A NEW STREAMER DISCHARGE CHAMBER FOR NO_X REMOVAL FROM HEAVY VEHICLES: A SIMULATION STUDY

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Special dedicated to my family members,
My dearest mother and all my friends and relatives,

All my teachers and lecturers,
For their love, support, cares, sacrifice and Doa

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Alhamdulillah, finally I have completed this project entitled *A New Streamer Discharge Chamber for NOx removal from Heavy Vehicles: A simulation study*Š.

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ABSTRACT

The problem of air pollution caused by the production of nitrogen Oxides (NOx) from diesel engine vehicle at this time is one of the contributor factor in human health problems and environmental. Currently, there are many methods being used to reduce and treat NOx including selective catalytic reduction (SCR), NO_x storage and reduction (NSR), exhaust gas recirculation (EGR) and electron beam irradiation. However, each method has its own limitations in removing the NOx from diesel engine exhaust. Non-thermal plasma (pulsed streamer discharge) was recognized as discharge of a potential technology for the removal of pollutants from diesel engine exhaust. Initial research finding shows that the use of Non-thermal Plasma equilibrium is a promising technique in controlling and removing the NOx from diesel engine vehicles. In this study, a new exhaust system that is a parallel cascaded chamber incorporating with Non-thermal plasma (pulse streamer discharge) was successfully designed and simulated. The use of parallel shape is to prevent any back pressure inside the chamber and the cascaded plasma chamber is chosen in order to repetitively remove and optimized the removal of NOx from exhaust chamber. A Simulation study have been carried out using Commercial Computational Fluid Dynamics (CFD) to assess the performance of the plasma Chamber design against the removal of NOx from diesel engine exhaust. Several parameters including gap distance, length of the chamber and the number of cascaded were accounted to study the effects of the parameters to the overall system performance. The simulation result indicates that a gap distance of 4-5 mm, chamber length of 190mm and three cascaded chamber have found to provide an optimum design of pulsed streamer discharge chamber for NOx removal.

ABSTRAK

Masalah pencemaran udara yang disebabkan oleh penghasilan nitrogen oksida (NOx) dari kenderaan berinjin diesel pada masa ini merupakan salah satu faktor penyumbang kepada masalah kesihatan manusia dan alam sekitar. Pada masa ini, terdapat banyak kaedah yang digunakan untuk mengurangkan dan merawat NOx termasuk pengurangan pemangkin terpilih (SCR), penyimpanan dan pengurangan NOx (NSR), edaran semula gas ekzos (EGR) dan sinaran pancaran elektron. Walau bagaimanapun, setiap kaedah mempunyai keterbatasan sendiri dalam menyingkirkan NOx yang terhasil dari kenderaan enjin diesel. Plasma bebas-haba (pelepasan aliran berdenyut) telah diiktiraf sebagai teknologi discas yang berpotensi untuk penyingkiran bahan pencemar dari ekzos enjin diesel. Dari kajian awal menunjukkan bahawa penggunaan keseimbangan Plasma bebas-haba adalah satu teknik yang berkesan dalam mengeluarkan dan mengawal NOx daripada kenderaan enjin diesel. Dalam kajian ini, sebuah ekzos baru dihasilkan iaitu kebuk bertingkat (*cascaded)* selari yang dilengkapkan dengan plasma bebas-haba (pelepasan aliran berdenyut) telah berjaya direkabentuk dan disimulasi. Penggunaan bentuk selari adalah untuk menghalang tekanan balik (back pressure) di dalam kebuk dan kebuk plasma bertingkat dipilih untuk menghapuskan dan menyingkirkan NOx secara berulang-ulang dari kebuk ekzos dapat dilakukan secara optimum. Kajian simulasi yang telah dijalankan menggunakan dinamik bendalir Komputeran komersial (CFD) untuk menilai prestasi reka bentuk kebuk plasma dalam meningkatkan penghapusan NOx dari ekzos enjin diesel. Beberapa parameter termasuk perbezaan jarak, panjang kebuk dan bilangan tingkat*(cascaded)* kebuk telah dianalisa untuk mengkaji kesan parameter kepada prestasi keseluruhan sistem. Hasil simulasi menunjukkan bahawa dengan jarak 4-5 mm, panjang kebuk 190mm dan susunan kebuk tiga peringkat telah membuktikan reka bentuk kebuk pelepasan aliran berdenyut menghasilkan kebuk aliran penyingkiran NOx yang optimum.

