Chemical Engineering Journal 276 (2015) 240–248

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Performance evaluation of non-thermal plasma on particulate matter, ozone and CO_2 correlation for diesel exhaust emission reduction

Meisam Babaie [a,b,*], Pooya Davari [c], Pouyan Talebizadeh [d], Firuz Zare [e], Hassan Rahimzadeh [d], Zoran Ristovski [a], Richard Brown [a]

[a] Biofuel Engine Research Facility, Queensland University of Technology, Brisbane, Australia
[b] Petroleum and Gas Engineering Division, School of Computing, Science and Engineering, University of Salford, Manchester, United Kingdom
[c] Department of Energy Technology, Aalborg University, Pontoppidanstraede 101, DK-9220 Aalborg East, Aalborg, Denmark
[d] Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran
[e] Danfoss Power Electronics A/S, Ulsnæs 1, DK-6300 Graasten, Denmark

HIGHLIGHTS

- Study the correlation between PM, O_3 and CO_2 under plasma treatment.
- Ozone strongly promotes oxidation of PM.
- When ozone concentration was increased, PM concentration found to be decreased.
- At high levels of discharge power, CO_2 dissociation by plasma has been observed.
- PM concentration has been reduced considerably by plasma treatment.

ARTICLE INFO

Article history:
Received 14 December 2014
Received in revised form 15 April 2015
Accepted 16 April 2015
Available online 21 April 2015

Keywords:
Non-thermal plasma
Dielectric barrier discharge
Diesel particulate matter
Ozone
Carbon dioxide
Environmental engineering

ABSTRACT

This study is seeking to investigate the effect of non-thermal plasma technology in the abatement of particulate matter (PM) from the actual diesel exhaust. Ozone (O_3) strongly promotes PM oxidation, the main product of which is carbon dioxide (CO_2). PM oxidation into the less harmful product (CO_2) is the main objective whiles the correlation between PM, O_3 and CO_2 is considered. A dielectric barrier discharge reactor has been designed with pulsed power technology to produce plasma inside the diesel exhaust. To characterise the system under varied conditions, a range of applied voltages from 11 kV_{PP} to 21 kV_{PP} at repetition rates of 2.5, 5, 7.5 and 10 kHz, have been experimentally investigated. The results show that by increasing the applied voltage and repetition rate, higher discharge power and CO_2 dissociation can be obtained. The PM removal efficiency of more than 50% has been achieved during the experiments and high concentrations of ozone on the order of a few hundreds of ppm have been observed at high discharge powers. Furthermore, O_3, CO_2 and PM concentrations at different plasma states have been analysed for time dependence. Based on this analysis, an inverse relationship between ozone concentration and PM removal has been found and the role of ozone in PM removal in plasma treatment of diesel exhaust has been highlighted.

1. Introduction

The road sector accounts for about three quarters of transport emissions and passenger cars and light trucks contribute to a considerable share of these emissions [1]. On the other hand, diesel engine applications in various heavy-duty and medium-duty vehicles are increasing compared to gasoline engines. The emissions produced by diesel engines, however, are a ubiquitous air pollutant consisting of a complex mixture of gases, vapour and particles. The negative health effects of diesel emissions have been emphasised in the literature [2,3] and lately, diesel exhaust has been classified as carcinogenic to humans (Group 1) by the International Agency for Research on Cancer (IARC) [4].

Carbon monoxide (CO), hydrocarbon (HC), Nitrous Oxides (NO_x) and diesel particulate matter (DPM) have been globally regulated by diesel emission standards. DPM is basically composed of elemental carbons, which results in agglomerating and also absorbing other particles to form structures of complex physical and also

* Corresponding author at: Biofuel Engine Research Facility, Queensland University of Technology, Brisbane, Australia. Tel.: +61 7 3138 1582; fax: +61 7 3138 8381.
E-mail address: meisam.babaie@hdr.qut.edu.au (M. Babaie).

http://dx.doi.org/10.1016/j.cej.2015.04.086
1385-8947/

chemical properties [5]. Up until now, several after-treatment technologies, such as diesel oxidation catalyst (DOC) [6], diesel particulate filter (DPF) [7], selective catalyst reduction (SCR) [8] and fuel borne catalyst (FBC) [9] have been employed to reduce diesel exhaust emissions. However, there are some drawbacks in using conventional after-treatment systems. For example, SCR catalysts require high temperatures (around 300 °C) for activation and there is the possibility of ammonia leakage, catalyst poisoning and catalyst discharge under high temperature conditions [10]. DPFs also produce an additional pressure drop inside the exhaust gas, due to the PM deposition. This deposition can cause filter choking and filter regeneration is required at about 600 °C. These effects cause more fuel consumption, which is not appropriate for low emission production and fuel economy. Furthermore, DPFs are inefficient in trapping small nanoparticles under 100 nm [11].

