Experimental Study on Regeneration of Diesel Particulate Filter by NTP Injection System: Postprint

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Abstract

Using oxygen as the gas source, DPF regeneration experiments were conducted at various temperatures utilizing a self-designed non-thermal plasma (NTP) injection system. The results indicate that after oxygen undergoes discharge in the NTP generator, reactive species with strong oxidizing capability are produced, enabling decomposition of PM to generate CO and CO_2. With increasing experimental temperature, the molar amount of CO exhibits an overall decreasing trend, while the molar amounts of CO_2 and COx (CO and CO_2) both display a trend of initially increasing then decreasing. At an experimental temperature of 80°C, the back pressure of the DPF decreases most rapidly, the regeneration effect is most significant, and both the internal temperature and temperature gradient are far below the service limit of the DPF, which is beneficial for DPF service life. The NTP technology achieves DPF regeneration at relatively low temperatures without catalyst addition, demonstrating the superiority of this regeneration method compared with traditional regeneration methods.

Full Text

Preamble

Experimental Study on DPF Regeneration Based on Non-thermal Plasma Injection System

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Abstract:

Using oxygen as the gas source, this study investigates Diesel Particulate Filter (DPF) regeneration at different temperatures with a self-designed Non-thermal Plasma (NTP) injection system. The results demonstrate that oxygen discharge in the NTP generator produces strongly oxidative active species (O_3 and O atoms) that decompose particulate matter (PM) into CO and CO_2. As the test temperature increases, the molar quantity of CO shows an overall decreasing trend, while both CO_2 and COx (combined CO and CO_2) exhibit an initial increase followed by a decrease. At 80°C, the DPF backpressure decreases most rapidly, achieving the most significant regeneration effect, with internal temperatures and temperature gradients far below the DPF service limits, which benefits DPF durability. NTP technology enables DPF regeneration at relatively low temperatures without catalysts, demonstrating superiority over conventional regeneration methods.

Keywords: Non-thermal Plasma; Diesel Particulate Filter; Regeneration; Oxygen; Temperature

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Introduction

Diesel engines are widely used in industrial, agricultural, and transportation applications due to their high thermal efficiency, good fuel economy, high reliability, and long service life [1-2]. However, their contribution to air pollution has been increasing, making efficient reduction of diesel emissions a growing concern. The primary pollutants from diesel engines are nitrogen oxides (NOx) and particulate matter (PM), with PM emissions posing severe threats to environmental safety and human health [3-4]. In September 2013, China’ s State Council issued the “most stringent” Air Pollution Prevention and Control Action Plan, requiring PM concentrations in cities above the prefecture level to decrease by 10% by 2017 compared to 2012 levels. This underscores the urgency of controlling diesel PM emissions. Currently, the most widely employed PM purification technology is the Diesel Particulate Filter (DPF). However, as PM accumulation increases, DPF pressure drop rises, eventually affecting normal engine operation. Therefore, the key challenge in DPF technology is filter regeneration [5-6].

DPF regeneration typically includes active and passive methods. Active regeneration utilizes external energy to raise the DPF internal temperature above the PM oxidation combustion threshold (typically above 650°C). Common active methods include electric heating, microwave heating, and fuel injection combustion heating, but these suffer from high energy consumption, elevated costs, and potential thermal damage to the filter substrate [7]. Passive regeneration achieves regeneration without external assistance by lowering the required combustion temperature, either through fuel-borne catalysts that reduce the minimum regeneration temperature or by installing oxidation catalysts to generate NO_2, which oxidizes PM. Passive regeneration faces issues such as catalyst sulfur poisoning and low regeneration efficiency [8-9].

Non-thermal Plasma (NTP) technology is a novel industrial decontamination approach that initiates chemical reactions difficult to achieve under normal conditions. It offers broad applicability, high conversion efficiency, low energy consumption, and no secondary pollution, making it a promising diesel aftertreatment technology [10-12]. Applying NTP technology to DPF regeneration has become a hot research topic in recent years.

This study employs a self-designed NTP injection system with oxygen as the gas source to conduct regeneration experiments on PM-loaded DPFs. The research explores the chemical reaction mechanism of NTP-assisted DPF regeneration, analyzes the influence of temperature on PM oxidation and DPF regeneration effectiveness, and investigates temperature and temperature gradient variations within the DPF, providing a foundation for further development of NTP-based DPF regeneration.

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1. Experimental System and Methods

The experimental apparatus consists of four main components: the NTP injection system, oxygen supply system, electrical parameter measurement system, and DPF regeneration system, as shown in [Figure 1: see original paper].

The NTP injection system includes the NTP generator, water cooling device, air cooling device, and temperature measurement unit. The NTP generator features a coaxial cylindrical structure: the inner electrode is a seamless stainless steel tube with an outer diameter of 32 mm; the dielectric barrier is a quartz tube with an inner diameter of 36 mm and wall thickness of 2 mm; the outer electrode is a stainless steel mesh with an axial length of 100 mm, tightly attached to the quartz tube outer wall; and the discharge gap is 2 mm. The water cooling system comprises a water pump, transfer pipelines, and control valves with circulating cooling water. The air cooling device is a cooling fan. Temperature measurement uses a TASI infrared thermometer ($±$1°C accuracy) to monitor the NTP generator discharge zone surface temperature.