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LIST OF SYMBOLS

P	-	Pressure
m	-	Flow rate
V	-	Applied voltage
f	-	Frequency
T	-	Temperature
ι_r	-	Relative permittivity
L	-	Length
M	-	Mass
T	-	Time
k	-	Arrhenius reaction rate

LIST OF ABBREVIATIONS

A/F	-	Air µto-fuel ratio
Al_2O_3	-	Aluminium oxide
APGD	-	Atmospheric pressure glow discharge
Ba	-	Barium
Ca	-	Calcium
CFD	-	Computational fluid dynamics
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
DBD	-	Dielectric barrier discharge
DEF	-	Diesel Exhaust Fluid
EB	-	Electron Beam
EGR	-	Exhaust gas recirculation
H_2	-	Hydrogen
H_2O	-	Water
HC	-	Hydrocarbon
HNO_3	-	Nitric acid
K	-	The Equilibrium Constant
Li	-	Lithium
N (^2D)	-	Metastable excited-state nitrogen atoms
N (^4S)	-	Ground-state nitrogen atoms
N_2	-	Nitrogen
N_2O	-	Nitrous oxide
N_2O_3	-	Dinitrogen trioxide
N_2O_4	-	Dinitrogen tetroxide
N_2O_5	-	Dinitrogen pentoxide
NH_3	-	Ammonia

NO	-	Nitrogen oxide
NO_2	-	Nitrogen dioxide
NO_x	-	Nitrogen oxides
NSR	-	NO_x storage and reduction
NTP	-	Non-thermal plasma
Mgo	-	Magnesium Oxide
O_2	-	Oxygen
PM	-	Particulate matter
sr	-	strontium
SCR	-	Selective catalytic reduction
SO_2	-	Sulfur dioxide
SO_x	-	Sulfur oxides
VOCs	-	Volatile organic compounds

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Malaysia is one of the developing countries which are currently extensively involved in many industrial activities. In line with this development, inevitably there be the existence of air pollution due to different reason. One of the prominent sources of air pollution is from burning of diesel gas used in transportation system.

Air pollution said to have the biggest impact to the environment. Air pollution causes global warming phenomenon which results in the occurrence of natural disasters that threaten our earth. Air pollution is a global issue and it needs to be addressed and preventive measures need to be in place so that the level of pollution can be controlled. Developed countries such as China have huge manufacturing industry directly affect air quality in the country and this is a big concern to World Health Organization.

Air pollution can be classified into two types, primary pollution and secondary pollution The primary pollution refers to pollution that contain sulfur monoxide and carbon monoxide as a results of incomplete combustion, which we

sees as fine particles suspended in the air. Most of this type of pollution were contributed by motor vehicles operation, or by industry that releases pollutants or smoke and those industries with uncontrolled coal burning. Secondary pollution however, is mainly due to sulfur dioxide reaction which formed gases that is not required by living things, as an example combination of sulfur dioxide, sulfur monoxide and water vapour will produced sulfuric acid.

Sources of air pollution include smoke emitted from motor vehicles, factory and smoke from the industry that uses coal burning without control in place. In addition to this, natural phenomenon such as forest fires and volcanoes eruptions can also contributed to the pollution. These natural disasters are capable of producing smoke, dust particles, that would affect visibility in its surrounding.

Air pollution has negative effect to human respiratory system. It will cause breathing difficulties and gases like carbon monoxide will poison the oxygen in the blood system. Once happen, it will slow down the human response and subsequently will cause tiredness and sleepiness, and finally will cause impaired lung. According to the study of the World Health Organization (WHO), 3 million people died of sickness every year due to air pollution.

