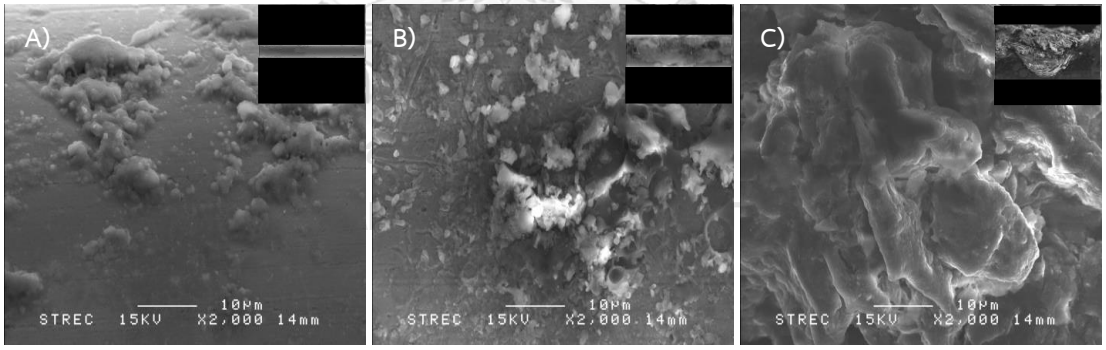


Fig 4.3 Surface appearance after discharge A) 0.\ mm, B) 0.3 mm and C) 0.6 mm.

Furthermore, **Figure 4.4** showed the deviation of different electrode size. **(A)** 0.1 mm, the deviation of removal efficiency was low at all input power. **(B)** 0.3 mm electrode, the deviation was increased when increasing of input power. **(C)** 0.6 mm electrode, the deviation was not stable but high removal efficiency was obtained. However, the deviation of 0.1 mm electrode is lower than other electrodes but the removal efficiency also low. Therefore, 0.6 mm electrode should be employed in corona reactor.

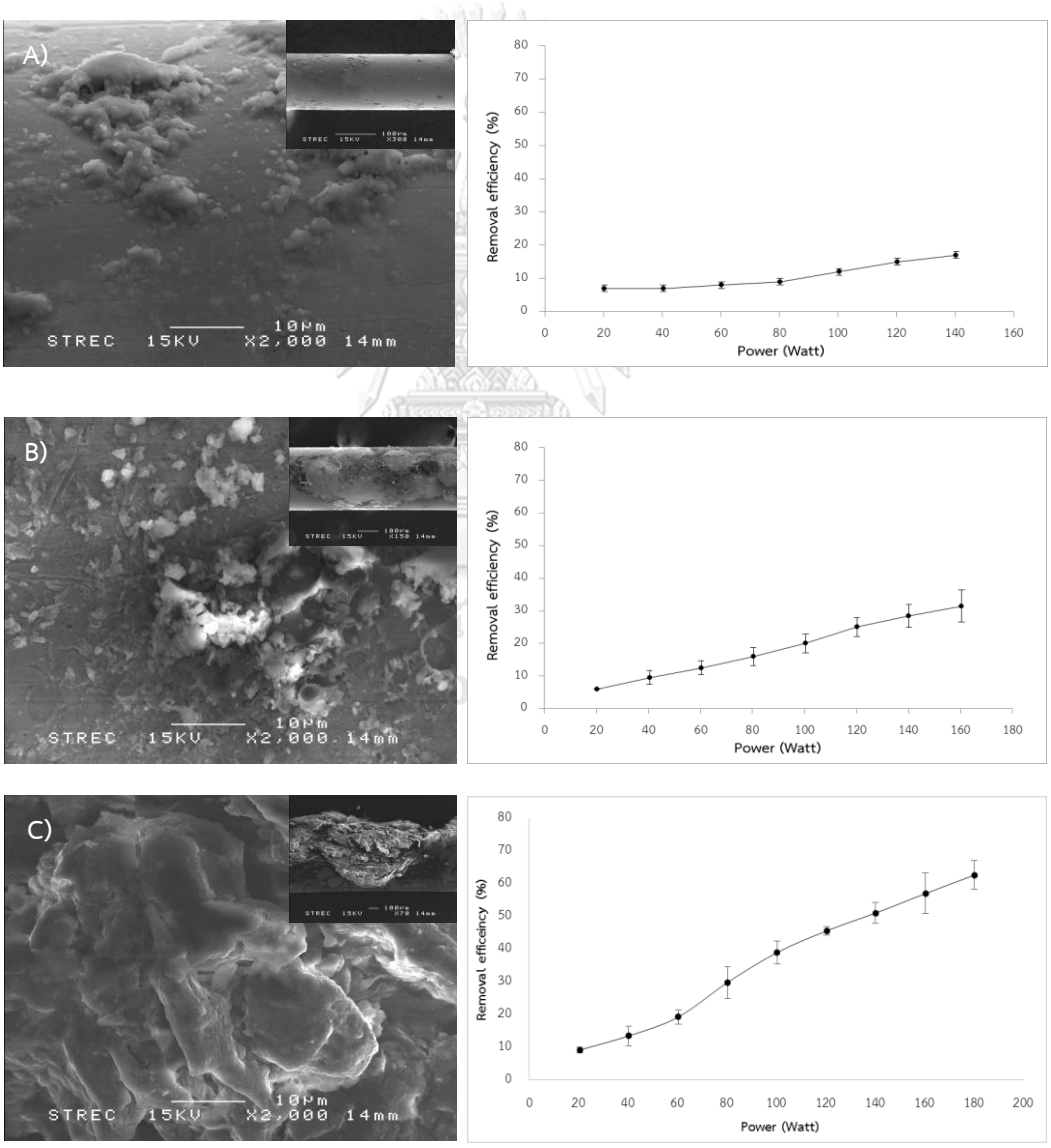


Fig 4.4 Removal efficiency with error bar plot A) 0.1 mm, B) 0.3 mm and C) 0.6 mm

4.2 Result of gas flow rate on benzene removal efficiency

From previous experiment 0.6 mm electrode reached high efficiency when compared with other electrode sizes. Therefore, in this experiment 0.6 mm electrode was fixed as an electrode. Benzene gas flow rate was varied in range 1,000 to 4,000 ml/min and other parameters were used as follows **Table 4.3**.

Table 4.3 Experimental conditions with effect of gas flow rate**.**

Parameter		Unit
Electrode size	0.6	mm.
Gas flow rate	1000, 2000, 3000 and 4000	ml/min
Benzene concentration	500	ppm
Distance of reaction zone	300	mm.
Number of channel	4	channel

Increasing of gas flow rate affects removal efficiency via changing the residence time in reactor. The residence time was obtained 309.5, 154.8, 103.2 and 77.4 seconds for 1000, 2000, 3000 and 4000 ml/min of gas flow rate, respectively (Calculation in Appendix A3). As shown in **Figure 4.5** the removal efficiency of benzene reached 60, 48, 13 and 4 percent for 1000, 2000, 3000 and 4000 ml/min of gas flow rate, respectively. When gas flow rate was increased from 1,000 to 4,000 ml/min removal efficiency drops quickly from 60 to 4 percent, which can be explain that rise of gas flow rate for a same reactor volume leads to decrease the attaching frequency of electron with benzene gas [26]. Therefore, as residence time was decreased, a higher applied voltage was needed to achieve complete removal of benzene.

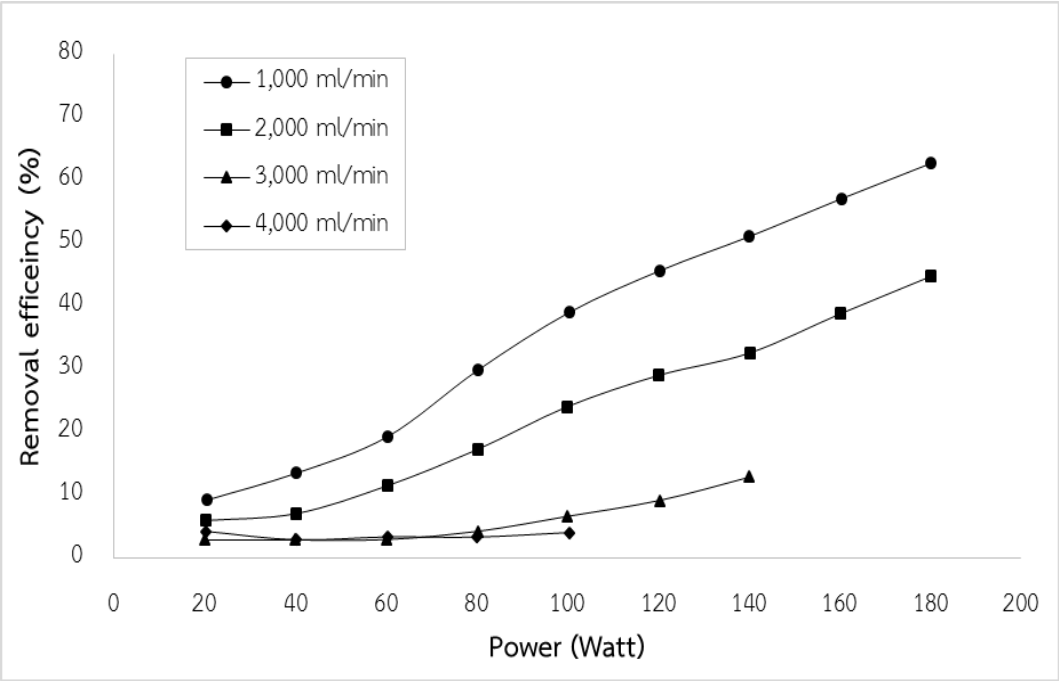


Fig 4.5 Removal efficiency with different gas flow rate

Furthermore, the input power drops from 180 to 100 watt when gas flow rate was increased. If the total gas flow rate was increased to 3,000 and 4,000 ml/min, the achievable corona generating power was only 140 and 100 watt, respectively. This is because the gas flow rate increases, it causes an increase in the number of collisions between the electrons and the gas atoms [30] as shows in **Table 4.4.**

Table 4.4 Measurement of voltage and current supplied with different gas flow rate.

