

Reducing exhaust emission values in gasoline vehicle using Al₂O₃ based dielectric barrier discharge catalyst system

Al₂O₃ tabanlı dielektrik bariyer deşarj katalizör sistemi kullanılarak benzinli araçlarda egzoz emisyon değerlerinin azaltılması

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Abstract

This study addresses the urgent issue of vehicle pollution and its impact on air quality and public health by investigating the use of non-thermal plasma (NTP) technology to reduce toxic emissions from gasoline-powered vehicles. Vehicle emissions contribute significantly to environmental degradation, and their control is vital to mitigating adverse effects on both health and the atmosphere. The research focuses on the effectiveness of dielectric barrier discharge (DBD) plasma catalysts compared to conventional catalytic methods. Unlike conventional systems that rely on high temperatures for activation, the DBD technique uses non-thermal plasma to activate the catalyst under low-temperature conditions, offering a novel approach to emissions reduction. In this study, alumina particles with a spherical geometry were selected as the catalyst material due to their high surface area and stability, which enhance catalytic efficiency. The DBD plasma, generated between an electrode and an insulating barrier, initiated the catalytic reactions necessary to reduce emissions. The results showed that the DBD plasma catalyst was significantly more effective in reducing harmful gases such as carbon monoxide (CO) and nitrogen oxides (NO_x) compared to conventional catalysts. The findings indicate that non-thermal plasma technology combined with a dielectric barrier discharge system offers a promising solution for reducing vehicle emissions. Potential benefits of this method include lower operating temperatures, improved energy efficiency, and enhanced catalytic performance. This makes it a viable alternative to existing emission control technologies, contributing to efforts to reduce vehicle pollution.

Keywords: Catalyst, Dielectric barrier, Emission, Non-thermal plasma, Pollution

Öz

Bu çalışma, benzinle çalışan araçlardan kaynaklanan toksik emisyonları azaltmak için termal olmayan plazma (NTP) teknolojisinin kullanımını araştırarak, araç kirliliği ve bunun hava kalitesi ile halk sağlığı üzerindeki etkisi gibi acil bir sorunu ele almaktadır. Araç emisyonları çevresel bozulmaya önemli ölçüde katkıda bulunur ve bunların kontrolü hem sağlık hem de atmosfer üzerindeki olumsuz etkileri azaltmak için hayati önem taşır. Araştırma, geleneksel katalitik yöntemlerle karşılaştırıldığında dielektrik bariyer deşarj (DBD) plazma katalizörlerinin etkinliğine odaklanmaktadır. Aktivasyon için yüksek sıcaklıklara dayanan geleneksel sistemlerin aksine, DBD tekniği, düşük sıcaklık koşulları altında katalizörü aktive etmek için termal olmayan plazma kullanır ve emisyon azaltımına yeni bir yaklaşım sunar. Bu çalışmada, yüksek yüzey alanı ve kararlılığı nedeniyle katalitik verimliliği artıran küresel geometriye sahip alümina parçacıkları katalizör malzemesi olarak seçilmiştir. Bir elektrot ve bir yalıtkan bariyer arasında üretilen DBD plazması, emisyonları azaltmak için gerekli katalitik reaksiyonları başlatmıştır. Sonuçlar, DBD plazma katalizörünün karbon monoksit (CO) ve azot oksitler (NO_x) gibi zararlı gazları azaltmada geleneksel katalizörlere kıyasla önemli ölçüde daha etkili olduğunu göstermiştir. Bulgular, dielektrik bariyer deşarj sistemiyle birleştirilmiş termal olmayan plazma teknolojisinin araç emisyonlarını azaltmak için umut verici bir çözüm sunduğunu göstermektedir. Bu yöntemin potansiyel faydaları arasında daha düşük çalışma sıcaklıkları, iyileştirilmiş enerji verimliliği ve gelişmiş katalitik performans yer almaktadır. Bu, onu mevcut emisyon kontrol teknolojilerine uygulanabilir bir alternatif haline getirerek araç kirliliğini azaltma çabalarına katkıda bulunmaktadır.

Anahtar kelimeler: Kataliz, Yalıtkan engeli, Emisyon, Termal olmayan plazma, Kirlilik

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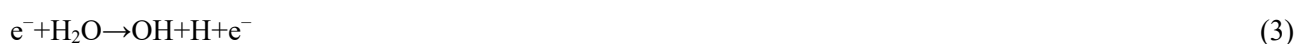
1. Introduction

Exhaust emissions from gasoline vehicles have become a pressing issue in recent years due to global recognition of the negative impacts of these emissions on the environment and human health. The combustion process in internal combustion engines releases various pollutants into the atmosphere, including carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter. These emissions contribute significantly to air pollution, smog, and climate change. Consequently, there is a growing need to develop innovative technologies that can effectively reduce exhaust emissions from gasoline vehicles. Plasma catalysis involves the integration of plasma with a suitable catalytic material to facilitate the production of desired products at higher efficiency, exceeding the capabilities of conventional catalytic methods (Whitehead, 2019). The combination of non-thermal plasma and catalysis is a promising and effective approach for converting carbon monoxide and hydrogen sources into renewable energy under mild conditions such as low temperature and atmospheric pressure. The application of plasma-based stimulation techniques can create a synergistic effect in these processes. In recent years, to overcome inherent limitations, interest in plasma catalytic hybrid technology has increased significantly as a viable method for the removal of a variety of chemical compounds (VOCs). Several VOCs include substances of diverse origin, including natural compounds such as isoprene, pinene, and limonene, as well as synthetic compounds such as benzene and nitrobenzene. Moreover, solvents including toluene, xylene, acetone, and perchloroethylene, which are widely applied in dry-cleaning processes, are known to emit volatile organic compounds (VOCs).