Transportation is a key factor to ensure smooth and effective daily activities as well as social and economic activities. Since two decades ago, Malaysian public transport has become increasingly important. Throughout the period of 2000 to 2012, the transport component index rose 36.9 points. All the index indicators, namely ownership of private motorcars and motorcycles, Road Development Index (RDI) per capita, the length of the street and the number of train passengers showed an increase between 35.1 to 39.8 points. The index number of the passenger train showing the highest increase with 24.7 points, followed by ownership of private motorcars and motorcycles with 37.5 points and the index of Transport Economic Well-being Index Component Development Road with 35.4 points. Road length per

capita index on the other hand, were the lowest recorded an increase with only 21.8 points, the data were illustrated in figure 1.1.

The index number for the ownership of private motorcars registered increased with 37.5 points in 2012. The number of private vehicles registered doubled from 14 million in 2005 to 20 million in 2009. This reflects the increasing number of Malaysians owning a vehicle as shown in figure 1.2.

Figure 1.1: Index Component Development Road

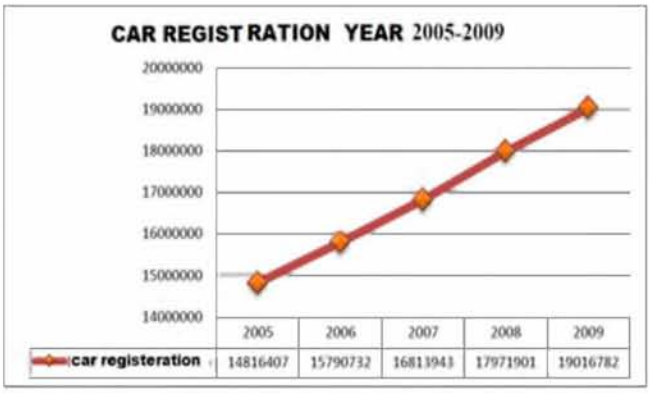

Figure 1.2: Car Registration in year 2005-2009

The second source of air pollutant is gases that were released by motor vehicles. Modern society is highly dependent on the transportation by motor vehicles which includes cars, trucks and buses. Every movement of the motor vehicle uses a lot of energy. Motor vehicles burn fossil fuels for movement that produces smoke that can pollute the air. The number of registered vehicles used in Malaysia is on the rise, this would also means the increase of air contamination in Malaysia.

Every movement of the motor vehicle using a lot of energy and almost all of which is produced by burning fossil fuels, which produce smoke and noise, which carries the adverse effects on the environment situation. Environmental air quality greatly depends on the type of system used, the type of energy source, the level of technology. In the transportation sector, motor vehicles were the main contributors to air pollution. In 2004, there are about 14 million registered motor vehicles in Malaysia and this figure has doubled compared to a decade ago. This figure will continue to increase every year.

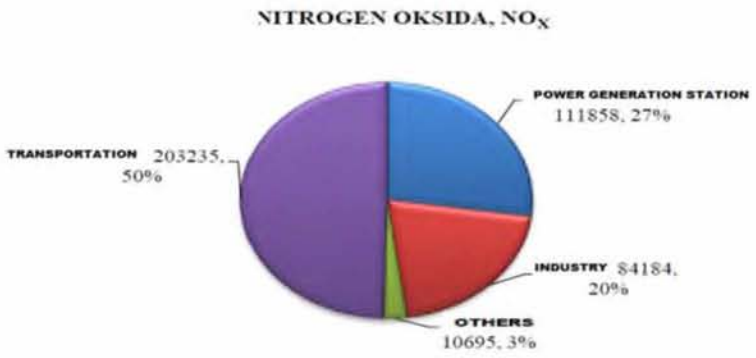

Figure 1.3: Sources of Nitrogen Oxides

Flue gas emission from fossil-fuel combustion refer to the combustion exhaust gas resulting from fossil fuels burning. A typical flue gas from most fossil fuels contains nitrogen oxides (NOx), sulfer dioxide (SO_2) and particulate matter [2]. The emission of NO_x into the atmosphere is found to be the main contributor to the formation of acid rain and atmospheric photochemical smog which cause damage to the vegetation and aquatic ecosystems. A large parts of NO_x produced mainly by diesel engines are also known to cause serious respiratory problems to humans and simultaneously reducing plant growth as it may decrease the ability of plants to convert sunlight to energy [5, 6]. Figure 1.3 had shown that transportation is the major sources of Nitrogen Oxides which is 50%, followed by power generation station, 27%, industrial, 20%, and others , 3% .