1,000 ml/min		2,000 ml/min		3,000 ml/min		4,000 ml/min	
Voltage (kV)	Current (mA)	Voltage (kV)	Current (mA)	Voltage (kV)	Current (mA)	Voltage (kV)	Current (mA)
15.6	1.32	14.0	1.46	13.1	1.53	10.9	1.85
16.8	2.41	15.9	2.54	14.3	2.82	11.3	3.54
18.3	3.31	17.1	3.53	15.3	3.92	11.6	5.19
20.2	3.99	19.5	4.12	16.5	4.85	12.6	6.35
21.9	4.60	21.0	4.75	17.2	5.82	13.6	7.36
22.9	5.27	22.1	5.43	19.1	6.29		
23.8	5.90	23.4	6.00	20.0	6.99		
24.5	6.56	24.3	6.6				
25.6	7.05	25.3	7.12				

In addition, the surface appearance of electrode was observed by SEM at all gas flow rate conditions. Contamination was covered on surface of electrode after benzene gas pass through the discharge zone. In case of low gas flow rate the electrode surface appearance is covered completely but high gas flow rate the electrode surface appearance is smooth. It could be explained that time to react between electrons and benzene was not sufficient with high flow rate. Therefore, benzene was not decomposed and nothing deposited on surface electrode as shows in **Figure 4.6.**

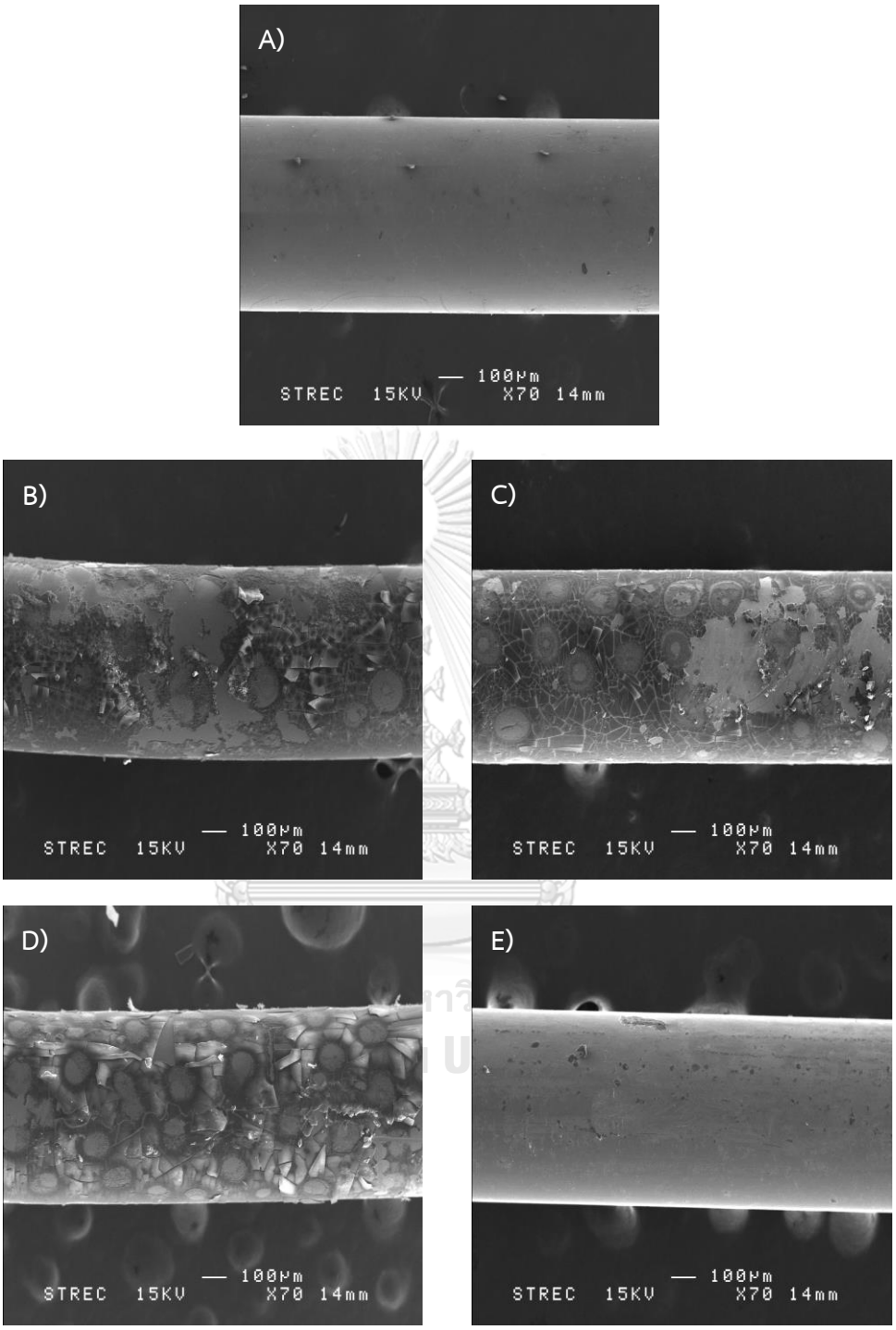


Fig 4.6 Surface appearance A) Before discharge and after discharge B) 1,000 ml/min, C) 2,000 ml/min D) 3,000 ml/min and E) 4,000 ml/min.

4.3 Result of initial concentration on benzene removal efficiency

The effect of benzene concentrations on the removal efficiency was examined with condition as follows **Table 4.5**.

Table 4.5 Experimental conditions with effect of gas flow rate**.**

Parameter		Unit
Electrode size	0.6	mm.
Gas flow rate	1,000	ml/min
Benzene concentration	500, 1000, 1500 and 2000	ppm
Distance of reaction zone	300	mm.
Number of channel	4	channel

In **Figure 4.7** shows obtained results 57, 30, 25 and 7 percent of benzene removal efficiency for 500, 1000, 1500 and 2000 ppm concentration respectively. The removal efficiency were decreased with the increasing of the benzene concentration. When the initial concentration was high, it means a lot of molecules of benzene in the reactor. Input power at 160 watt (21.6 kV and 7.44 mA) of condition 2,000 ppm was used for calculation. There are quantity of electron around 4.18×10^{25} (Calculation in Appendix A4). After converting ppm unit to molecule unit using ideal gas law (Calculation in Appendix A4). Amount of benzene molecules was obtained 3.05×10^{19}, 6.09×10^{19}, 9.14×10^{19} and 1.22×10^{20} molecules for 500, 1000, 1500 and 2000 ppm respectively. Therefore, quantity of electron was more than the molecules of benzene in the reactor, there are sufficient of electron for removal of benzene.