The integration of non-thermal plasma with catalysts stands out with its significant advantages, particularly increased energy efficiency, enhanced product selectivity, and favorable carbon balance, as described in (Lu et al., 2019). Although numerous research studies have been conducted on the removal of VOCs using plasma catalytic hybrid technology, our review focuses on specific target pollutants. For example, Zhu et al. (2018) conducted a study using plasma catalysis combined with Ag/CeO₂/Al₂O₃ catalyst. This approach achieved an impressive toluene conversion rate of approximately 93% and exhibited an energy efficiency of 0.07 g/kWh. Their research highlighted the effectiveness of the Ag/CeO₂/Al₂O₃ catalyst in the hybrid plasma catalysis system and demonstrated the capacity to significantly convert toluene to CO₂ and H₂O while maintaining low ozone and nitrogen oxide concentrations (Zhu et al., 2018). S. Yao and co-workers (2020) reported that the incorporation of a hybrid reactor into plasma catalysis could substantially enhance the efficiency of toluene degradation. A rise in operational temperature from 50 °C to 250 °C nearly doubled both the toluene conversion (from 45.3% to 95.5%) and the energy efficiency (from 53.5 g/kWh to 113.0 g/kWh) (Yao et al., 2020). In addition, Song et al. (2019) conducted experiments to investigate the decomposition of various active plasma species during toluene decomposition using dielectric barrier discharge plasma with and without a CoMnO_x/TiO₂ catalyst. The results showed that the CoMnO_x/TiO₂ catalyst efficiently decomposed ozone (O₃) and significantly increased the utilization of active species, regardless of whether it was in the plasma region or in the post-plasma process. As a result, this increase increased the toluene removal efficiency and improved the selectivity towards carbon oxides (CO_x) (Song et al., 2019). In addition to catalytic effects, the chemical reactions occurring in non-thermal plasma play a crucial role in the removal of harmful exhaust gases. In non-thermal plasma systems such as dielectric barrier discharge (DBD), energetic electrons generated in the plasma initiate a wide range of plasma-assisted reactions through elastic and inelastic collisions. These processes lead to ionization, dissociation, excitation, and radical formation in the gas phase. The energetic electrons interact with oxygen and water vapor molecules in the exhaust gas, producing highly reactive species such as atomic oxygen (O), hydroxyl radicals (OH), and ozone (O₃). These reactive species play a key role in the oxidation and decomposition of harmful exhaust gases. For example, NO molecules can be oxidized to NO₂ by atomic oxygen, while hydrocarbons undergo partial oxidation reactions. Furthermore, the presence of Al₂O₃ catalyst surfaces enhances adsorption and plasma-assisted reduction processes, facilitating the conversion of NO_x species into N₂ and promoting the oxidation of CO and hydrocarbons to CO₂ and H₂O. These reactions significantly contribute to the overall emission reduction efficiency of plasma catalytic systems (Shi et al., 2022, 2025).

The main plasma-induced reactions involved in this process can be summarized as follows:

Electron collisions and ion formation;



Radical and active species formation;



NO_x oxidation;



Hydrocarbon oxidation;



Catalytic surface reactions (Al_2O_3 effect);



Energetic electrons generated in the plasma initiate several key reactions responsible for the formation of reactive species and pollutant conversion. As shown in Eq. (1), electron impact dissociation of oxygen molecules produces atomic oxygen, which is one of the most important oxidizing species in plasma systems. In Eq. (2), electron impact dissociation of water vapor generates hydroxyl radicals and hydrogen atoms, both of which contribute to oxidation reactions. Electron impact ionization of oxygen, presented in Eq. (3), produces positive oxygen ions and additional electrons that sustain the plasma discharge. Similarly, Eq. (4) describes the ionization of nitrogen molecules by energetic electrons. The recombination of atomic oxygen with molecular oxygen in the presence of a third body leads to ozone formation, as shown in Eq. (5), while ozone can also decompose back into molecular and atomic oxygen as presented in Eq. (6). The oxidation of nitric oxide by atomic oxygen producing NO_2 is given in Eq. (7), which is a key step in NO_x conversion. In addition, NO can also react with ozone as shown in Eq. (8), further promoting the formation of NO_2 . Hydrocarbon oxidation reactions are initiated by hydroxyl radicals as shown in Eq. (9), generating intermediate radicals that continue the oxidation chain. Carbon monoxide oxidation by atomic oxygen is described in Eq. (10), producing carbon dioxide. The plasma-catalyst interaction also facilitates reduction reactions on the catalyst surface, such as the conversion of NO_2 into N_2 as given in Eq. (11). These plasma-generated reactive species initiate a chain of secondary oxidation and reduction reactions, ultimately contributing to the removal of NO_x , CO , and hydrocarbon pollutants from the exhaust stream.