NOx may be removed by improving combustion process such as using low NOx burners, improved gas circulation and staged combustion [1]. It can also be removed by using post combustion removal techniques such as selective catalytic reduction (SCR). In recent years, discharged based techniques namely electron beam (EB) irradiation (Chmielewsky 1997;Hashim et al,2001) and dielectric barrier discharge (DBD) are gaining respect as viable technologies for air pollution control, namely to remove NOx and SO_2 .(Kogelschatz et al. 1999; Xu 2001; Mok 2005).

Nitrogen oxide (NOx) from diesel exhaust gas is one of the main products when fuel burns under high temperature and oxygen-rich conditions, which is highly toxic. Figure 1.3 shows the activities that contributed to the generation of NOx. It can form acid rain, photochemical smog and other harmful substances, which can threaten human health and has already been the main source of atmospheric and environmental pollution in the city and its surrounding areas. NOx removal has always been one of the focuses and difficulties in the field of diesel emission control.

1.2 Problem Statement

Now days, the effect of the NOx on environment has become a serious problem as humans continue to improve their technology advancement. Nitrogen oxides (NOx) is one of typical air pollutants which cause acid rain. Fossil fuel burning from activities such as electricity generation in fossil fueled power plant and fossil fuel based transportation had released millions of tonnes nitrogen oxides (NOx) into the atmosphere .

Many researchers have been studying several methods including selective catalytic reduction (SCR), NO_x storage and reduction(NSR), exhaust gas recirculation (EGR) and electron beam irradiation in their previous work. Nevertheless, each method has their own limitations in removing the pollutant gases from diesel engine exhaust [5, 9-11].

Non-thermal plasma (NTP) utilizing electrical discharge is found to be very promising technology for the removal of pollutant gases from diesel engine exhaust, which is extremely effective and economical approach. NTP technology offers great significance in controlling pollutant gases as it is characterized by low gas temperature and high electron temperature [12-14]. As a result of their rapid reactions, high electron energies and simple operation, these methods have shown significant outcome [15].

Electrical discharge plasma has a great potential on air pollution control as it offer advantages of high energy efficiency, low operation cost, easy operation, no-secondary pollution and able to remove various pollutant simultaneously [16]. NTP discharge can be generated by several type of electrical discharges such as dielectric barrier discharge, pulsed corona discharge and dielectric-packed bed reactors.

The main focus of this research is to design an optimum prototype of a parallel cascaded pulse streamer discharge plasma chamber as an excellent removing medium of pollutant gases from diesel engine exhaust. This plasma reactor is made cascaded so that the gas treatment process able to be conducted in three stages to fully cover the exhaust gas path to have a more efficient treatment. A simulation study has been conducted to verify the optimum performance of the chamber design before constructing the real chamber.

1.3 Objectives

The aim of this project is to obtain the optimum design of pulsed streamer discharge chamber for NO_x removal from diesel engine exhaust by parallel cascaded pulsed streamer discharge plasma. This will be met through these objectives:

1. To design a model of parallel and cascaded exhaust chamber incorporating the non-thermal plasma technique.
2. To conduct a simulation study using ANSYS-fluent 14 (CFD) to evaluate the effectiveness of the design in reducing NOx.
3. To analyse the design parameters of parallel cascaded pulsed streamer discharge plasma chamber for optimum removal of NO_x from diesel engine exhaust.

1.4 Scope of Project

The following scope of work will be done in order to achieve the objectives of the project.

