PULSED STREAMER DISCHARGE CHAMBER TO REDUCE NITROGEN OXIDES FROM DIESEL ENGINE EXHAUST

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MAY 2014

Special dedicated to my beloved husband, Mohd Hamizan Bin Omar and my son
Muhammad Ammar Amsyar bin Mohd Hamizan,
My dearest mother and father,
Mrs. Fadzillah Binti Abbas & Mr.Roslan Bin Othman

The rest of my family members and family in law,
All my friends and relatives,

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

ACKNOWLEDGEMENT

Alhamdulillah, finally I have completed this project entitled 'Pulsed Streamer Discharge Chamber to Reduce Nitrogen Oxides from Diesel Engine Exhaust'.

Firstly, praise be to ALLAH, the Lord of the Worlds, for His blessing and giving me a little strength in completing my research work. I would like to take this opportunity to express my appreciation to my supervisor, Assoc. Prof Dr. Zolkafle bin Buntat for his direct supervision, encouragement and guidance throughout this project.

I would like to thank Dr. Muhammad Abu Bakar Sidik, other lecturers and technicians for their kindness and guidance. I am very grateful to get their help and advices. Besides that, I would also like to express my appreciations to my fellow friends for their supporting towards completing this research.

I am also indebted to Universiti Teknologi Malaysia (UTM) and Ministry of Higher Education (MOHE) of Malaysia for providing the financial support and cooperation during the course of the research. Librarians at UTM and staff at Faculty of Electrical Engineering, UTM also deserve special thanks for their assistance in supplying the relevant literatures.

Last but not least, thanks to everyone who involved directly or indirectly in completing this project either in opinion, advice or support from the beginning of the project until its completion.

ABSTRACT

Major air pollution problem contributed by Nitrogen Oxides (NO_x) has a noxious effect on human health and environment. Implementation of stringent regulation of NO_x emission has greatly increased interest in the development of new effective pollution control technology. Non-Thermal Plasma (NTP) utilizing electrical discharge has been recognized as a promising technology for the removal of pollutant gases from diesel engine exhaust. In this research, cascaded pulsed streamer discharge plasma reactor was designed to investigate the removal of NO_x from diesel engine exhaust. A simulation study consists of flow analysis of cascaded pulsed streamer discharge plasma reactor was conducted using Commercial Computational Fluid Dynamics (CFD) to evaluate the performance of the discharge plasma chamber on the removal of NO_x from diesel engine exhaust together with engine performance. Several parameters including gap spacing, chamber length and number of stages were varied to investigate their effects on system performance. The results from simulation study show that the cascaded pulsed streamer discharge plasma reactor with three stages of treatment process provides more effective performance on the removal of NO_x pollutant from diesel engine exhaust without affecting engine performance. This is in line with the initial assumption that three stages cascaded chamber will effectively remove the NO_x from diesel engine exhaust. A mathematical modelling by using dimensional analysis has been developed that is appropriate in investigating the relation of the electrical and physical parameters on the removal of NO_x concentration from diesel engine exhaust. To verify the viability of the analysis, results obtained from the dimensional analysis were compared with the experimental results reported in previous research. These predictions calculation demonstrates a reasonable agreement with the experimental data.