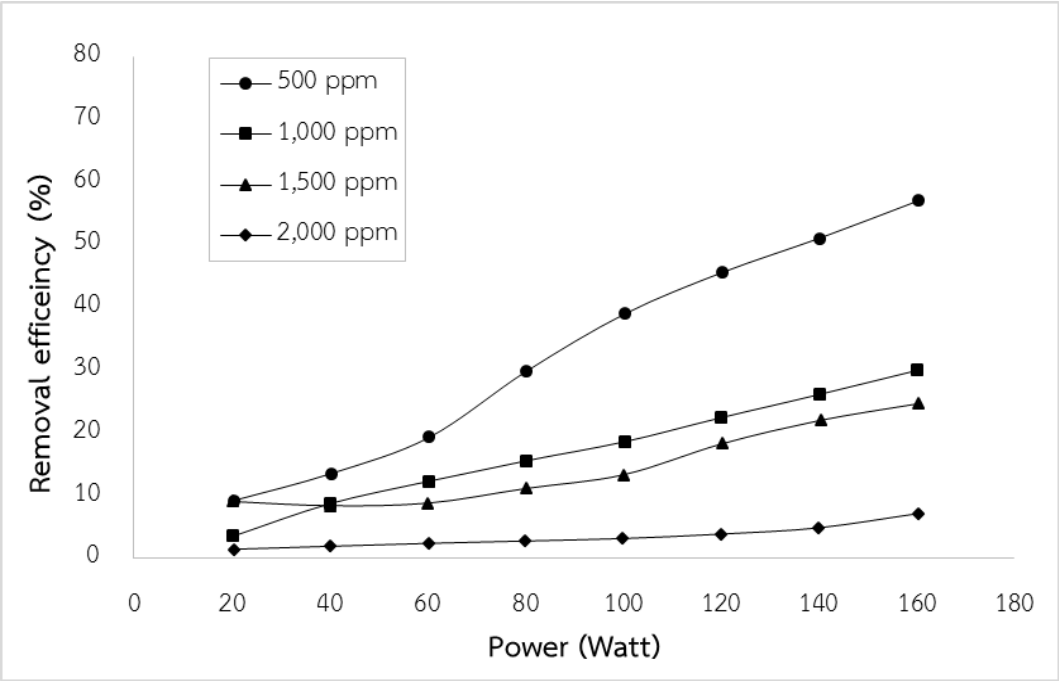


Fig 4.7 Removal efficiency of benzene with different initial concentration.

In this study, there were two reasons that explained the result. First, there are sufficient electrons in the reactor but it did not attach with all of benzene molecules. When considering about input power, all conditions could obtain the maximal input power at 160 watt. On the other hand, voltage and current of each condition were not equal. In case of current, it showed that condition 2,000 ppm of initial concentration had the highest current (a lot of electrons) comparing with other initial concentrations. As a result, current of conditions 2,000 > 1,500 > 1,000 > 500 ppm, respectively. In case of voltage, it showed that condition 2,000 ppm of initial concentration had the lowest voltage which concluded that voltage of conditions 2,000 < 1,500 < 1,000 < 500 ppm, respectively as shown in **Table 4.6**. Therefore, at the same input power, removal of benzene with low initial concentration would provide the highest efficiency.

Table 4.6 Measurement of voltage and current supplied with different initial concentration.

500 ppm		1,000 ppm		1,500 ppm		2,000 ppm	
Voltage (kV)	Current (mA)	Voltage (kV)	Current (mA)	Voltage (kV)	Current (mA)	Voltage (kV)	Current (mA)
15.6	1.32	14.0	1.45	14.8	1.38	14.4	1.42
16.8	2.41	15.8	2.55	16.6	2.44	15.6	2.58
18.3	3.31	17.3	3.50	17.4	3.46	16.4	3.68
20.2	3.99	18.6	4.35	18.8	4.27	17.3	4.64
21.9	4.60	19.8	5.10	19.7	5.09	18.1	5.54
22.9	5.27	20.6	5.85	21.0	5.74	18.9	6.38
23.8	5.90	21.3	6.61	21.9	6.43	20.4	6.88
24.5	6.56	22.1	7.24	22.5	7.13	21.6	7.44

The second reason, corona would generate around the electrode. A high negative voltage is applied to the small radius wire and the cylinder is grounded. The corona discharge is initiated when the electric field near the wire is sufficient to ionize the gaseous species. The minimum electric field in dry air is a function of the wire radius [31] as following **Figure 4.8**. If the distance from the electrode to the reactor wall was very close, a spark discharge could occur. Moreover, corona discharge intensity would decrease when the further corona was from the electrode. In this study, the distance between the electrode and the reactor wall was 37 mm. Therefore, around the electrode was high intensity of electron (0 mm.) and the further corona was from electrodes, the lower energy and intensity of electron would be as following **Figure 4.9.**

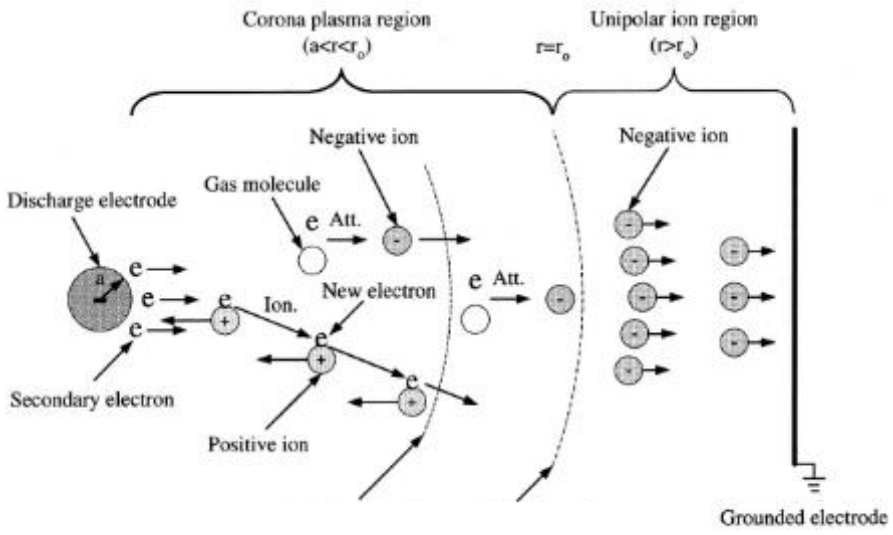


Fig 4.8 Description of the corona discharge [31].

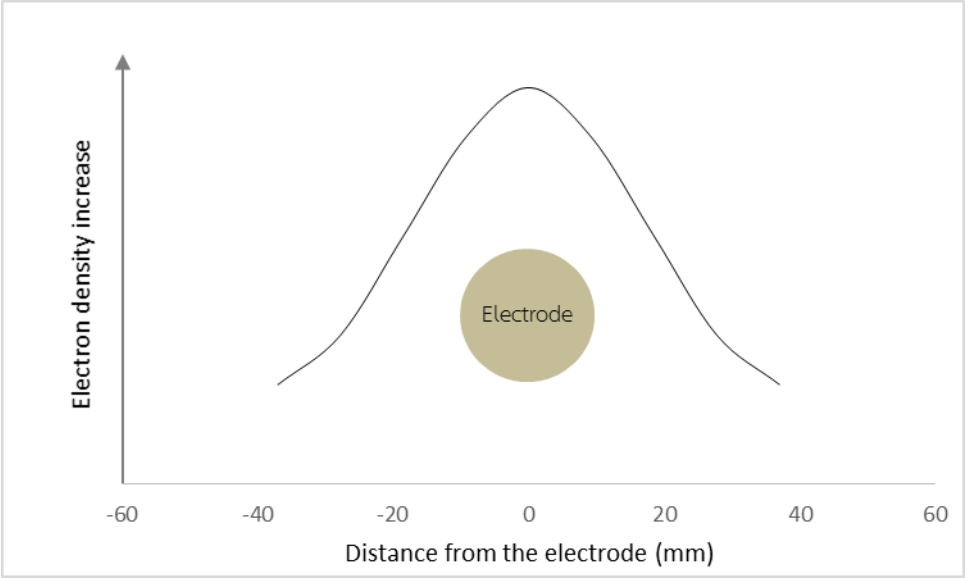


Fig 4.9 Dependence of electron density on distance from the electrode.

Furthermore, flow pattern of benzene gas is laminar flow (Calculation in Appendix A5), velocity profile was assumed as following **Figure 4.10**. Therefore, benzene gas near the wall would attach with electrons difficultly. Increase of benzene initial concentration would provide more benzene molecules in the reactor, resulting in decreased efficiency. In addition, voltage were related with the removal efficiency because the voltage could increase potential energy of electron. Therefore, high voltage would provide the highest efficiency.

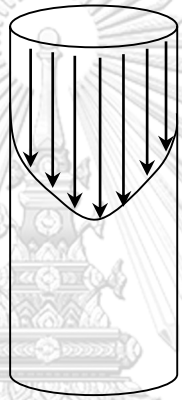


Fig 4.10 Velocity profile of benzene gas in corona reactor

4.4 Result of number of channels on benzene removal efficiency.

In this study, corona discharge reactor was separate to 4 channels as called multi-channels. Flow pattern in the reactor was confirmed by Reynolds's number (Calculation in Appendix A5). Calculation results shows that flow pattern is laminar flow, suppose that the total gas flow rate was also equally divided into 4 channels and the total input power was equally distributed into 4 channels also as shows in **Figure 4.11.** This experiment was operated under condition as follows **Table 4.7.**

Table 4.7 Experimental conditions with effect of number of channels**.**

Parameter		Unit
Electrode size	0.6	mm.
Gas flow rate	1,000	ml/min
Benzene concentration	500	ppm
Distance of reaction zone	300	mm.
Number of channel	1, 2 and 4	channel

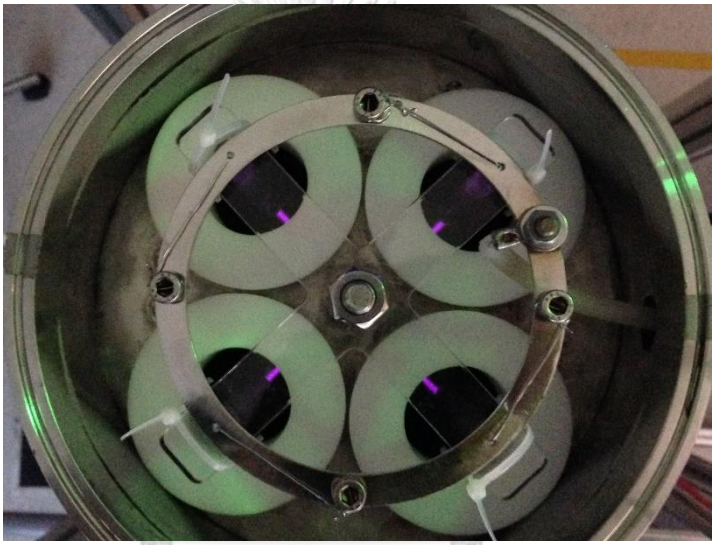


Fig 4.11 Distribution of input power in 4 channels reactor.