1. A literature study (journal, articles, book etc) on various types of non-thermal plasma reactor used in removal of pollutant gases from diesel engine exhaust vehicles.
2. Focus on removal of NO_x released from diesel engine exhaust system by using parallel cascaded pulsed streamer discharge plasma method.
3. Design of parallel cascaded pulse streamer discharge plasma chamber by using Solidworks.
4. Analysis on design performance of cascaded pulsed streamer discharge plasma chamber using Commercial Computational Fluid Dynamics (CFD), Ansys Fluent 14. The optimum parameters that have significant effects on the removal of NO_x as well as on the engine performance will be identified.

1.5 Thesis Outline

This thesis comprises five chapters. Each chapter is briefly discussed as below:

Chapter 1 is the introduction of this research which includes brief description on background, problem statement, objectives and scope of project.

The literature review of this project is being discussed in Chapter 2. Noxious effect of NO_x pollutant and various types of non-thermal plasma reactor

used for abatement of this pollutant from diesel engine exhaust are further elaborated. It also summarizes several aspects of NO_x removal including an overview of diesel engine emission reduction strategies.

Chapter 3 describes the methodology of the project. This chapter provides the design of parallel cascaded pulsed streamer discharge plasma chamber using Solidworks. The materials and dimensions used in the design of cascaded discharge chamber are briefly explained in this chapter. This chapter also summarizes method used in this research work to predict the removal of NO_x from diesel engine exhaust. The section describes the flow analysis of exhaust chamber conducted using commercial CFD.

Chapter 4 presents all the results and analysis from the studies. The first section presents the results of output performance of exhaust chamber on the removal of NO_x and flow field using commercial CFD for different gap spacing, diameter of hole of perforated metal, exhaust chamber length and numbers of stages. The plot of pressure and velocity are also included to show the effect of reaction on the flow field of the exhaust chamber.

Chapter 5 summarizes present study and presented the recommendations for future studies in this area. The conclusions are written based on the results obtained in Chapter 4, whereas the recommendations for future research are made due to their significance with the current research.

REFERENCES

1. B.M. Penetrante, M.C. Hsiao, B.T. Merritt, G.E. Vogtlin, P.H. Wallman, IEEE Trans. Plasma Sci. 23 (1995) 679.
2. H.H. Kim, Plasma Process. Polym. **1** (2004) 91.
3. Office of Air Quality EPA 456/F-99-006R Environmental Protection Planning and Standards November 1999.
4. Selective Catalytic Reduction Control of NOx Emissions, SCR Committee of Institute of Clean Air Companies, November 1997.
5. Skalska, K., Miller, J.S., and Ledakowicz, S. Trends in NOx abatement: A review. *Science of The Total Environment*, 2010, 408(19): 3976-3989.
6. Devahasdin, S., Fan Jr, C., Li, K., and Chen, D.H. TiO2 photocatalytic oxidation of nitric oxide: transient behavior and reaction kinetics. *Journal of Photochemistry and Photobiology A: Chemistry*, 2003, 156(1μ3): 161-170.
7. Nitrogen Oxides, www.ccinet.ab.ca/casa/nitrogen.htm
8. http://www.dieselforum.org/a
9. Emission Control Technologies for Diesel-Powered Vehicles. December 2007.
10. Roy, S., Hegde, M.S., and Madras, G. Catalysis for NOx abatement. *Applied Energy*, 2009, 86(11): 2283-2297.
11. Hussain, J., Palaniradja, K., Algumurthic, N., and Manimarana, R. Diesel Engine Emissions And After Treatment Techniques-A Review.
12. Hackam, R. and Aklyama, H. Air pollution control by electrical discharges. *Dielectrics and Electrical Insulation, IEEE Transactions on*, 2000, 7(5): 654-683.
13. Dinelli, G., Civitano, L., and Rea, M. Industrial experiments on pulse corona simultaneous removal of NO< sub> x</sub> and SO< sub> 2</sub> from flue gas. in *Industry Applications Society Annual Meeting, 1988., Conference Record of the 1988 IEEE*. 1988: IEEE: 1620-1627.
14. Masuda, S. and Nakao, H. Control of NO< sub> x</sub> by positive and negative pulsed corona discharges. *Industry Applications, IEEE Transactions on*, 1990, 26(2): 374-383.
15. Mohapatro, S., Rajanikanth, B., Rajkumar, R., Ramadas, C., and Mishra, A. Treatment of NOx from Diesel Engine Exhaust by Dielectric Barrier Discharge Method. *Aceee International Journal on Communication*, 2011, 2(1).
16. Wang, P., Cai, Y., Wang, J., Zheng, R., and Yan, Y. Carbon Particles Reduction in Diesel Engine with Non-thermal Plasma Technology. in

Electrical and Control Engineering (ICECE), 2010 International Conference on. 2010: 3447-3449.