In various discharge processes, such as pulsed corona, DC discharge, capillary tube discharge, and microwave discharge, most power supplies operate at 50–60 Hz. To improve energy efficiency and minimize undesirable byproducts, hybrid systems combining non-thermal plasmas (NTPs) and catalysts are used, with the expectation of synergistic effects. Byproduct accumulation during these processes is prevented. Perovskite oxides, such as barium titanate (BaTiO_3), function as high-dielectric compounds and can be catalytically activated by ultraviolet radiation from the plasma. For example, implementing a DBD system can significantly improve the catalytic processes that break down pollutants in exhaust streams. It has been found that such technologies can facilitate the oxidation of CO and HC to less harmful products such as carbon dioxide (CO_2) and water (H_2O) by providing additional energy pathways and increased electron density in the exhaust (Ravi et al., 2023). This method allows efficient oxidation reactions under varying combustion conditions, thereby optimizing overall emission reductions. Research shows that DBD systems exhibit their highest efficiency under specific thermal conditions. Operating temperatures around 215 degrees Celsius, found in conventional gasoline engine exhaust scenarios, are conducive to maximizing the catalytic effect of Al_2O_3 -based systems (Arif et al., 2024). This thermal stability, combined with the electrical activation of the DBD, creates optimal conditions for HC and CO reduction, resulting in significant reductions of up to 20% and 4%, respectively, under practical engine conditions (Nugroho et al., 2023; Arif et al., 2024). Furthermore, enhanced fuel cleanliness has shown a significant synergistic effect by reducing CO and HC emissions when applied in conjunction with advanced combustion technologies (R. Zhang et al., 2023).

Studies have elucidated the dynamics of exhaust emission reduction under different operating parameters, such as engine speed. When engines operate at higher speeds, studies show a complex relationship between HC and

CO emissions, where CO emissions tend to increase initially and then decrease at higher speeds (Nugroho et al., 2023). This behavior suggests that DBD systems can operate optimally by matching the engine operating range, particularly at engine speed transition points where conventional catalytic converters may struggle in efficiency due to temperature fluctuations (Böhm et al., 2022; Ravi et al., 2023). Furthermore, the beneficial effect of using ethanol blends with gasoline further complements the reduction achieved by DBD systems, improving combustion efficiency while simultaneously reducing CO and HC emissions (Dhande et al., 2021; R. Zhang et al., 2023). Furthermore, the effectiveness of combining Al₂O₃-based DBD systems with gasoline particulate filters (GPFs) offers a layered approach to meeting increasingly stringent environmental regulations on particulate matter emissions. Designed to capture particulate emissions from combustion processes, BPFs can be integrated downstream of DBD systems, improving overall emission control effectiveness (Yue et al., 2020). This integrated approach enables simultaneous addressing of gaseous and particulate emissions from gasoline engines, reflecting the increasing regulatory challenges requiring multifaceted solutions (Hakkarainen et al., 2020; Ravi et al., 2023).

Modern gasoline engines equipped with three-way catalysts exhibit improved emissions characteristics; however, their efficiency can be significantly affected by exhaust gas temperature and air-fuel ratio, both of which can fluctuate under transient conditions (Böhm et al., 2022).

A DBD system can balance these conditions, facilitating optimum catalyst performance regardless of operating dynamics. The balance achieved with DBD systems ensures maximum conversion rates of harmful gases by allowing three-way catalysts to operate within their most effective temperature ranges (Böhm et al., 2022). Researchers assessing the future of emission control technologies emphasize the need for a holistic strategy encompassing not only catalyst improvements but also improvements in fuel composition and engine design.

The synergistic application of advanced aftertreatment processes and alternative fuel compositions plays a key role in increasing the efficiency and effectiveness of emission reduction strategies. For example, ethanol blends have been shown to significantly reduce CO and HC exhaust emissions due to their higher oxygen content, resulting in more complete combustion (Dhande et al., 2021; Q. Zhang et al., 2022) and significantly improve the performance of DBD systems by reducing soot formation, which can negatively impact catalyst performance. Proper corona discharge generation allows for more consistent plasma activity throughout the reactor, helping to effectively reduce toluene. Additionally, pellet size influences plasma uniformity and contributes to higher toluene removal efficiency (Penetrante & Schultheis, 1993). Figure 1 shows a DBD reactor. The electrode is coated with dielectric materials. To prevent charging of dielectric materials, the power source uses AC or burst AC signals with frequencies from 50 Hz to several tens to hundreds of kHz (Nishida et al., 2001). Parallel-plate, multipoint, and coaxial electrode configurations are used for electrode arrangements. A series of filamentary discharges are formed in the gap. Figure 2 shows the coaxial electrode configuration for generating corona discharges. The central electrode consists of a thin wire. When a high voltage is applied, corona discharges are generated around the wire by constant (AC and DC) and pulsed discharges. DC corona discharges exhibit a polar effect (positive and negative corona discharges). Electrode configurations include wire, tube, and nozzle electrodes. Various electrode arrangements exist for generating pulsed corona discharges, such as point-plate, wire-plate, wire-cylinder, nozzle-plate, and pin-plate (Moon et al., 2000). For power supplies, DC/AC superimposed welding and bipolar polarity of pulsed welding are also used. Streamer corona discharges, with voltage rise times of 10-50 ns and FWHM times of 50-500 ns, can decompose pollutant gases. The catalyst-coated electrode configuration for facilitating NO_x removal is shown in Figure 3. NO_x gases pass through the plasma and catalyst and undergo decomposition. Figure 4 shows a tubular packed bed corona reactor. Pellets made of dielectric material are either coated with catalyst or not. The catalyst is activated by energetic particles, i.e., electrons, photons, excited molecules, ions, etc. Applying a high AC voltage to pellets packed in a chamber creates microdischarges in the gap and/or on the surface. This is called a packed bed discharge and is also expected to have a catalytic effect on the surface of the pellets (Becker, 2005).