At first, gas flow rate was considered because different number of channels were applied in the reactor, surely the residence time of each condition would be different. From initial setting condition gas flow rate was fixed at 1,000 ml/min, the residence time is 309.5 seconds for 4 channels. If used the same gas flow rate with 1 and 2 channels the residence time is 76.13 and 152.26 seconds, respectively. Therefore, new condition of gas flow rate was set up to equal the residence time 309.5 seconds as shows in **Table 4.8.**

Table 4.8 New condition of gas flow rate to equal the residence time.

Parameters	1 Channel	2 Channels	4 Channels	Unit
Flow rate (Q)	250	500	1,000	ml/min
Residence time (τ)	309.5			Second
Distance of Reaction zone	300			mm

*Calculation in Appendix A5

In **Figure 4.12** the result shows that 180 watt maximum power was obtained from all conditions included 1, 2 and 4 channels. The removal efficiency of benzene could reached 93, 89 and 63 percent for 1, 2 and 4 channels respectively. For condition of 1 channel the benzene removal efficiency was similar to condition of 2 channels but condition of 4 channels the benzene removal was quite different. Even through, input power is equal at 180 watt for all condition but voltage and current are different. Voltage was drop when increasing the number of channels. On the other hand, current was increased when increasing the number of channels. **Table 4.9** shows the electrical input data for each condition.

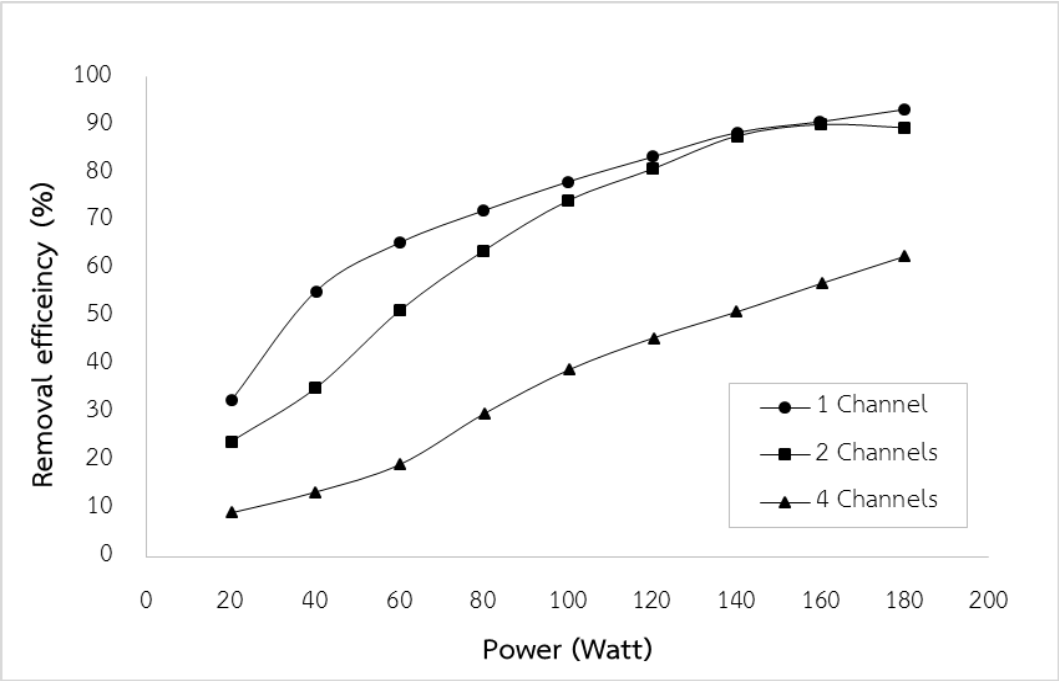


Fig 4.12 Removal efficiency with different number of channels

Table 4.9 Measurement of voltage and current supplied with different number of channels

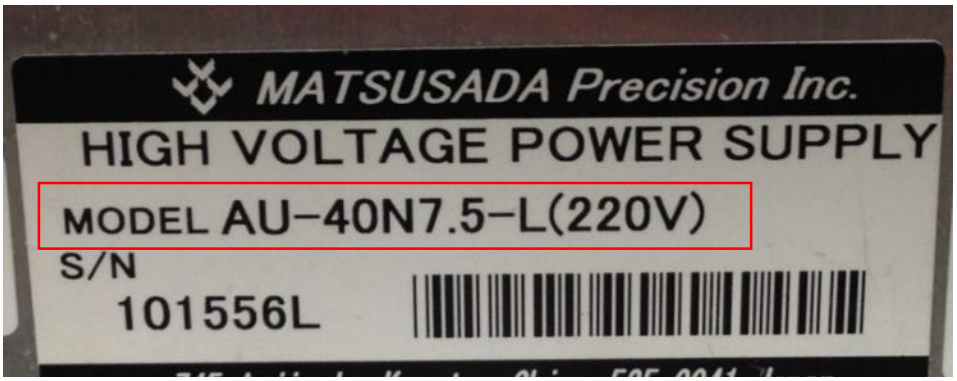
1 Channel			2 Channels			4 Channels		
Voltage (kV)	Current (mA)	Power (Watt)	Voltage (kV)	Current (mA)	Power (Watt)	Voltage (kV)	Current (mA)	Power (Watt)
21.3	0.96	20	17.2	1.18	20	15.6	1.32	20
24.2	1.67	40	19.6	2.06	40	16.8	2.41	40
27.4	2.21	60	21.7	2.78	60	18.3	3.31	60
28.3	2.84	80	23.3	3.44	80	20.2	3.99	80
29.4	3.42	100	24.7	4.06	100	21.9	4.60	100
30.7	3.93	120	25.9	4.65	120	22.9	5.27	120
31.8	4.42	140	27.1	5.18	140	23.8	5.90	140
32.6	4.91	160	28.0	5.73	160	24.5	6.56	160
33.3	5.15	180	28.1	6.10	180	25.6	7.05	180

The results shows that voltage could reached 33.3, 28.1 and 25.6 kV for 1, 2 and 4 channels, respectively and current could reached 5.15, 6.10 and 7.05 mA for 1, 2 and 4 channels, respectively. According to Kirchhoff's current law, the current entering a point in a circuit is equal to the summation of the currents exiting therefore the total current was equally distributed into 4 channels as shows in **Figure 4.11** and **Table 4.10**.

Table 4.10 Current supplied follow as Kirchhoff's current law.

Number of channels	Current (mA)	Total current (mA)
1	5.15	5.15
2	3.05	6.10
4	1.76	7.05

From current supplied results refer as Kirchhoff's current law, current supplied per electrode was decrease resulting in reduce of the benzene removal efficiency. However these results, voltage and current for 1 and 2 channels could increase more because maximum of voltage and current specification were 40 kV and 7.5 mA, respectively as show in **Figure 4.13**.



Output Voltage	Output Current (mA)	Output Power (W)	MODEL
30kV	1	30	★ AU-30*1
	2	60	★ AU-30*2
	3.3	100	★ AU-30*3.3
	5	150	★ AU-30*5
	10	300	★ AU-30*10
	20	600	AU-30*20
	40	1200	AU-30*40
	73.3	2200	AU-30*73.3
40kV	0.75	30	★ AU-40*0.75
	1.5	60	★ AU-40*1.5
	2.5	100	★ AU-40*2.5
	3.75	150	★ AU-40*3.75
	7.5	300	★ AU-40*7.5
	15	600	AU-40*15
	30	1200	AU-40*30
	55	2200	AU-40*55

Fig 4.13 Specification of high voltage power supply of MATSUSADA model AU-40N7.5-L(220V)

4.5 Byproducts analysis

In this study, all experiments were operated under nitrogen atmosphere. The brown residue deposited on the inner wall surface of the reactor was dissolved in acetone for GC-MS analysis. The results shows that the large peak around 11 minutes in **Figure. 4.14** can be identified as biphenyl [32]. However, the products in gas phase are not CO and CO_2 because there are only nitrogen and benzene gas in the system.

