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# Advancing the Regeneration of Diesel Particulate Filters through the Utilization of Ozone Generated by Non-Thermal Plasma: An Experimental Investigation

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**Abstract.** Particulate matter (PM2.5) from diesel engines poses significant environmental and health risks. Diesel Particulate Filters (DPF) mitigate emissions but suffer from soot accumulation, which increases back pressure and requires regeneration, often impractical at low urban driving temperatures. This study investigated Non-Thermal Plasma (NTP)-generated ozone and hydrogen for DPF regeneration, assessing their impact on particulate matter, pressure drop, and DPF lifespan. Experiments utilized a 4-stroke diesel engine, with ozone produced from pure oxygen or air through NTP at 20 VPP, 50-1000 Hz, and 5-10 L/min, and introduced into a soot-filled DPF at 200°C. Regeneration was monitored by differential pressure. Findings showed ozone effectively reduced DPF pressure drop, with pure oxygen at 1,000 Hz and 5 L/m yielding the best regeneration above 5,000 ppm ozone. Lower flow rates increased ozone concentration. Hydrogen addition of 3-6% did not significantly improve efficiency and caused system anomalies, possibly due to the formation of water. In conclusion, ozone is a promising, low-energy DPF regeneration solution, effective at temperatures ranging from 200-300°C to 600°C, which is ideal for urban conditions. Optimizing ozone generation is crucial, while hydrogen addition may not be beneficial.

## 1 Introduction

The escalating global concern over particulate matter (PM2.5) concentrations in the atmosphere presents a continuous and severe environmental and public health crisis, particularly in densely populated urban and industrial areas. Diesel engines are a primary contributor to PM2.5 pollution [1,2], disproportionately responsible for a larger share of emissions compared to gasoline vehicles, even when conforming to the Euro 6 emission standards [3]. This exceedance of emission limits highlights the urgent need for innovative and more effective exhaust after-treatment solutions [4]. A Diesel Particulate Filter (DPF) is a critical after-treatment device designed to capture particulate matter from the exhaust of diesel engines. However, DPF has a finite capacity for soot accumulation, leading to clogging, increased exhaust back pressure, and reduced engine efficiency. To restore filter performance, periodic regeneration is essential, involving the oxidation of accumulated soot [5]. Conventional regeneration methods, such as active and passive regeneration, often require high temperatures or substantial energy input, which are frequently impractical during typical urban driving cycles characterized by lower exhaust temperatures [6]. The challenge of PM2.5 emissions from diesel engines, coupled with the limitations of conventional DPF regeneration methods that struggle to operate efficiently at lower temperatures or with reduced energy consumption, necessitates the exploration of alternative, more versatile, and energy-efficient regeneration approaches. This investigates the efficacy of ozone ($O_3$) as a potent oxidizing agent for the low-temperature breakdown of particulate matter, thereby facilitating DPF regeneration in urban driving conditions [7]. To meticulously study the pressure drop across the DPF under various regeneration conditions [8]. To experimentally determine methods that can effectively increase the operational lifespan of the diesel particulate filter [9]. The generation of particulate matter from diesel engines is intrinsically linked to the chemical properties of diesel fuel and the dynamics of its combustion, often resulting from incomplete combustion and leading to the formation of soot through a multi-stage process involving inception, nucleation, growth, agglomeration, and aggregation [10–12]. Non-Thermal Plasma (NTP) technology offers an innovative method for ozone generation, which is crucial for DPF regeneration [13,14], as it can produce ozone at relatively low temperatures, enhancing energy efficiency. Oxidation is a fundamental chemical reaction in which soot, composed of solid carbon particles, reacts with oxidizing agents, such as ozone, to convert into gaseous products, including carbon dioxide or carbon monoxide.