In this study, an Al₂O₃-based dielectric barrier discharge (DBD) plasma catalyst system was developed to investigate its effectiveness in reducing exhaust emissions from gasoline vehicles. The study focuses on the integration of a packed-bed DBD reactor filled with spherical alumina pellets into the exhaust line and evaluates its capability to reduce CO and NO_x emissions under real engine operating conditions. Unlike conventional catalytic converters that require high operating temperatures, the proposed plasma catalytic system operates at relatively low temperatures and atmospheric pressure.

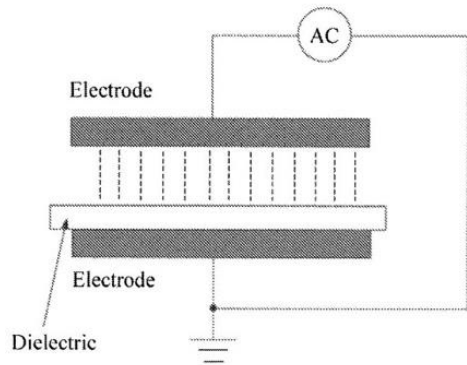


Figure 1. Dielectric barrier discharge reactor (Becker, 2005)

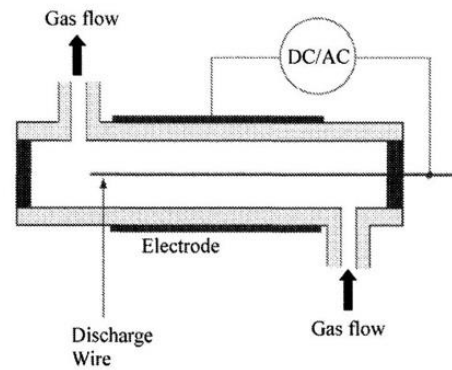


Figure 2. Corona discharge reactor (Kim et al., 2001)

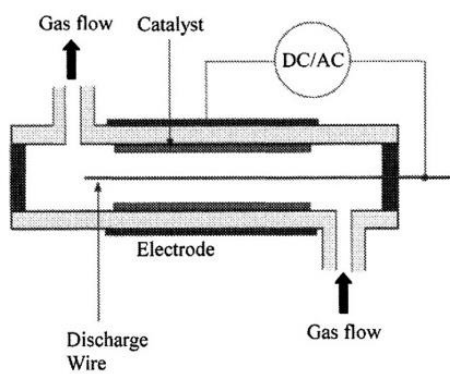


Figure 3. Corona discharge-catalyst reactor (Nishida et al., 2001)

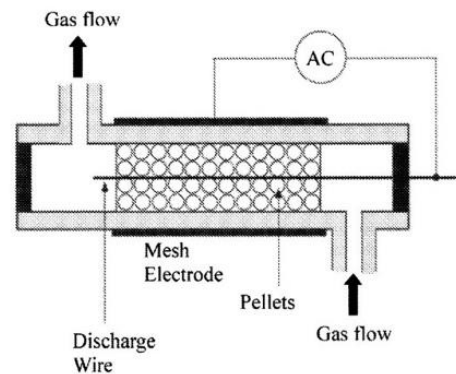


Figure 4. Packed-bed corona discharge reactor (Nishida et al., 2001)

The objective of this research is to analyze the emission reduction performance of the developed system and to assess its feasibility as an alternative or complementary technology for automotive exhaust emission control.

2. Materials and methods

Provide in this study, a Dielectric Barrier Discharge (DBD) reactor using Al_2O_3 as a catalyst was used. The packed bed corona discharge reactor in Figure 4 given in the literature was designed as the reactor design. The system utilizes a coaxial-type cylindrical reactor equipped with paired stainless-steel electrodes and dielectric barriers, enabling the formation of an ionized plasma region between them. However, when purifying gases at higher flow rates, efficiency tends to decrease due to the need to increase energy input, which often strains the reactor's structural integrity. Another limitation of this material is that it cannot be installed in a vehicle's exhaust outlet, as proposed in this study. The strong vibrations and harsh conditions of anti-pollution systems can lead to material failure. Therefore, a reactor made of more durable materials and efforts to minimize energy consumption are essential. The DBD reactor was connected to a power source using a combination of internal and external electrodes, incorporating pulsed power technology, to initiate the plasma. The reactor's design and fabrication were carried out in strict accordance with guidelines established by numerous scientific sources. In any DBD configuration, the electrode geometry is determined by the dielectric arrangement. The cylindrical configuration is generally preferred for applications involving gas conversion because it allows for a homogeneous gas treatment process within the chamber volume. Furthermore, it is relatively easy to implement, particularly in the context of cylindrical automotive exhaust systems. A DBD reactor can have one or both electrodes coated with a non-conductive material and is therefore classified as having a single or double barrier configuration. This insulating system chemically isolates the electrodes from the gases to be treated and the reaction-electrode interaction, preventing breakdown and/or interactions between the gases. Materials with high dielectric strength and low dispersion loss, such as quartz glass, are generally preferred, although some studies have investigated the use of alumina, despite its low dielectric strength. An experimental setup (shown in Figure 5) was designed to effectively remove NO_x and CO_2 from vehicle emissions. The

methodology aimed to achieve sufficient air ionization, create plasma discharge for pollutant degradation and integration into the vehicle exhaust system. An Arduino Uno R4 data acquisition board was used to measure the output values of the CO and NO_x gas sensors. The computer interface was designed using Labview, a free student version. Formulas from the sensor datasheets were used to convert the gas sensor output voltage values to ppm.