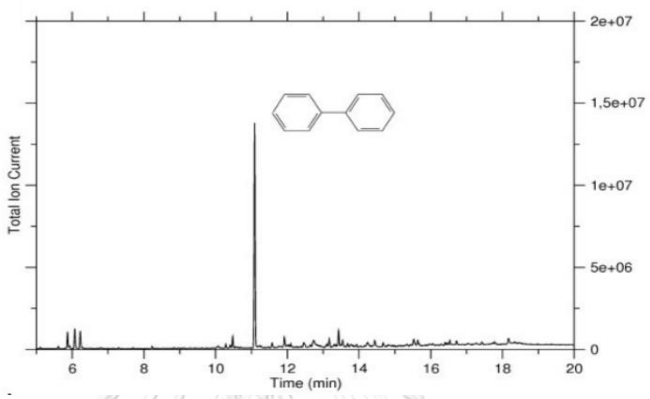


Fig 4.14 Library of mass spectrum of residue on inner wall

In addition, the brown residue on the electrode surface was also found. It was dissolved in acetone for GC-MS analysis same as the residue on the inner wall. The results shows that the peak around 7.5 minutes in **Figure. 4.15** can be identified as 2-Penanone.

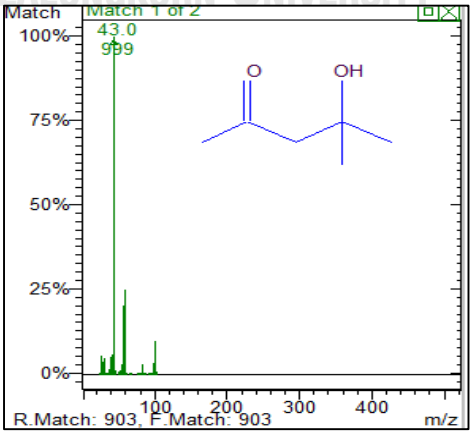


Fig 4.15 Library of mass spectrum of residue on electrode surface.

On the other hand, the experiments were operated under nitrogen and oxygen atmosphere, the results shows most of the products in the effluent were CO and CO_2 by on-line GC analysis. In addition, the brown residue was deposit in the inner wall of reactor, which can dissolve in methanol (CH_3OH) or acetone (C_3H_6O). GC-MS analysis has shown that the main components of residues dissolved in acetone are phenol, heptanoic acid, 2-nitro-phenol, hydroquinone, resorcinol, 3-nitro-phenol, 4-nitrocatechol, and 4-phenoxy-phenol [26] as shown in **Figure 4.16**.

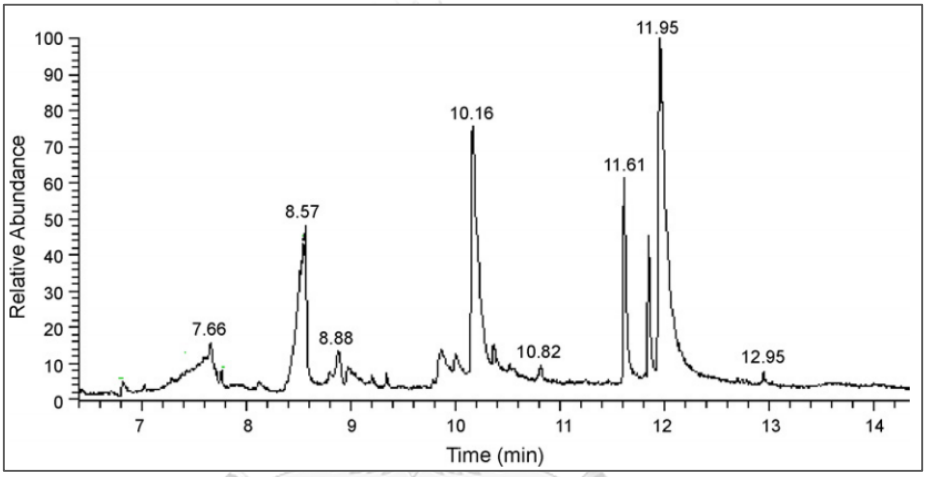


Fig 4.16 GC–MS spectrum of solid residues of benzene destruction in DBD (80 W, 20 kHz) (7.66: phenol; 8.57: heptanoic acid; 8.88: 2-nitro-phenol; 10.16: hydroquinone; 10.82: resorcinol; 11.61: 3-nitro-phenol; 11.95: 4-nitrocatechol; 12.95: 4-phenoxy-phenol) [26].

Chapter 5
Conclusion and Recommendations

5.1 Conclusion

In this study, effect of parameter including 1). Electrode size, 2). Gas flow rate, 3). Initial concentration and 4). Number of channels were study and all of the results could be summarize as follow. First result, effect of electrode size situated in the multi-channeled reactor on the benzene removal efficiency was investigated experimentally. A higher benzene removal efficiency could be achieved when a bigger electrode was employed because the lower resistance could stimulate more energetic electrons necessary for attaching with benzene in the gas flow. Second result, within the multi-channeled corona discharge reactor, the benzene removal efficiency was significantly affected by the gas flow rate and input power. An increase in the gas flow rate generally shortened the residence time and contact time of benzene with the corona, resulting in the lower benzene removal efficiency. Effect of gas flow rate was more significant than that of residence time but it effect on exerted detectable current supplied at a same corona voltage. Third result, increase of benzene concentration would provide more benzene molecules in the reactor resulting in decrease of collision. Corona discharge would generate around the electrode, benzene gas near the wall would attach with electrons difficultly. Therefore, benzene removal efficiency was decreased with the increasing of the benzene concentration. Finally, the current was decreased when increasing the number of channels because the current was distributed to other electrode in the reactor resulting in decreased of current per electrode (follow as Kirchhoff's current law). Therefore, benzene removal efficiency was decreased.

5.2 Recommendations for future work

In this study, the benzene removal efficiency of 93% was achieved with 1 channel condition because the obtained energy per electrode is high. Meanwhile, the removal efficiency of 89% was achieved with 2 channels condition. The results of both 1 and 2 channels are not different because the voltage and current is nearby same. On the other hand, the removal efficiency of 4 channels condition is lower than other conditions because the current was separate to 4 electrode. Therefore, to obtained high removal efficiency some recommendations would be suggest as follow

1. One channel condition should be apply in the corona reactor.
2. High voltage generator should be add more.

All experiments in this study are operate under dried-wall condition. The practical application such removal efficiency is still low. The corona reactor which use in this study can be change to wetted-wall system. The wetted-wall corona discharge reactor in which a thin liquid film flows can improved the removal efficiency. Oxidizing radical was form at the liquid or gas-liquid interface and it is effective for the removal of benzene or other VOCs. Therefore, to enhance the removal efficiency wetted-wall corona discharge reactor would be suggested.

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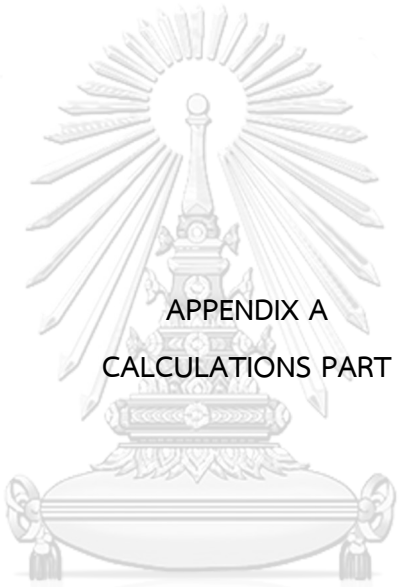
APPENDIX A

CALCULATIONS PART



A1. Calculation of resistance.

$$R = \rho L/A$$

Where, ρ is resistivity of material (stainless steel = 6.9×10^{-7} Ωm)

L is length (300 mm.)

A is cross sectional area

For 0.1 mm electrode size

$$R = (6.9 \times 10^{-7}\ \Omega m)(0.3\ m)/(3.14 \times 0.00005^2\ m)$$

$$R = 26.37\ \Omega$$

For 0.3 mm electrode size

$$R = (6.9 \times 10^{-7}\ \Omega m)(0.3\ m)/(3.14 \times 0.00015^2\ m)$$

$$R = 2.93\ \Omega$$

For 0.6 mm electrode size

$$R = (6.9 \times 10^{-7}\ \Omega m)(0.3\ m)/(3.14 \times 0.0003^2\ m)$$

$$R = 0.73\ \Omega$$

A2. Calculation of specific surface area.

Specific surface area (SSA) = Surface area / Volume

Surface area = $2\pi rh + 2\pi r^2$

Volume = $2\pi r^2 h$

Where, r is radius of electrode

h is high of electrode in reaction zone

* Cross sectional area can neglect because the corona discharge was generated from surface.