Considering the increasing environmental concerns and stringent emission standards, there is an imperative to develop new strategies for emission reduction [12]. Non-thermal plasma (NTP) technology has shown notable potential for emission control in various applications [3,13,14]. Plasma is the fourth state of matter that can be considered as an ionised gas. In the plasma state, sufficient energy is provided to free electrons from atoms or molecules and to allow species, ions and electrons, to coexist. Based on the relative temperature of the gas, plasmas can be classified into thermal and non-thermal plasma (NTP) [15]. In non-thermal plasma, the kinetic energy (temperature) of charged particles and kinetic energy (temperature) of background gas are similar [16]. In the NTP application for exhaust emission reduction, the input electrical energy is transferred to the electrons which generates free radicals through collisions of electrons and promotes the desired chemical changes in the exhaust gas. While the applied electric energy in NTP reactors will be consumed for the purpose of breaking the bonds in the parent molecules, there is no sensible heating of the gas, and discharged energy is not lost either in heating up the gas or to the surroundings [17].

A variety of research studies, concerning different aspects of NTP application for NO_x removal, have been documented in the literature [3,18]. NTP NO_x reduction generally can be divided in two groups: NO_x removal reactions that result in NO_x reduction to N_2 and NO to NO_2 conversion reactions which is more dominant [3]. In comparison with the large amount of research conducted on the influence of plasma on NO_x removal, much less has been dedicated to the effect of plasma on PM removal. Okubo et al. employed indirect or remote NTP for DPF regeneration [19,20]. In this method, plasma is not introduced into the exhaust gas directly. Instead, plasma was introduced into the air and the NTP-treated air was injected into the exhaust gas, which causes the NO oxidation to NO_2. This induced NO_2 with other produced activated oxygen species by plasma oxidise deposited carbon soot on the DPF surface effectively. Furthermore, the simultaneous PM, HC and NO_x removal efficiency of about 80%, 70% and 65% was reported in literature from the exhaust gas [21].

Few studies on PM removal of diesel engines have been conducted in the literature and removal mechanisms have not been studied extensively [3,22,23]. Furthermore, most of the research in this area was considered simulated diesel exhaust instead of actual exhaust. Many electron-impact reactions such as momentum transfer, dissociation, ionisation reaction, etc. and also numerous secondary reactions induced by products of the electron-impact reactions are possible in the plasma state [24]. This would be more complicated when plasma treatment of the diesel exhaust which is a complex mixture of thousands of gases is targeted. Therefore, the results of experiments for actual diesel exhaust may be different from what is happening in simulated exhaust. Furthermore, recently ozone has been studied as a possible solution for PM removal even in industries [12]; however, the advantage of ozone production in NTP systems for PM removal is not well established.

The objective of this paper is to investigate the effect of NTP on reduction of PM emitted by a diesel engine and oxidise it to less harmful combustion products (essentially carbon dioxide) at different discharge voltages and repetition rates. Furthermore, the mechanism of PM removal has been discussed in detail and the effect of ozone as the key parameter for PM removal has been highlighted. To examine the system in real condition which is the first step towards the applicability of NTP as an after-treatment system, the actual exhaust emission has been examined in this research.

2. Experimental apparatus and method

2.1. Experimental setup

The experiments have been conducted using a modern turbocharged 6 cylinder Cummins diesel engine. The engine has a capacity of 5.9 L, a bore of 102 mm, a stroke length of 120 mm, compression ratio of 17:3:1, and maximum power of 162 kW at 2500 rpm. All experiments have been conducted at a speed of 1500 rpm and at the load of 160 Nm to achieve the most uniform exhaust gas performance. For all experiments, exhaust gas from the exhaust pipe was passed through the dilution tunnel before flowing into the DBD reactor. The role of the dilution tunnel is to reduce the temperature and concentration of exhaust gas before flowing into the measurement instruments. By manipulating the flow direction at the reactor inlet using a three way valve, the emission concentration has been measured before and after plasma treatment. Flow rate was 12 L/min and kept constant during the experiments. The schematic diagram of the experimental set-up is shown in Fig. 1.

2.2. Dielectric barrier discharge reactor

In all experiments, a conventional DBD reactor was used, as shown in Fig. 2. The overall dimensions of the DBD were also shown in this figure. It consists of two concentric quartz tubes with dimensions of 400 mm long and wall thickness of 1.5 mm. The outer diameters of the tubes are 20 and 25 mm, respectively. The diesel engine exhaust generated by the diesel engine was passed through the gap between these two quartz tubes. With its predesigned geometry, the discharge gap was 1 mm. The reactor is equipped with external and internal electrodes which can be energised through a pulsed power supply. The internal electrode is a copper cylinder and the external electrode is made of copper mesh that wraps the exterior part of the outer quartz tube. The electrodes were located in the middle of the DBD reactor, the length of which was 100 mm. The quartz tubes were installed by using two Teflon caps at both ends of the DBD reactor. The diesel engine exhaust enters the reactor at the angle of 45° and then flows throughout the gap; it leaves the reactor with the same angle as well. The mean residence time of 0.13 s can be calculated for the given geometry and flow rate for the exhaust gas passing through the DBD reactor.

2.3. Electrical and pulsed power system

Rapid release of stored energy as electrical pulses into a load, thereby resulting in the delivery of large amount of instantaneous voltage over short period of time, is known as pulsed power. Pulsed power technology has been previously considered by different researchers in different applications [25]. Furthermore, pulsed power technology for NTP generation in pollution control application has gained a lot of advantages [3,26,27] and using power