The oxygen supply system consists of an oxygen cylinder, transfer pipelines, control valves, and a rotary flowmeter for gas flow monitoring. The electrical parameter measurement system comprises a non-thermal plasma power supply, electrical circuit, and TDS3034B digital oscilloscope. The plasma power supply is a CTP-2000K intelligent electronic impact machine with adjustable voltage (0–25 kV) and frequency (7–20 kHz). The circuit includes voltage divider capacitors C_1=47 pF and C_2=47 nF, and charge transfer measurement capacitor C =0.47 F. The TDS3034B oscilloscope has a 50 MHz sampling frequency with output waveforms averaged over 250 cycles. Discharge voltage and frequency are measured using a TekP6139A high-voltage probe.

The DPF regeneration system includes a constant temperature chamber, differential pressure gauge, thermocouples, and a Photon infrared flue gas analyzer. The temperature-controlled chamber houses the PM-loaded DPF. The DPF substrate is made of cordierite with specifications listed in . The differential pressure gauge measures DPF backpressure variations during experiments. The Photon analyzer measures CO and CO_2 concentrations from PM oxidation, while thermocouples monitor internal DPF temperatures.

[Figure 2: see original paper] shows the thermocouple positions within the DPF, labeled 0–13. K-type thermocouples (0–1200°C range, Φ0.48$×$1500 mm) measure temperatures at different axial and radial positions, providing comprehensive internal temperature distribution data. [Figure 3: see original paper] illustrates the DPF substrate structure.

During experiments, oxygen flow was controlled at 5 L/min. The plasma power supply was activated with discharge voltage set to 20 kV and frequency to 9 kHz. Since active species concentration is significantly affected by generator surface temperature [13], fan airflow and cooling water flow were adjusted to maintain the NTP generator surface temperature at 90°C. After high-voltage discharge in the NTP generator, the resulting active gas was introduced into the DPF preheated to the test temperature, and relevant data were recorded. The constant temperature chamber temperature served as the test temperature. All experiments ran for 4 hours at different test temperatures.

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2. Chemical Reaction Mechanism of NTP-Assisted DPF Regeneration

Oxygen discharge in the NTP generator produces strongly oxidative active species O_3 and O atoms through the reaction model shown in equations (1)-(3) [14-15]:

$$e + O_2 \rightarrow e + O_2(A^3\Sigma_u^+) \rightarrow e + O(^{3P}) + O(^{3P}) \tag{1}$$

$$e + O_2 \rightarrow e + O_2(B^3\Sigma_u^-) \rightarrow e + O(^{3P}) + O(^{1D}) \tag{2}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{3}$$

Ozone synthesis during discharge occurs in two steps. First, energetic electrons from micro-discharges dissociate oxygen molecules to form nascent oxygen atoms, as shown in equations (1) and (2). Second, these oxygen radicals undergo three-body reactions to form ozone, as in equation (3), where M represents a third-body participant.

Diesel exhaust PM consists primarily of unburned soot, adsorbed organic soluble fractions (SOF), and inorganic salts. Active species from the NTP generator can decompose both soot and SOF components. The confirmed chemical reaction kinetic models are shown in equations (4)-(9):

$$O + HC \rightarrow RO_2, RO, OH \tag{4}$$
$$O_3 + SOF \rightarrow CO(CO_2) + O_2 + H_{2O} \tag{5}$$
$$C + O \rightarrow CO \tag{6}$$
$$C + 2O \rightarrow CO_2 \tag{7}$$
$$C + O_3 \rightarrow CO + O_2 \tag{8}$$
$$C + 2O_3 \rightarrow CO_2 + 2O_2 \tag{9}$$

Active species first collide with SOF components (primarily hydrocarbons) on the PM surface, producing gaseous CO, CO_2, and H_2O as shown in equations (4) and (5), thereby stripping SOF from the soot surface. When active species contact the central soot, chemical reactions generate CO and CO_2 (equations 6-9), achieving PM decomposition. As equations (4)-(9) indicate, the primary reaction products are CO and CO_2; monitoring these gases reveals the extent of PM oxidation.

3.1 Effect of Temperature on PM Decomposition

DPF regeneration experiments were conducted at various test temperatures. The temporal variations of CO and CO_2 volume fractions are shown in [Figure 4: see original paper] and [Figure 5: see original paper].

At test temperatures of 17°C and 40°C, CO volume fraction initially increased sharply then remained relatively stable, while CO_2 volume fraction first increased then decreased. At 60°C, 80°C, and 100°C, CO volume fraction exhibited a two-step rising trend: the first step occurred at reaction onset with a sharp increase followed by stabilization and slight decline; the second step appeared between 80-120 minutes with another sharp rise before stabilization. CO_2 volume fraction increased sharply initially, then stabilized with slight decline, followed by a sharp drop between 80-120 minutes. Notably, at 60°C, 80°C, and 100°C, abrupt changes in CO and CO_2 occurred simultaneously. At 150°C, 200°C, 250°C, and 300°C, both CO and CO_2 volume fractions showed an initial sharp increase followed by gradual decline.