17. www.catalytica-inc.com/cs/nox_control.html
18. Summary of NOx Control Technologies and Their Availability and Extent of Application, EPA 450/3-92-004
19. López JM,JiménezF,AparicioF,FloresN.On-road emissions from urban buses with SCR,Urea and EGR ,DPF systems using diesel and biodiesel.
20. Brigitte Martin, Emissions control techniques applied to industrial vehicles. 2005.
21. McWilliam L, Zimmerman A Emissions and performance implications of biodiesel use in an SCR-equipped caterpillar 6.6.SAE Technical Paper 2010-01-2157;2010.
22. K. Urashima, J.S. Chang, IEEE Trans Dielectr. Electr. Insul.7 (2000) 602.
23. Epling WS, Campbell LE, Yezerets A, Currier NW, Parks JE. Overview of the fundamental reactions and degradation mechanisms of NOx storage/reduction catalysts. Catalysis Reviews, Science and Engineering 2004;46 163-245.
24. Roy S, Baiker A. NOx Storage-reduction catalysis: from mechanism and materials properties to storage-reduction performance. Chemical Reviews 2009;109 4054-4091.
25. Liu G, Gao PX. A review on NOx storage/reduction catalysts: mechanism, materials and degradation studies. Catalysis Science & Technology 2011;1 552-568.
26. Takahashi N, Shinjoh H, Iijima T, Suzuki T, Yamazaki K, Yokota K, Suzuki H, Miyoshi N, Matsumoto S, Tanizawa T, Tanaka T, Tateishi S, Kasahara K. The new concept 3-way catalyst for automotive lean-burn engine: NOx storage and reduction catalyst. Catalysis Today 1996;27 63-69
27. Miyoshi N, Matsumoto S, Katoh T, Tanaka T, Harada J, Takahashi N, Yokota K, Sugiara M, Kasahara K. Development of new concept three-way catalyst for automotive leanburn engines. SAE Technical Paper Series 950809; 1995.
28. Li YJ, Roth S, Dettling J, Beutel T. Effects of lean/rich timing and nature of reductant on the performance of a NOx trap catalyst. Topics in Catalysis 2001;16 139-144.
29. Epling WS, Yezerets A, Currier NW. The effect of exothermic reactions during regeneration on the NOx trapping efficiency of a NOx storage/reduction catalyst.Catalysis Letters 2006;110 143-148.
30. Eliasson B, Kogelschatz U. Non-equilibrium Volume Plasma Chemical Processing [J]. IEEE Transaction on Plasma Science,1991,19(6):1063-1077
31. Bernie.M.Penetrante, ŠComprasion of electrical discharge techniques for non-thermal Plasma processing of NO in N2Š, IEEE Transactions on plasma science, Vol 23, No 4,1991