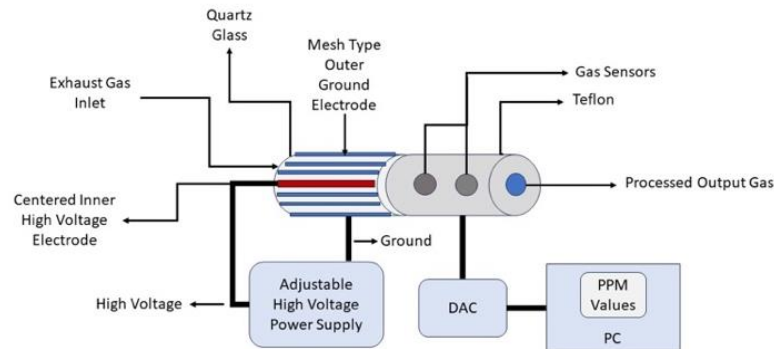


Figure 5. Experimental setup

The dielectric barrier discharge (DBD) reactor utilized in this work includes an internal aluminum electrode (34 mm in outer diameter) and a quartz glass tube acting as the dielectric barrier (43 mm inner diameter). The gas sensors used for measurements are presented in Figure 6.



Figure 6. CO and NO_x gas sensors used in the study

An external grounding electrode surrounds a glass tube with a steel mesh cover. The high voltage required for the system was generated by an industrial power amplifier. Alumina beads were used as catalysts and were filled in the gap between the quartz glass tube and the aluminum rod electrode. A high-frequency signal generating an output voltage of 11.6 kV was supplied to the discharge electrode to trigger the dielectric barrier discharge. As the exhaust gases flowed through the high-voltage discharge region, they interacted with numerous reactive and charged species such as electrons, ions, atomic oxygen, ozone, hydroxyl radicals, and various excited molecules and atoms.

Plasma-assisted processes occurring in dielectric barrier discharge (DBD) systems involve a complex network of physical and chemical reactions initiated by energetic electrons. In non-thermal plasmas, electrons possess significantly higher kinetic energy than heavy species, enabling them to efficiently induce ionization, excitation, and dissociation of gas molecules through elastic and inelastic collisions. As a result, a variety of reactive species are generated in the plasma phase. In exhaust gas environments containing oxygen and water vapor, these electron-impact reactions lead to the formation of reactive oxygen species such as atomic oxygen (O), hydroxyl radicals (OH), and ozone (O₃). These highly reactive intermediates play a crucial role in initiating oxidation and reduction pathways that contribute to pollutant removal. For example, nitric oxide (NO), which is a major component of NO_x emissions, can be oxidized by atomic oxygen to form nitrogen

dioxide (NO₂). Hydrocarbon compounds present in the exhaust stream can undergo partial oxidation reactions in the plasma phase, producing intermediate species that are further converted in the presence of catalytic surfaces.

In addition to gas-phase reactions, the catalyst surface also contributes significantly to the overall conversion mechanism. Alumina (Al₂O₃) particles provide a high surface area that facilitates adsorption of reactive species and enhances heterogeneous reactions. The interaction between plasma-generated radicals and catalyst surfaces promotes plasma-assisted reduction pathways, which may contribute to the conversion of NO_x species into molecular nitrogen (N₂). At the same time, oxidation reactions involving CO and hydrocarbons are promoted, leading to the formation of more stable products such as CO₂ and H₂O. The combined effect of plasma-phase chemistry and surface catalytic reactions improves the efficiency of pollutant removal in DBD plasma catalytic systems.

The fundamental plasma-induced reactions that contribute to these processes can be expressed as follows:



Electron attachment to oxygen molecules, presented in Eq. (12), results in the formation of negative oxygen ions (O₂⁻), which are important intermediates in plasma chemistry and contribute to subsequent dissociation processes. As indicated in Eq. (13), these ions can further decompose into atomic oxygen and negative oxygen species, generating highly reactive particles within the plasma environment. The oxidation of nitric oxide by atomic oxygen is described in Eq. (14), leading to the formation of NO₂, which represents a key intermediate step in NO_x conversion pathways. Eq. (15) illustrates the interaction between nitrogen dioxide and hydrocarbon species (C_xH_y), resulting in the formation of environmentally benign products such as N₂, CO₂, and H₂O through plasma-assisted oxidation and reduction mechanisms.

Finally, hydroxyl radicals generated in the plasma phase are highly reactive oxidizing agents and readily interact with hydrocarbon molecules, as shown in Eq. (16). During this reaction, OH radicals initiate the fragmentation and partial oxidation of hydrocarbons (C_xH_y), leading to the formation of simpler products such as CO and H₂O together with various intermediate oxygenated species. These intermediates can undergo further plasma-assisted oxidation reactions, ultimately contributing to the conversion of hydrocarbons into more stable end products. These reactions represent the primary pathways responsible for the generation of reactive species and the subsequent oxidation–reduction processes occurring inside the DBD plasma catalytic reactor.