ABSTRAK

Masalah utama pencemaran udara yang dihasilkan oleh Nitrogen Oksida (NO_x) mempunyai kesan berbahaya terhadap kesihatan manusia dan alam sekitar. Perlaksanaan peraturan perlepasan NO_x yang ketat telah meningkatkan minat dalam membangunkan teknologi kawalan pencemaran baru yang lebih berkesan. Plasma bukan terma menggunakan discas elektrik telah diiktiraf sebagai satu teknologi yang berpotensi untuk penyingkiran gas pencemar dari ekzos enjin diesel. Dalam penyelidikan ini, kebuk *plasma cascaded pulsed streamer discharge* telah direka untuk mengkaji penyingkiran NO_x dari ekzos enjin diesel. Satu kajian simulasi yang terdiri daripada analisis aliran kebuk *plasma cascaded pulsed streamer discharge* yang telah dijalankan dengan menggunakan C*ommercial Computational Fluid Dynamics* (CFD) untuk menilai prestasi kebuk plasma discas terhadap penyingkiran NO_x dari ekzos enjin diesel bersama dengan prestasi enjin. Beberapa parameter termasuk sela jarak, panjang kebuk dan bilangan peringkat telah diubah bagi mengkaji kesan parameter tersebut terhadap prestasi sistem. Hasil daripada kajian simulasi menunjukkan bahawa kebuk *plasma cascaded pulsed streamer discharge* dengan tiga peringkat proses rawatan memberikan prestasi yang lebih berkesan terhadap penyingkiran NO_x daripada ekzos enjin diesel tanpa menjejaskan prestasi enjin. Ini sejajar dengan andaian awal bahawa tiga peringkat kebuk kaskad dapat menyingkirkan NO_x dari ekzos diesel dengan lebih berkesan. Permodelan matematik dengan menggunakan analisis dimensi yang sesuai telah dibangunkan untuk menyiasat hubungan antara parameter elektrik dan fizikal ke atas penyingkiran NO_x daripada ekzos enjin diesel. Untuk mengesahkan kesesuaian analisis, keputusan yang diperolehi daripada analisis dimensi tersebut telah dibandingkan dengan keputusan eksperimen yang telah dilaporkan di dalam kajian lepas. Pengiraan ramalan ini mempamerkan persetujuan yang munasabah dengan data eksperimen.

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LIST OF SYMBOLS

V_{peak}	-	Peak voltage
τ	-	Residence time
P	-	Pressure
d_g	-	Gap spacing
f_r	-	Flow rate
V	-	Applied voltage
f	-	Frequency
T	-	Temperature
ε_r	-	Relative permittivity
L	-	Length
M	-	Mass
T	-	Time
A	-	Current
π	-	Dimensionless product
D_c	-	Dimensional constant
k	-	Arrhenius reaction rate

LIST OF ABBREVIATIONS

AC	-	Alternating current
Al_2O_3	-	Aluminium oxide
APGD	-	Atmospheric pressure glow discharge
Ba	-	Barium
$BaTiO_3$	-	Barium titanate
CAD	-	Computer-aided design
CFD	-	Computational fluid dynamics
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
DBD	-	Dielectric barrier discharge
DC	-	Direct Current
EGR	-	Exhaust gas recirculation
ESP	-	Electrostatic precipitators
H_2	-	Hydrogen
H_2O	-	Water
HC	-	Hydrocarbon
HNO_3	-	Nitric acid
$N\ (^2D)$	-	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
O_2	-	Oxygen
PM	-	Particulate matter
Pt	-	Platinum
Rh	-	Rhodium
SCR	-	Selective catalytic reduction
SD	-	Surface discharge
SI	-	International system of units
SO_2	-	Sulfur dioxide
SO_x	-	Sulfur oxides
TiO_2	-	Titanium oxide
UV	-	Ultraviolet
VD	-	Volume discharge
VOCs	-	Volatile organic compounds
VUV	-	Vacuum ultraviolet

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Malaysia is a rapidly developing country that is working hard towards achieving its Vision 2020, of becoming a developed country. Indeed, the increase in economic activities has also resulted in the increase of the country air pollution problems. Survey conducted by Department of the Environment, Malaysia in 1996 had shown that mobile source is the major sources of air pollution in Malaysia which is 82%, followed by power station, 9%, industrial fuel burning, 5%, industrial production processes, 3%, open burning at solid waste disposal site, 0.8% and domestic and commercial furnaces, 0.2% as seen in Figure 1.1 [1].

Statistically has shown that nowadays diesel engines are widely used instead of gasoline engines for heavy duty transportation due to their excellent in fuel economy, high thermal efficiency, reliability, long durability and low operating costs. Since it has higher thermal efficiency, diesel engines have lower fuel consumption of about 20-40% lower compared to gasoline engines. Table 1.1 shows the characteristics of diesel engine and gasoline engine [2].