3.2 Effect of Temperature on DPF Regeneration Effectiveness

Integration of the curves in [Figure 4: see original paper] and [Figure 5: see original paper] yielded the molar quantities of CO and CO_2 at different temperatures using equations (10) and (11):

$$n(CO) = \int c_1 \cdot t \, dt \cdot \frac{v}{V_m} \tag{10}$$

$$n(CO_2) = \int c_2 \cdot t \, dt \cdot \frac{v}{V_m} \tag{11}$$

where c_1 and c_2 are the volume fractions of CO and CO_2, v is the gas flow rate (5 L/min), and V_m is the molar volume (22.4 L/mol).

Greater PM decomposition indicates better DPF regeneration. Since CO and CO_2 are the primary decomposition products, their total molar quantity (COx) serves as an evaluation metric for regeneration effectiveness. [Figure 6: see original paper] shows the variation of CO, CO_2, and COx moles with temperature.

Below 80°C, increasing temperature decreased CO moles while increasing CO_2 moles. This occurs because CO formation has lower activation energy than CO_2 formation, making reactions (6) and (8) dominant at low temperatures. As temperature rises, reactions (7) and (9) intensify while reactions (6) and (8) weaken, reducing CO and increasing CO_2. Above 80°C, both CO and CO_2 moles decreased continuously because O_3 decomposes at high temperatures, reducing available oxidants. COx moles initially increased then decreased with temperature, following the CO_2 trend due to its higher yield. Maximum COx occurred at 80°C, indicating the most complete PM oxidation.

[Figure 7: see original paper] shows DPF backpressure variation over time at different temperatures. At 17°C and 40°C, backpressure decreased slightly, indicating slow PM oxidation. At 60°C, 80°C, and 100°C, backpressure dropped significantly and rapidly, showing vigorous oxidation. At 150°C, 200°C, 250°C, and 300°C, the backpressure decline slowed, reducing oxidation rates. At 80°C, backpressure decreased fastest, reaching near-clean DPF levels after 120 minutes, demonstrating optimal regeneration. Compared with conventional methods, NTP technology achieves low-temperature regeneration without catalysts, proving its superiority.

3.3 DPF Internal Temperature During Regeneration

The maximum temperatures at various DPF positions were similar, but the PM oxidation interface moved from upstream to downstream along the gas flow direction. The highest temperature occurred at measurement point 3, where heat from upstream PM oxidation accumulated downstream while heat loss was significant near the outlet (points 4 and 5), creating maximum temperature in the middle-rear section.

3.4 DPF Internal Temperature Gradient Over Time

Although maximum temperatures at different positions were comparable, the moving oxidation interface from upstream to downstream created axial temperature gradients. Calculations revealed the maximum axial temperature gradient occurred along the DPF centerline. [Figure 10: see original paper] shows the axial temperature gradient variation at 80°C, with the maximum gradient of $27.21°\mathrm{C} \cdot \mathrm{cm}^{-1}$ appearing between points 3 and 4 in the middle-rear section.

[Figure 11: see original paper] illustrates the radial temperature gradient at 80°C for the cross-section with the maximum gradient. The maximum radial temperature gradient of $20.24°\mathrm{C} \cdot \mathrm{cm}^{-1}$ occurred at the 1-6-10 interface between points 6 and 10. Comparing axial and radial gradients shows the substrate' s maximum temperature gradient was $27.21°\mathrm{C} \cdot \mathrm{cm}^{-1}$, well below the $35°\mathrm{C} \cdot \mathrm{cm}^{-1}$ threshold for thermal stress damage [16]. This is significant for DPF durability and provides experimental evidence for the safety of NTP-based regeneration.

Conclusions

This study investigated DPF regeneration at various temperatures using a self-designed NTP injection system with oxygen. The research explored the chemical reaction mechanism, analyzed temperature effects on PM oxidation and regeneration effectiveness, and examined internal temperature and gradient variations. Key conclusions are:

1) Oxygen discharge in the NTP generator produces strongly oxidative O_3 and O atoms that oxidize and decompose PM into CO and CO_2.
2) Increasing test temperature decreases CO moles overall, favoring CO production at lower temperatures. Both CO_2 and COx moles initially increase then decrease, reaching maximum values at 80°C.
3) At 17°C and 40°C, DPF backpressure decreased slightly. At 60°C, 80°C, and 100°C, backpressure dropped rapidly and significantly. At 150°C, 200°C, 250°C, and 300°C, the decline slowed. At 80°C, backpressure decreased fastest with optimal regeneration. NTP technology enables low-temperature regeneration without catalysts, demonstrating superiority over conventional methods.
4) At 80°C, internal DPF temperatures remained far below maximum service limits, with axial and radial temperature gradients below damage thresholds. This is crucial for extending DPF life and provides safety validation for NTP regeneration technology.

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Note: Figure translations are in progress. See original paper for figures.