Figure 7 shows the discharge at the surface of alumina particles when the power is activated. When high voltage was applied to the reactor, a dark blue colored dielectric barrier discharge was created as shown in Figure 7.

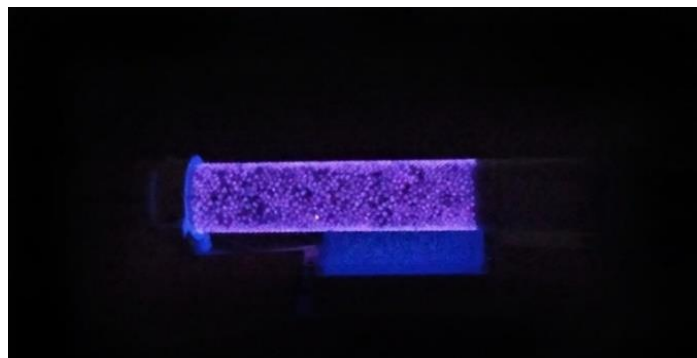


Figure 7. Operation of the plasma catalyst system without gas inlet

The catalyst material is typically molded into various shapes, such as pellets, honeycomb monoliths, foam structures, or coatings applied to electrodes or reactor walls. These alumina-based dielectric pellets are placed in direct contact with the discharge plasma, enabling interaction with short-lived energetic species such as radicals, photons, electrons, and excited molecular entities. The study explores the direct integration of catalysts into the discharge zone of a coaxial DBD reactor. Plasma-driven modification of the catalyst surface alters its chemisorption and desorption characteristics, enhancing both catalytic activity and selectivity. This plasma–catalyst coupling provides a pathway toward more effective catalysis compared with conventional techniques. Alumina is considered a suitable oxidation catalyst primarily due to its ability to easily adjust its oxidation state.



Figure 8. Plasma catalyst reactor

To maintain thermal stability and permit continuous visualization of the plasma discharge, the reactor was equipped with an aluminum mesh electrode that effectively prevented overheating during operation. A 40 MHz bandwidth Owon HDS242 dual-channel digital oscilloscope was used to monitor and record signal values from the power supply output that powers the DBD reactor. For data acquisition, an Arduino Uno microcontroller was employed to record sensor outputs and relay the collected information to a computer for further analysis. Specifically, the MQ107 and MQ135 gas sensors were used to detect carbon monoxide (CO) and nitrogen oxide (NO_x) gases at parts per million (ppm) concentrations, respectively. The CO sensor had a measurement range of 0 to 10,000 ppm, while the NO_x sensor covered a range of 0 to 1,000 ppm. An IOS compatible Seek XR thermal camera monitored the reactor temperature. This portable thermal camera can measure temperatures from -40°C to +330°C and has a resolution of 206x156 pixels. The high-voltage output power supply shown in Figure 5 was used to power the reactor.



Figure 9. High voltage power supply

Figure 8 shows the interior of a dielectric barrier discharge reactor filled with Al₂O₃ pellets. The pellets are spherical and approximately 1 mm in diameter. Figure 9 shows the high-voltage power supply connected to the reactor to create the dielectric barrier discharge. The power supply's output is bipolar. The output voltage and frequency can be controlled. This advantage allows for the appropriate parameters to be set for the reactor.

3. Results and discussion

This section provides a comprehensive description of the experimental conditions used in this study and a detailed presentation of the results obtained before proceeding to investigate the effect of Dielectric Barrier

Discharge (DBD) on exhaust emissions. The experiments were conducted under two different conditions: blank tests without a plasma catalyst and tests with a catalyst under plasma conditions. The experiments aimed to evaluate the effectiveness of NO_x and CO removal from vehicle exhaust gases. A kraft pipe was used to connect the exhaust and the reactor. Sensors were then installed downstream of the DBD reactor to measure the percentages of CO and NO_x gases before and after the DBD process, as shown in Figure 10.



Figure 10. Application of plasma catalytic systems

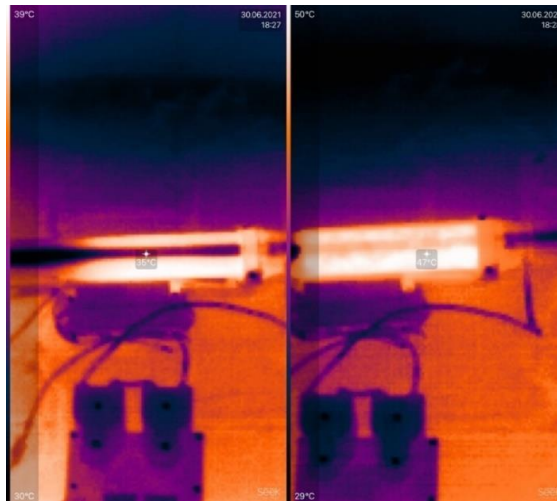


Figure 11. Thermal camera images of the plasma reactor in open and closed states

Figure 11 shows the temperature of the DBD catalyst reactor under open and closed conditions with thermal camera for precise temperature measurement. Specifically, when the plasma is not operating, the reactor temperature is recorded as 35°C . However, when the plasma is activated, the reactor temperature rises to 47°C .