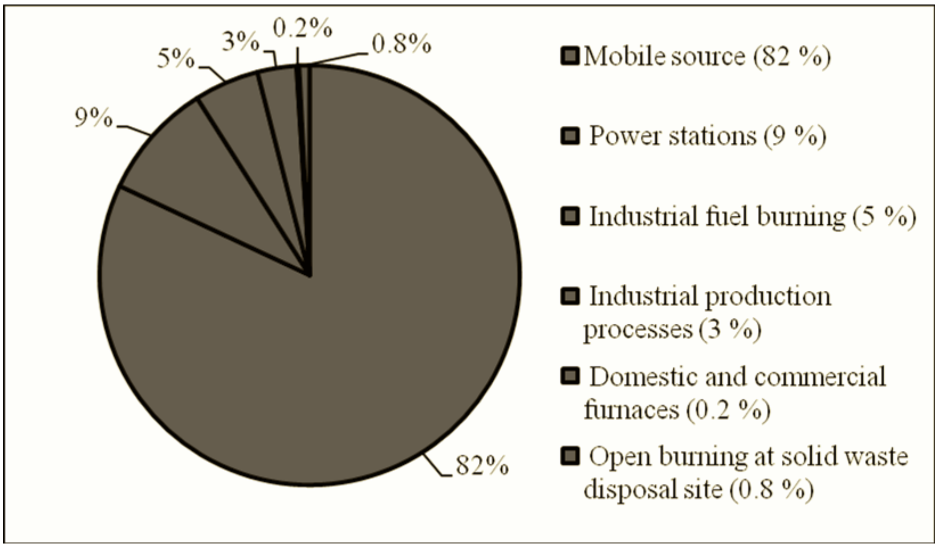

Figure 1.1 Sources of air pollution in Malaysia [1]

Table 1.1: The characteristics of diesel engine and gasoline engine [2]

	Gasoline Engine	**Diesel Engine**
Combustion Process	Air and fuel are mixed in advance and then drawn into the cylinder and compressed. The compressed mixture is ignited by an ignition plug.	Air is drawn into the cylinder and highly compressed. Then, fuel is sprayed into the cylinder under high pressure. Ignition occurs spontaneously as a result of the high temperature generated through compression.
Thermal Efficiency (Ratio of heat converted into power against total heat generated during combustion)	25-30%	35-42%

The total number of registered vehicles in Malaysia increase each year from 9,928,238 in 2005 to 12,763,452 in 2011 as reported by the Road Transport Department of Malaysia shown in Table 1.2 [3]. High dependence on motorized transportation by modern society has increase the demand for transportation.

An increase of these vehicles brings along the man-made air pollution problem, especially in urban area due to incomplete fuel combustion that is emitted from engine exhaust such as nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) in the form of soot [4]. All these emissions are considered to be harmful to human health and environment. As can be seen in Figure 1.2, the production of NO_x is much higher in the operation of diesel engine compared to gasoline engine. The NO_x pollutant can also be produced by undesired reaction between nitrogen and oxygen from the air in the combustion chamber [2].

Table 1.2: Number of registered vehicles in Malaysia from 2005-2011 [3]

Year	Number of Register Vehicles
2005	9,928,238
2006	10,351,332
2007	10,769,531
2008	11,227,144
2009	11,697,306
2010	12,236,254
2011	12,763,452

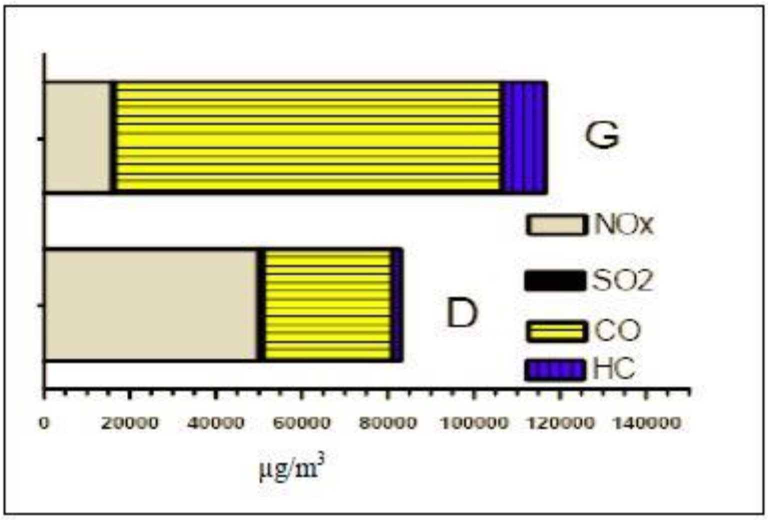

Figure 1.2 Composition of pollutant emission from diesel engine and gasoline engine [2]

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].