For 0.1 mm electrode size

SSA = $2 \times \pi \times 0.05$ mm $\times$ 300 mm / $2 \times \pi \times 0.05^2$ mm $\times$ 300 mm

= 20.00 mm^{-1}

For 0.3 mm electrode size

SSA = $2 \times \pi \times 0.15$ mm $\times$ 300 mm / $2 \times \pi \times 0.15^2$ mm $\times$ 300 mm

= 6.67 mm^{-1}

For 0.6 mm electrode size

SSA = $2 \times \pi \times 0.30$ mm $\times$ 300 mm / $2 \times \pi \times 0.30^2$ mm $\times$ 300 mm

= 3.33 mm^{-1}

A3. Calculation of residence time.

$$\tau = \frac{nAL}{Q}$$

Where $A = \frac{\pi}{4}D^2$ is Area (0.074 m^2)

D is Diameter of reactor

L is Length of reaction zone (0.3 m)

Q is Flow rate (m^3/s)

n is Number of channels (4 channels)

For 1,000 ml/min of flow rate

$$\tau = \frac{4 \times \frac{\pi}{4}(0.074)^2(0.300)\ m^2 \cdot m}{(1.66 \times 10^{-5})\frac{m^3}{s}}$$

$$\tau = 309.5\ sec.$$

For 2,000 ml/min of flow rate

$$\tau = \frac{4 \times \frac{\pi}{4}(0.074)^2(0.300)\ m^2 \cdot m}{(3.33 \times 10^{-5})\frac{m^3}{s}}$$

$$\tau = 154.8\ sec.$$

For 3,000 ml/min of flow rate

$$\tau = \frac{4 \times \frac{\pi}{4}(0.074)^2(0.300)\ m^2 \cdot m}{(5 \times 10^{-5})\frac{m^3}{s}}$$

$$\tau = 103.2\ sec.$$

For 4,000 ml/min of flow rate

$$\tau = \frac{4 \times \frac{\pi}{4}(0.074)^2(0.300)\ m^2 \cdot m}{(6.66 \times 10^{-5})\frac{m^3}{s}}$$

$$\tau = 77.4\ sec.$$

A4. Calculation of amount of electrons.

First, find out amount of charge from below formula

$$I = Q/t$$

Where, I is Current (Volt)

Q is Amount of charge (Coulomb)

t is time of current flow (Second)

Consider at 160 watt input power (22.2 kV and 7.22 mA) and 309.5 seconds (residence time)

$$Q = I \times t$$

$$= (22.2 \times 1000\ V) \times 309.5\ seconds$$

$$= 6.8709 \times 10^{6}\ Coulomb$$

Next, find out amount of electrons from below formula

$$N = Q/e$$

Where, N is Number of electrons

Q is Amount of charge (Coulomb)

e is Quantity of charge (1.6×10^{-19} Coulomb)

So, $N = (6.8709 \times 10^{6}\ Coulomb) / (1.6 \times 10^{-19}\ Coulomb)$

$$= 4.29 \times 10^{25}$$

A5. Calculation of amount benzene molecules.

From ideal gas law

$$PV = nRT$$

Where, P is Pressure (atm)

V is Volume of gas (L)

n is amount of substance of gas (in moles)

R is gas constant (L·atm/mole·K)

T is Temperature (K)

First, find out volume of gas (V)

$$V = [(1.67 \times 10^{-18} \text{ mole}) \times (0.082 \text{ L·atm/mole·K}) \times (298 \text{ K})] / 1 \text{ atm}$$

$$= 4.07 \times 10^{-17} \text{ L or}$$

$$= 4.07 \times 10^{-14} \text{ cm}^3$$

Next, find out volumetric flow rate

$$Q = Av$$

Where, A is Area

v is velocity (L/t)

$$Q = \pi r^2(v)$$

$$= (\pi \times 37^2 \text{ mm}) \times (300 \text{ mm} / 310 \text{ s})$$

$$= 4160 \text{ mm}^3$$

$$= 4.160 \text{ cm}^3/\text{s}$$

So, volume of benzene gas per unit time was obtained

$$V_{benzene} = (4.07 \times 10^{-14} \text{ cm}^3) \times (4.160 \text{ cm}^3/\text{s})$$

$$= 1.69 \times 10^{-13} \text{ cm}^3$$

Next, find out molecule of benzene at n ppm (In 10^6 molecules of nitrogen compose with n molecules of benzene)

500 ppm Benzene = 500 molecules / 1.69×10^{-13} cm^3

= 2.95×10^{15} molecules/cm^3

1,000 ppm Benzene = 1,000 molecules / $1.69 \times 10^{-13} cm^3$

= 5.90×10^{15} molecules/cm^3

1,500 ppm Benzene = 1,500 molecules / 1.69×10^{-13} cm^3

= 8.85×10^{15} molecules/cm^3

2,000 ppm Benzene = 2,000 molecules / 1.69×10^{-13} cm^3

= 1.18×10^{16} molecules/cm^3

Next, find out volume of the reactor

Volume = $n2\pi r^2 h$

Where, r is Radius of reactor

h is high of reactor

n is number of channels

So, Volume = $4 \times 2 \times \pi \times (37 \text{ mm})^2 \times (300 \text{ mm})$

= $10322016.8 \text{ mm}^3 \approx 10.32 \text{ L}$

So, there are total molecules of benzene

500 ppm Benzene = (2.95×10^{15} molecules/cm^3) x 10332 cm^3

= 3.05×10^{19} molecules

1,000 ppm Benzene = (5.90×10^{15} molecules/ cm^3) x 10332 cm^3

= 6.09×10^{20} molecules

1,500 ppm Benzene = (8.85×10^{15} molecules/cm^3) x 10332 cm^3

= 9.14×10^{19} molecules

2,000 ppm Benzene = (1.18×10^{16} molecules/cm^3) x 10332 cm^3

= 1.22×10^{20} molecules

A6. Calculation of Reynolds's number

Equation of continuity was used to calculate velocity as follows equation (1) – (3) to control flow pattern to laminar flow.

For single-channel reactor

$$Q = A\nu = \left(\frac{\pi}{4}\right) D^2\nu \quad (1)$$

Where Q is Flow rate (m^3/s)

A is Area (m^2)

D is Pipe diameter (m)

ν is Velocity (m/s)

$$\nu = \frac{4Q}{\pi D^2} \quad (2)$$

For 1 channel at Q = 1,000 ml/min and D = 74 mm.

$$\nu = \frac{4\left(1.66\times10^{-5}\right)\frac{m^3}{s}}{\pi(0.074)^2\ m^2} \quad (3)$$

$$= 0.0038\ m/s$$

$$= 3.80\ mm/s$$

In case of 2 and 4 channels gas flow rate is Q/2 and Q/4 respectively.

Next, Reynolds number could be used to confirm the flow pattern of gas flow in the reactor as referring to equation (4) and (5).

$$Re = \frac{\rho\nu D}{\mu} = \frac{\nu D}{\upsilon} \quad (4)$$

Where ρ is gas density (kg/m^3)

ν is gas superficial velocity (m/s)

D is pipe diameter (m)

μ is gas viscoscity (Ns/m^2)

$\upsilon = \mu/\rho$ is Kinetic viscosity of air at 25 °C ($1.568 \times 10^{-5}\ m^2/s$)

$$Re = \frac{\nu D}{\upsilon} = \frac{(0.0038)\frac{m}{s}(0.074)\ m}{(1.568\times10^{-5})\frac{m^2}{s}} \quad (5)$$

$$= 17.93$$

(With Re < 2,000, the flow pattern is laminar flow, while Re > 4,000 the flow pattern will be turbulent and if 2000 < Re < 4000 it is transition flow.)

This calculation shows only 1 channel condition for multi-channeled reactor included 2 and 4 channels. Equations (1) to (6) were used to calculate same as 1 channel. Therefore, calculation of velocity, Reynolds number and residence time of condition 1,000 ml/min of flow rate was shown as **Table A1.**

Table A1 Calculation at total flow rate of 1,000 ml/min (1.66×10^{-5} m^3/s)

Parameters	1 Channel	2 Channels	4 Channels	Unit
Flow rate (Q)	1.66×10^{-5}	$\frac{1.66 \times 10^{-5}}{2}$	$\frac{1.66 \times 10^{-5}}{4}$	m^3/s
Reynolds number (Re)	17.93	9.11	4.55	-
Residence time (τ)	76.13	152.26	309.5	Second

From calculation, the residence time of each conditions is not equal. Therefore, gas flow rate was adjusted to equal the residence time as shows in **Table A2**.

Table A2 New condition of gas flow rate to equal the residence time.

Parameters	1 Channel	2 Channels	4 Channels	Unit
Flow rate (Q)	250	500	1,000	ml/min
Residence time (τ)	309.5			Second

APPENDIX B

RAW DATA

B1. Result of benzene removal efficiency with 500 ppm initial concentration, 1,000 ml/min gas flow rate and 1 channel of corona reactor.