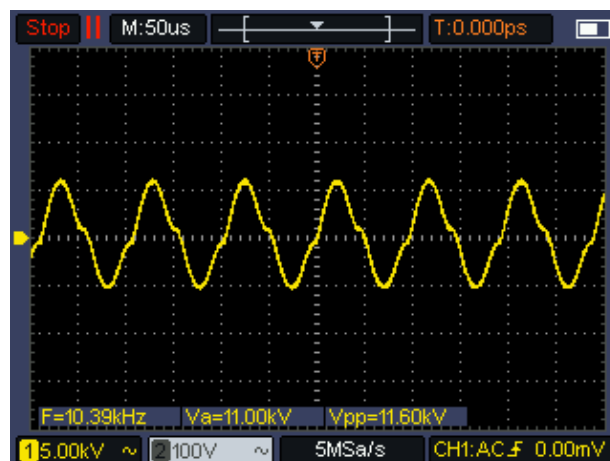


Figure 12. Oscilloscope screen image when plasma is active

Figure 12 shows a screenshot obtained from a digital oscilloscope using a high-voltage probe at the moment the plasma was formed. The oscilloscope screenshot shows a sinusoidal waveform with an estimated frequency of 10 kHz and a peak-to-peak voltage magnitude of 11.6 kV. The graphs shown in Figure 13 and Figure 14 show CO and NO_x emission values measured under both active and passive plasma conditions. The graphs show the reduction in CO and NO_x emissions in ppm when the plasma is active. CO and NO_x emission values appear higher when the DBD is coated, demonstrating that the emission reduction process has been successfully achieved. The graphs in Figure 13 and Figure 14 were obtained with 1000 measurements, each with 5 repetitions. These reductions are modest compared to the higher reductions reported in the literature; established studies have reported a wide range of efficiencies due to different reactor geometries, supported active metals, operating temperatures, specific energy inputs (J/L), and gas-volume flow rates (space velocity/residence time). For example, some studies report conversion/particularly CO_x selectivity close to 90% for toluene and other VOCs in systems such as pack-DBD or DBD+Ag/CeO₂/Al₂O₃ (Ag/CeO₂/Al₂O₃: high toluene conversion) (Zhu et al., 2018). Furthermore, some DBD setups and optimized catalysts report NO_x reductions of 50%–80% or even higher; these values generally depend on the type of catalyst (e.g., zeolite, metal-impregnated Al₂O₃ vs. Al₂O₃ only), the reactor type (packed-bed vs. post-plasma catalysis vs. in-plasma catalysis), and the suitability of the temperature window (e.g., 150–260 °C range) (Brandenburg et al., 2011).

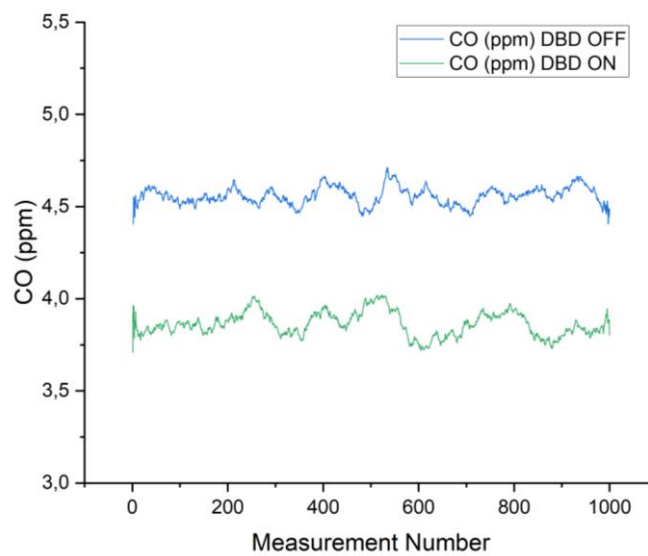


Figure 13. Emission values of CO gas in ppm measured with plasma on and off

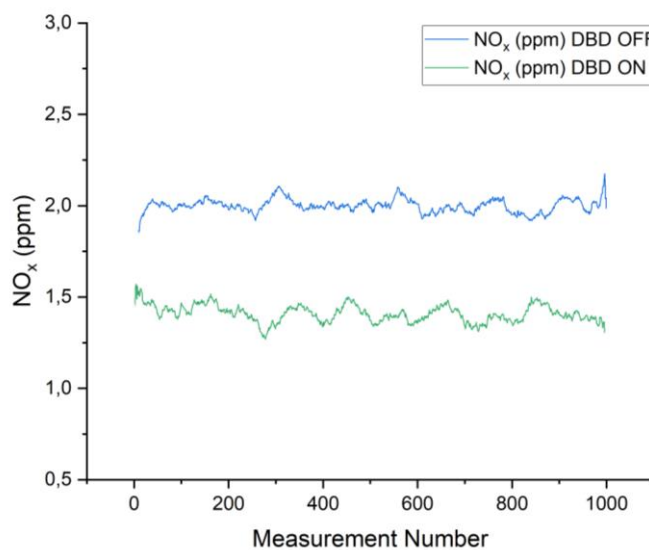


Figure 14. NO_x gas emission values in ppm measured with plasma on and off

In our study, pure Al₂O₃ (spherical pellets) was used as the filler; supports containing redox-active additives such as Ag, CeO₂, or noble metal/metal oxide additives are generally reported to provide higher efficiency in VOC/CO/NO_x oxidation and NO_x reduction. Combinations such as Ag/CeO₂/Al₂O₃ have been reported in the literature to provide significant performance improvements, particularly in VOC oxidation (Zhu et al., 2018). In the study, the reactor surface temperature measured with the plasma active was ≈ 47 °C; however, the temperature window in which some catalysts operate most effectively is reported in the literature as being around 150–260 °C (Brandenburg et al., 2011).