32. Xueji X , Yiaxing J. Kinetics of Ar-Hg Plasma in Dielectric Barrier Discharge [J]. Physical Scripta ,1995,(52):603-606.
33. Zhi Cheng Wang, Reaction Mechanism of NOx Destruction by Non-thermal or Dissertation Plasma Discharge,1999.
34. R.Hackam, H. Akiyama, IEEE Trans. Dielectr, Electr. Insul. **7** (2000) 654.
35. TransportationResearchPartD:TransportandEnvironment2009;14:1μ5.
36. Epling WS, Campbell LE, Yezerets A, Currier NW, Parks JE. Overview of the fundamental reactions and degradation mechanisms of NOx storage/reduction catalysts. Catalysis Reviews, Science and Engineering 2004; 46 163-245.
37. Roy S, Baiker A. NOx Storage-reduction catalysis: from mechanism and materials properties to storage-reduction performance. Chemical Reviews 2009;109 4054-4091.
38. Abdul Hamid H, Fridell E, Skoglundh M. The reduction phase in NOx storage catalysis: Effect of type of precious metal and reducing agent. Applied Catalysis B: Environmental 2006;62 319-328.
39. http://www.iaccsea.com/scr/
40. T. Yamamoto, M. Okubo," Towards Ideal NOx Control Technology Using Plasma Chemical Hybrid Process", Department of Energy Systems Engineering, Osaka Prefecture University 1-1 Gakuen- cho, Sakai, Osaka 599- 8531, JAPAN
41. Zulkifli, A., Zulkefli, Y., Rahmat, M., and Yasmin, A. Managing our environmental through the use of clean fuel. *Gas Technology Centre (GASTEG), Faculty of Chemical Engineering and Natural Resources Engineering, Universiti Teknologi Malaysia, Malaysia*, 2002.
42. Matsumoto, T., Wang, D., Namihira, T., and Akiyama, H. Exhaust gas treatment using nano seconds pulsed discharge. in *Pulsed Power Conference, 2009. PPC'09. IEEE*. 2009: IEEE: 1035-1040.
43.. Daito, S., Tochikubo, F., and Watanabe, T. NOx removal process in pulsed corona discharge combined with TiO2 photocatalyst. *Japanese journal of applied physics*, 2001, 40: 2475.
44. Huang, L. and Matsuda, H. Removal of NO by a pulsed-corona reactor combined with in situ absorption. *AIChE journal*, 2004, 50(11): 2676-2681.
45. Mok, Y. and Huh, Y. Simultaneous Removal of Nitrogen Oxides and Particulate Matters from Diesel Engine Exhaust using Dielectric Barrier Discharge and Catalysis Hybrid System. *Plasma Chemistry and Plasma Processing*, 2005, 25(6): 625-639.
46. Abdullah, A.Z. and Bhatia, S. High Performance Catalysts For Storage And Reduction Of NOx In Diesel Engine Exhaust. 2005.
47. Balle, P., Bockhorn, H., Geiger, B., Jan, N., Kureti, S., Reichert, D., and Schröder, T. A novel laboratory bench for practical evaluation of catalysts useful for simultaneous conversion of NOx and soot in diesel exhaust. *Chemical Engineering and Processing: Process Intensification*, 2006, 45(12): 1065-1073.

48. Rezaei, M., Taeb, A., and Habibi, N. Non-Thermal Plasma Treatment of Automotive Exhaust Gases.
49. Oxides, N. Why and How They Are Controlled. *Research Triangle Park, NC*, 1998.
50. Dora, J., Gostomczyk, M.A., Jakubiak, M., Kordylewski, W., Mista, W., and Tkaczuk, M. Parametric Studies of the Efeectiveness of NO Oxidation Process by Ozone.
51. Mogili, P.K., Kleiber, P.D., Young, M.A., and Grassian, V.H. N2O5 hydrolysis on the components of mineral dust and sea salt aerosol: Comparison study in an environmental aerosol reaction chamber. *Atmospheric Environment*, 2006, 40(38): 7401-7408.
52. I.Hadjiivanov, K. Identification of neutral and charged N x O y surface species by IR spectroscopy. *Catalysis Reviews*, 2000, 42(1-2): 71-144.
53. Malpartida, I., Guerrero-Pérez, M., Herrera, M., Larrubia, M., and Alemany, L. MS-FTIR reduction stage study of NSR catalysts. *Catalysis Today*, 2007, 126(1): 162-168.
54. Muncrief, R.L., Kabin, K.S., and Harold, M.P. NOx storage and reduction with propylene on Pt/BaO/alumina. *AIChE journal*, 2004, 50(10): 2526-2540.
55. Takahashi, N., Yamazaki, K., Sobukawa, H., and Shinjoh, H. The low-temperature performance of NO< sub> x</sub> storage and reduction catalyst. *Applied Catalysis B: Environmental*, 2007, 70(1): 198-204.