B1-1. Result of benzene removal efficiency with 0.1 mm electrode.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
10.5	1.94	20	453	7.0
13.3	3.04	40	454	7.0
14.4	4.19	60	450	8.0
16.1	4.99	80	443	9.0
17.5	5.74	100	429	12.0
18.6	6.47	120	416	15.0
19.0	7.39	140	404	17.0

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
10.4	1.94	20	487	5.0
13.1	3.09	40	481	6.0
14.5	4.15	60	477	7.0
15.9	5.06	80	469	9.0
17.3	5.80	100	462	10.0
18.1	6.65	120	446	13.0
18.9	7.43	140	433	16.0

B1-1. Result of benzene removal efficiency with 0.1 mm electrode. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
10.5	1.94	20	470	6.0
13.2	3.07	40	468	6.5
14.5	4.17	60	464	7.5
16.0	5.03	80	456	9.0
17.4	5.77	100	446	11.0
18.4	6.56	120	431	14.0
19.0	7.41	140	419	16.5

B1-2. Result of benzene removal efficiency with 0.3 mm electrode.

First time				
Voltage (kV)	Current (mA)	Conc. (ppm)	Power (Watt)	Efficiency (%)
12.5	1.61	480	20	6.0
14.4	2.81	465	40	8.0
15.6	3.87	453	60	11.0
16.9	4.76	439	80	14.0
18.3	5.49	415	100	18.0
19.4	6.20	390	120	23.0
20.8	6.74	374	140	26.0
21.5	7.46	365	160	28.0

B1-2. Result of benzene removal efficiency with 0.3 mm electrode. (Con)

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
12.5	1.62	20	488	6.0
15.0	2.69	40	464	11.0
16.3	3.69	60	449	14.0
17.6	4.55	80	425	18.0
19.0	5.28	100	406	22.0
20.0	6.00	120	383	27.0
20.9	6.70	140	360	31.0
21.7	7.39	160	337	35.0

Average

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
12.5	1.62	20	484	6.0
14.7	2.75	40	465	9.5
16.0	3.78	60	451	12.5
17.3	4.66	80	432	16.0
18.7	5.39	100	411	20.0
19.7	6.10	120	387	25.0
20.9	6.72	140	367	28.5
21.6	7.43	160	351	31.5

B1-3. Result of benzene removal efficiency with 0.6 mm electrode.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
16.5	1.24	20	446	9.8
17.2	2.33	40	418	15.6
18.7	3.23	60	392	20.8
20.5	3.92	80	330	33.3
22.1	4.54	100	290	41.5
22.8	5.28	120	265	46.5
23.7	5.91	140	231	53.3
24.6	6.52	160	191	61.4
25.9	6.96	180	170	65.7

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.7	1.39	20	466	8.6
16.3	2.48	40	451	11.4
17.8	3.39	60	419	17.8
19.8	4.05	80	375	26.4
21.6	4.65	100	323	36.5
22.9	5.26	120	282	44.7
23.8	5.89	140	261	48.8
24.3	6.60	160	241	52.6
25.2	7.14	180	206	59.5

B1-3. Result of benzene removal efficiency with 0.6 mm electrode. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
15.6	1.32	20.4	456.0	9.2
16.8	2.41	40.3	434.6	13.5
18.3	3.31	60.4	405.4	19.3
20.2	3.99	80.3	352.6	29.8
21.9	4.60	100.4	306.5	39.0
22.9	5.27	120.4	273.1	45.6
23.8	5.90	140.1	246.0	51.0
24.5	6.56	160.4	216.1	57.0
25.6	7.05	180.1	187.8	62.6

B2. Result of benzene removal efficiency with 0.6 mm electrode, 500 ppm initial concentration and 1 channel of corona reactor.

B2-1. Result of benzene removal efficiency with 1,000 ml/min of gas flow rate.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
16.5	1.24	20	446	9.8
17.2	2.33	40	418	15.6
18.7	3.23	60	392	20.8
20.5	3.92	80	330	33.3
22.1	4.54	100	290	41.5
22.8	5.28	120	265	46.5
23.7	5.91	140	231	53.3
24.6	6.52	160	191	61.4
25.9	6.96	180	170	65.7

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.7	1.39	20	466	8.6
16.3	2.48	40	451	11.4
17.8	3.39	60	419	17.8
19.8	4.05	80	375	26.4
21.6	4.65	100	323	36.5
22.9	5.26	120	282	44.7
23.8	5.89	140	261	48.8
24.3	6.60	160	241	52.6
25.2	7.14	180	206	59.5

B2-1. Result of benzene removal efficiency with 1,000 ml/min of gas flow rate. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
15.6	1.3	20	456	9.2
16.8	2.4	40	435	13.5
18.3	3.3	60	405	19.3
20.2	4.0	80	353	29.8
21.9	4.6	100	307	39.0
22.9	5.3	120	273	45.6
23.8	5.9	140	246	51.0
24.5	6.6	160	216	57.0
25.6	7.1	180	188	62.6

B2-2. Result of benzene removal efficiency with 2,000 ml/min of gas flow rate.

First time				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.0	1.46	20	468	5.1
15.9	2.54	40	456	7.6
17.1	3.53	60	434	12.0
19.5	4.12	80	408	17.3
21.0	4.75	100	377	23.6
22.1	5.43	120	342	30.6
23.4	6.00	140	314	36.3
24.3	6.6	160	283	42.6
25.3	7.12	180	256	48.0

B2-2. Result of benzene removal efficiency with 2,000 ml/min of gas flow rate. (Con)

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
13.4	1.51	20	473	6.8
15.1	2.65	40	474	6.6
17.0	3.55	60	452	11.0
18.9	4.25	80	419	17.3
20.0	5.00	100	383	24.4
21.4	5.62	120	368	27.4
22.4	6.25	140	361	28.8
23.3	6.88	160	329	35.1
24.3	7.41	180	297	41.4

Average

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
13.7	1.5	20.3	470	6.0
15.5	2.6	40.2	465	7.1
17.1	3.5	60.4	443	11.5
19.2	4.2	80.3	414	17.3
20.5	4.9	99.9	380	24.0
21.8	5.5	120.1	355	29.0
22.9	6.1	140.2	338	32.6
23.8	6.7	160.3	306	38.8
24.8	7.3	180.1	277	44.7

B2-3. Result of benzene removal efficiency with 3,000 ml/min of gas flow rate.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
13.1	1.53	20	501	4.5
14.3	2.82	40	504	3.9
15.3	3.92	60	502	4.4
16.5	4.85	80	496	5.5
17.2	5.82	100	484	7.7
19.1	6.29	120	472	10.0
20.0	6.99	140	456	13.1

*Initial concentration in this experiment is 525 ppm.

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.1	1.42	20	490	1.3
15.1	2.63	40	488	1.8
16.4	3.67	60	489	1.5
17.1	4.70	80	482	3.0
18.2	5.50	100	469	5.6
19.0	6.34	120	455	8.3
20.1	6.99	140	434	12.7

B2-3. Result of benzene removal efficiency with 3,000 ml/min of gas flow rate. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
13.6	1.5	20.0	496	2.9
14.7	2.7	40.0	496	2.9
15.9	3.8	60.1	495	3.0
16.8	4.8	80.2	489	4.3
17.7	5.7	100.1	477	6.7
19.1	6.3	120.3	464	9.2
20.1	7.0	140.1	445	12.9

B2-4. Result of benzene removal efficiency with 4,000 ml/min of gas flow rate.

First time				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
12.5	1.63	20	483	6.5
12.9	3.11	40	496	3.9
13.0	4.65	60	497	3.8
13.3	6.02	80	497	3.7
13.6	7.38	100	495	4.2

B2-4. Result of benzene removal efficiency with 4,000 ml/min of gas flow rate. (Con)

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
10.9	1.85	20	497	2.0
11.3	3.54	40	498	2.0
11.6	5.19	60	494	3.0
12.6	6.35	80	492	3.0
13.6	7.36	100	489	4.0

Average

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
11.7	1.7	20	490	4.3
12.1	3.3	40	497	2.9
12.3	4.9	60	495	3.4
13.0	6.2	80	495	3.4
13.6	7.4	100	492	4.1

B3. Result of benzene removal efficiency with 0.6 mm electrode, 1,000 ml/min gas flow rate and 1 channel of corona reactor.