As perceived during the recent haze crisis, although Malaysia has a decent environment to stabilize the pollutant, it has already reached a critical level [4, 7]. From 2007 onwards, the emission standards for NO_x concentration from heavy duty vehicles require 90% reduction from 2003 level [8]. Since legal limits for emission of noxious pollutants becoming stricter year by year, a new emission control technology has been implemented while currently used techniques have been improved to obtain more efficient technology in order to remove the harmful pollutants from diesel engine exhaust at reasonable costs.

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 diversity of electrical discharges including dielectric barrier discharge, pulsed corona discharge and dielectric-packed bed reactors.

1.2 Problem Statement

A keen interest toward establishing more effective pollution control technologies are owing to the increasing concern about the environmental problems. Many conventional methods such as Selective Catalytic Reduction (SCR), exhaust gas recirculation (EGR) and Electron Beam method could not reduce the level of exhaust gases to stipulated limits put across various countries. Literature often tends to show that SCR technique could not treat the pollutant gases completely because requires strict operation conditions while the Electron Beam technique needs high energy [17, 18].

SCR also facing several problems such as ammonia slip, requirement for urea distribution network and ammonia storage. Moreover, these conventional methods sometimes have difficulties in disposing the harmful by-products and become dangerous to handle. Therefore, the conventional techniques are still in negative condition for reducing of pollutant gases.

The upcoming technology being used for air pollution control application is the electrical discharge plasma methods as it is cost effective and has high energy efficiency [19-24]. Several techniques have been widely studied by many researchers for removal of hazardous gases, for example; dielectric barrier discharge, surface discharge, DC and pulsed corona discharge and dielectric-packed bed discharge.

The electrical discharge plasma can facilitate the removal of pollutants by generating reactive species (radicals). However, electrical discharge plasma alone cannot attain high pollutant removal from diesel engine exhaust. This demands the discharge plasma to be combined with others after treatment techniques such as hybrid plasma techniques which is a combination of NTP with catalyst. Application of very short high voltage pulses also has a great influence on the energy efficiency of the removal of pollutant gases.

The main focus of this research is to design an optimum prototype of a cascaded pulse streamer discharge plasma chamber as an excellence 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.

1.3 Objectives

The aim of this project is to study the removal rate of NO_x from diesel engine exhaust by cascaded pulsed streamer discharge plasma. This aim will be met through these objectives:

1. To design a novel prototype of portable cascaded pulsed streamer discharge plasma reactor which is possible to be installed at diesel engine exhaust system
2. To analyse the design performance of cascaded pulsed streamer discharge plasma chamber on removal of NO_x from diesel engine exhaust
3. To develop a mathematical model for prediction of NO_x removal

4. To compare the theoretical modelling results with experiment results in order to improve the removal mechanisms and the effects of system parameters on overall removal efficiency
5. To optimize the removal rate of NO_x by cascaded pulsed streamer discharge plasma method

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 cascaded pulsed streamer discharge plasma method.
3. Design of 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 were identified.
5. Development of mathematical modelling for the discharge chamber by using dimensional analysis. It is necessary to determine the significant electrical and physical parameters that influence the removal rate of NO_x.

1.5 Thesis Outline

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

Chapter 1 is the introduction of this research study which includes brief description on background of study, 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 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 two methods used in this research work to predict the removal of NO_x from diesel engine exhaust. The first section describes the flow analysis of exhaust chamber conducted using commercial CFD followed by second section which discussed the mathematical modelling by using dimensional analysis.

Chapter 4 covers results and analysis and presents all the obtained results and provides an analysis for the findings. 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.

The next section presents the steps to obtain a general form of equation that define the relationship of the electrical and physical parameters on NO_x removal. It also covers the comparisons of the mathematical modelling using dimensional analysis with experimental results reported in the previous research.

Chapter 5 summarizes the conclusions made in the present study and 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.

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