Table 1. Experimental operating conditions of the output power supply along with the measured values from the gas sensors

Parameters	Power OFF	Power ON (1)	Power ON (2)	Power ON (3)	Power ON (4)	Power ON (5)
CO (ppm)	4.62	3.9	3.8	3.8	3.7	3.9
NO _x (ppm)	1.98	1.4	1.5	1.3	1.4	1.4
Voltage (kV)	0	11.6	11.6	11.6	11.6	11.6
Frequency (kHz)	0	10	10	10	10	10
Power (W)	0	100	100	100	100	100

An examination of the data in Table 1 clearly demonstrates significant decreases in CO and NO_x concentrations. The data collection process included periodic measurements every 4 minutes, and when saturation was reached, relevant ppm data were recorded. Furthermore, average values were taken for all measurements presented in Table 1. It should be noted that hydrocarbon values were not included in this study due to their low concentrations. To perform statistical analyses, descriptive statistics (mean, standard deviation, percentage change) were calculated on the pre- and post-treatment CO and NO_x data in five replicates of 1000 measurements each. To quantify system performance, a paired t-test was applied to test the statistical significance of the mean differences ($p < 0.0001$). Pearson's correlation coefficient ($r = 0.65$ for CO; $r = 0.58$ for NO_x) was used to examine the relationship between the variables. All analyses were performed at a 95% confidence level, and the findings revealed that plasma treatment provided a significant and consistent reduction in both types of pollutants. Statistical parameters are shown in Table 2. PSPP, a free open source statistical analysis program, was used. The t-value for CO was calculated as 48.72, p-value: < 0.0001 , and the t-value for NO_x was calculated as 42.15, p-value: < 0.0001 . A positive correlation ($r = 0.65$) was found between CO before and after treatment. This shows that the plasma treatment provided a consistent reduction even at high initial values. The correlation coefficient for NO_x was calculated as $r = 0.58$. The findings show that the DBD plasma catalyst system reduces both CO and NO_x emissions at a statistically significant level. In particular, the 26.8% reduction observed in NO_x emissions supports the fact that the plasma activation process is highly effective on NO_x decomposition.

Table 2. Statistical parameters

Parameters	Power OFF (Mean \pm SD)	Power ON (Mean \pm SD)	Variation (%)
CO (ppm)	4,62 \pm 0,38	3,86 \pm 0,41	-16,5%
NO _x (ppm)	1,98 \pm 0,29	1,45 \pm 0,34	-26,8%

The 16.5% decrease in CO emissions indicates the efficiency of the catalytic oxidation process. P-values below 0.0001 reveal that the results are statistically reliable. This study demonstrated that the DBD catalyst system can statistically significantly reduce CO and NO_x emissions from gasoline engines. Both descriptive statistics and hypothesis testing support the system's potential use as an effective method for emission control. Future studies could further improve efficiency by optimizing different engine conditions and plasma parameters. Consequently, the research focused on CO and NO_x, which are common components in vehicle exhaust emissions. Integrating the plasma-assisted catalytic unit to the vehicle's conventional catalytic converter led to a marked improvement in overall emission reduction and environmental performance.

4. Conclusions

Consequently, reducing exhaust emissions from gasoline-powered vehicles is a critical issue that must be addressed to mitigate the negative impacts on the environment and human health. The introduction to exhaust emissions from gasoline vehicles highlights harmful pollutants such as NO_x, CO, and hydrocarbons released during combustion. These emissions contribute to air pollution and global warming, making it essential to find effective solutions. An overview of the dielectric barrier discharge catalyst system demonstrates its potential as a promising technology for reducing exhaust emissions. This system combines plasma discharge and catalytic reactions to convert harmful pollutants into less harmful substances. Implementing this system offers numerous benefits, including improving air quality, reducing greenhouse gas emissions, and increasing fuel efficiency. However, there are also challenges to overcome, such as high cost, durability issues, and compatibility with different vehicle models. In conclusion, reducing exhaust emissions in gasoline vehicles through the implementation of a dielectric barrier discharge catalyst system is an effective approach to achieving cleaner transportation. By addressing both the environmental concerns and technological challenges associated with this system, we can pave the way for a more sustainable future. In conclusion, the integration of Al₂O₃-based dielectric barrier discharge catalyst systems with other technologies offers a promising solution for reducing exhaust emissions from gasoline vehicles. By focusing on optimizing these systems for specific engine conditions and integrating them with existing aftertreatment technologies, significant progress can be made in achieving stringent emissions targets. Continued exploration of the interactions between different fuel types, combustion technologies, and exhaust aftertreatment systems will be crucial in shaping the future of cleaner gasoline vehicle operations. Our study has the advantage of being easier and more cost-effective to implement compared to studies in the existing literature. The portability and simplicity of the power source are significant advantages. The easy availability and efficiency of the spherical alumina particles used as catalysts in the reactor guarantee the high integration capability of this system.

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Author contribution

Ferhat Bozduman; Design, methodology, review, editing, Abdallah Dwaikat; Experimental procedure, writing.

Declaration of ethical code

The authors of this article declare that the materials and methods used in this study do not require ethics committee approval and/or legal-special permission.

Conflicts of interest

The authors declare that there is no conflict of interest.

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