B3-1. Result of benzene removal efficiency with 500 ppm concentration.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
16.5	1.24	20	446	9.8
17.2	2.33	40	418	15.6
18.7	3.23	60	392	20.8
20.5	3.92	80	330	33.3
22.1	4.54	100	290	41.5
22.8	5.28	120	265	46.5
23.7	5.91	140	231	53.3
24.6	6.52	160	191	61.4
25.9	6.96	180	170	65.7

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.7	1.39	20	466	8.6
16.3	2.48	40	451	11.4
17.8	3.39	60	419	17.8
19.8	4.05	80	375	26.4
21.6	4.65	100	323	36.5
22.9	5.26	120	282	44.7
23.8	5.89	140	261	48.8
24.3	6.60	160	241	52.6
25.2	7.14	180	206	59.5

B3-1. Result of benzene removal efficiency with 500 ppm concentration. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
15.6	1.32	20	456	9.2
16.8	2.41	40	435	13.5
18.3	3.31	60	405	19.3
20.2	3.99	80	353	29.8
21.9	4.60	100	307	39.0
22.9	5.27	120	273	45.6
23.8	5.90	140	246	51.0
24.5	6.56	160	216	57.0
25.6	7.05	180	188	62.6

B3-2. Result of benzene removal efficiency with 1,000 ppm concentration.

First time				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
13.3	1.52	20	1004	2.7
14.8	2.71	40	968	6.2
16.3	3.69	60	947	8.3
17.3	4.65	80	923	10.6
18.6	5.40	100	901	12.7
19.7	6.09	120	856	17.1
20.6	6.82	140	787	23.8
21.9	7.31	160	725	29.8

*Initial concentration in this experiment is 1033 ppm.

B3-2. Result of benzene removal efficiency with 1,000 ppm concentration. (Con)

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.7	1.38	20	960	4.3
16.7	2.40	40	891	11.2
18.2	3.31	60	840	16.3
19.8	4.05	80	797	20.5
20.9	4.80	100	758	24.5
21.4	5.61	120	725	27.7
21.9	6.40	140	717	28.5
22.3	7.18	160	701	30.1

Average

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.0	1.45	20	982	3.5
15.8	2.56	40	930	8.7
17.3	3.50	60	894	12.3
18.6	4.35	80	860	15.6
19.8	5.10	100	830	18.6
20.6	5.85	120	791	22.4
21.3	6.61	140	752	26.2
22.1	7.25	160	713	30.0

B3-3. Result of benzene removal efficiency with 1,500 ppm concentration.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.1	1.44	20	1344	10.4
15.9	2.54	40	1379	8.1
16.8	3.58	60	1364	9.1
18.5	4.34	80	1325	11.7
19.4	5.17	100	1300	13.4
20.9	5.75	120	1205	19.7
21.6	6.50	140	1162	22.6
22.3	7.19	160	1116	25.6

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
15.5	1.31	20	1383	7.7
17.2	2.33	40	1367	8.7
18.0	3.34	60	1370	8.5
19.1	4.20	80	1338	10.6
20.0	5.00	100	1298	13.3
21.0	5.73	120	1245	16.8
22.1	6.35	140	1176	21.4
22.7	7.06	160	1143	23.7

B3-3. Result of benzene removal efficiency with 1,500 ppm concentration. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.8	1.38	20	1363	9.0
16.6	2.44	40	1373	8.4
17.4	3.46	60	1367	8.8
18.8	4.27	80	1332	11.1
19.7	5.09	100	1299	13.3
21.0	5.74	120	1225	18.3
21.9	6.43	140	1169	22.0
22.5	7.13	160	1130	24.6

B3-4. Result of benzene removal efficiency with 2,000 ppm concentration.

First time				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.3	1.42	20	2169	1.2
15.3	2.64	40	2139	2.5
16.3	3.70	60	2127	3.1
17.0	4.69	80	2120	3.4
17.8	5.61	100	2106	4.0
18.7	6.43	120	2091	4.7
20.1	6.97	140	2069	5.7
21.4	7.49	160	2039	7.0

*Initial concentration in this experiment is 2194 ppm.

B3-4. Result of benzene removal efficiency with 2,000 ppm concentration. (Con)

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.4	1.42	20	2127	1.7
15.9	2.51	40	2137	1.3
16.5	3.65	60	2129	1.7
17.5	4.58	80	2119	2.1
18.3	5.47	100	2116	2.3
19.0	6.32	120	2099	3.0
20.6	6.79	140	2078	4.0
21.7	7.39	160	2009	7.2

*Initial concentration in this experiment is 2165 ppm.

Average

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.4	1.42	20	2148	1.4
15.6	2.58	40	2138	1.9
16.4	3.68	60	2128	2.4
17.3	4.64	80	2119	2.8
18.1	5.54	100	2111	3.1
18.9	6.38	120	2095	3.9
20.4	6.88	140	2073	4.9
21.6	7.44	160	2024	7.1

B4. Result of benzene removal efficiency with 0.6 mm electrode, 1,000 ml/min gas flow rate and 500 ppm concentration.

B4-1. Result of benzene removal efficiency with 1 channel of corona reactor.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
21.6	0.94	20	317	30.1
23.8	1.69	40	217	52.1
27.5	2.19	60	169	62.8
28.8	2.78	80	127	72.1
30.3	3.31	100	91	80.0
31.5	3.82	120	62	86.2
32.4	4.33	140	44	90.2
33.2	4.82	160	32	92.9
33.4	5.13	171	27	94.1

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
20.9	0.97	20	288	35.3
24.5	1.65	40	184	58.6
27.2	2.22	60	141	68.3
27.8	2.89	80	123	72.3
28.4	3.53	100	105	76.4
29.8	4.04	120	86	80.6
31.1	4.51	140	59	86.7
32.0	5.00	160	51	88.5
33.2	5.16	171	34	92.5

B4-1. Result of benzene removal efficiency with 1 channel of corona reactor. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
21.3	0.96	20	303	32.7
24.2	1.67	40	201	55.4
27.4	2.21	60	155	65.5
28.3	2.84	80	125	72.2
29.4	3.42	100	98	78.2
30.7	3.93	120	74	83.4
31.8	4.42	140	52	88.5
32.6	4.91	160	42	90.7
33.3	5.15	180	30	93.3

B4-2. Result of benzene removal efficiency with 3 channel of corona reactor.

First time				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
17.3	1.17	20	374	26.0
19.6	2.06	40	325	35.6
21.7	2.78	60	237	53.0
23.4	3.42	80	176	65.1
24.6	4.07	100	126	75.1
25.7	4.68	120	101	80.0
27.0	5.20	140	60	88.1
28.0	5.72	160	53	89.5
28.1	6.09	171	52	89.8

B4-2. Result of benzene removal efficiency with 3 channel of corona reactor. (Con)

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
17.1	1.18	20	379	22.1
19.5	2.06	40	317	34.8
21.7	2.77	60	245	49.7
23.2	3.45	80	183	62.4
24.8	4.04	100	129	73.4
26.0	4.62	120	89	81.8
27.2	5.15	140	61	87.4
27.9	5.74	160	45	90.8
28.0	6.11	171	53	89.2

Average

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
17.2	1.18	20	376	24.0
19.6	2.06	40	321	35.2
21.7	2.78	60	241	51.3
23.3	3.44	80	180	63.8
24.7	4.06	100	128	74.3
25.9	4.65	120	95	80.9
27.1	5.18	140	61	87.7
28.0	5.73	160	49	90.1
28.1	6.10	180	52	89.5

B4-3. Result of benzene removal efficiency with 4 channel of corona reactor.

First time

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
16.5	1.24	20	446	9.8
17.2	2.33	40	418	15.6
18.7	3.23	60	392	20.8
20.5	3.92	80	330	33.3
22.1	4.54	100	290	41.5
22.8	5.28	120	265	46.5
23.7	5.91	140	231	53.3
24.6	6.52	160	191	61.4
25.9	6.96	180	170	65.7

Repeat

Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
14.7	1.39	20	466	8.6
16.3	2.48	40	451	11.4
17.8	3.39	60	419	17.8
19.8	4.05	80	375	26.4
21.6	4.65	100	323	36.5
22.9	5.26	120	282	44.7
23.8	5.89	140	261	48.8
24.3	6.60	160	241	52.6
25.2	7.14	180	206	59.5

B4-3. Result of benzene removal efficiency with 4 channel of corona reactor. (Con)

Average				
Voltage (kV)	Current (mA)	Power (Watt)	Conc. (ppm)	Efficiency (%)
15.6	1.32	20	456	9.2
16.8	2.41	40	435	13.5
18.3	3.31	60	405	19.3
20.2	3.99	80	353	29.8
21.9	4.60	100	307	39.0
22.9	5.27	120	273	45.6
23.8	5.90	140	246	51.0
24.5	6.56	160	216	57.0
25.6	7.05	180	188	62.6

VITA

Mr. Thanunwut Thanahirumthitichote was born on October 19, 1988 in Ubonratchathani, Thailand. In 2007, He was graduate from Ubonratchathani University in Bachelor's Degree of Chemical Engineering. His senior project was focused on the extraction of lactic acid into vegetable oil. In his junior year, he gained useful experience from Toyoda Gosei Rubber (Thailand) company as a trainee engineering. He gained admission to study for a Master Degree in Chemical Engineering at Chulalongkorn University in 2015. In first year of master degree he joined the Corona discharge project with PTT Research and Technology Institute (PTT-RTI). He graduated Master Degree in 2017 with a thesis entitled "Effect of operating variables of corona discharge reactor on benzene removal efficiency".