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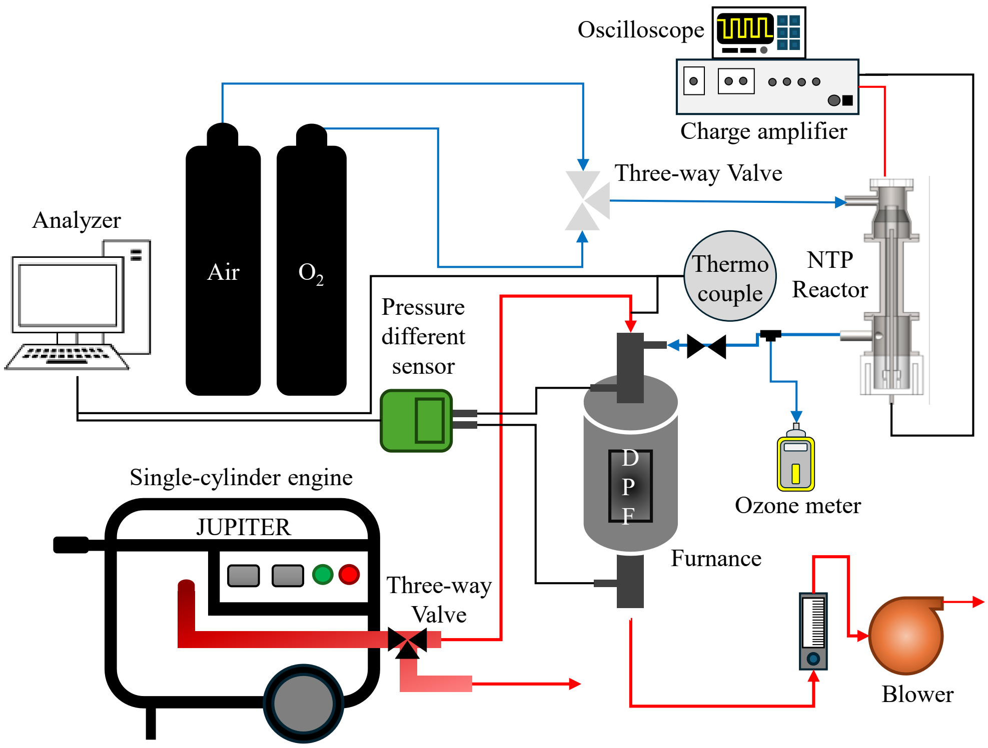


**Fig. 1.** Schematic diagram of the experimental setup for DPF regeneration using NTP.

The ability of ozone to facilitate this process at lower temperatures is essential [15,16]. DPF functions by trapping particulate matter; however, their finite capacity necessitates regeneration, which can be either active or passive. Both conventional methods have limitations in urban driving conditions [14]. Ozone's inherent instability and strong oxidizing capability can break down soot at significantly lower temperatures, around 200-300°C, compared to conventional methods, which operate at around 600°C, making it suitable for urban cycles. It also investigates hydrogen's potential to enhance this process by providing a localized heat source [17,18].

This study aims to address the critical challenge of PM 2.5 emissions from diesel engines. Conventional DPF regeneration methods are impractical in urban driving due to their high temperature and energy requirements. To propose a more effective solution using $O_3$ generated by NTP. This work aims to investigate the efficacy of this method in facilitating low-temperature DPF regeneration. The experiment examines the impact of factors such as gas feedstock and NTP frequency on regeneration performance, laying the groundwork for the development of cleaner and more efficient exhaust after-treatment technologies.

## 2 Experimental setup

The setup for DPF regeneration is depicted in the experimental system in Figure 1. The core components of the system included a Jupiter single-cylinder diesel engine, which served as the controlled source of particulate matter, and a DPF where soot accumulation and regeneration experiments were performed. To maintain the temperature of the DPF during regeneration, a furnace was integrated into the system. Gas generation for regeneration was achieved through the NTP reactor, and a blower was used to induce and control the gas flow throughout the system. The data were collected by the sensors placed within the system. Pressure differential sensors were installed at both the inlet and outlet of the DPF to measure the pressure drop across the filter accurately. Thermocouples were positioned to monitor temperatures at various points, including the DPF, ensuring that the desired thermal conditions were maintained. An ozone meter was incorporated to provide real-time measurements of ozone concentration, allowing for direct monitoring of the generated gas. The experimental setup comprised a specific array of tools and equipment, each selected for its role in ensuring precise control and accurate measurement during the investigation.

### 2.1 Experimental setup

A Jupiter model JP-D5GF diesel engine was employed as the consistent source of particulate matter. This is a 4-stroke, 1-cylinder engine. The engine detail was as shown in Table 1.

**Table 1.** The engine specifications.

| | Value | Unit |
|---|---|---|
| Engine speed | 3,000 | Revolution per minute (rpm) |
| Displacement | 406 | Cubic centimeter (cc) |
| Power output | 10 | Horsepower (HP) |
| Voltage | 220 | Volt (V) |
| Output | 5 | Kilowatt (kW) |

**Table 2.** The conditions and parameters of the experiment, using different gas inlets, consist of $O_2$ and air for ozone production.

| Flow rate to NTP (L/m) | Gas inlet | Voltage (kV) | Frequency (Hz) |
|---|---|---|---|
| 5 | $O_2$ | 20 | 50 |
| | | | 500 |
| | | | 1,000 |
| | Air | | 50 |
| | | | 500 |
| | | | 1,000 |
| | | | 500 |
| | | | 1,000 |
| 10 | $O_2$ | | 50 |
| | | | 500 |
| | | | 1,000 |
| | Air | | 50 |
| | | | 500 |
| | | | 1,000 |
| | | | 500 |
| | | | 1,000 |

## 2.2 Tools and equipment

A Carbolite Eva vertical tube furnace was used to control the temperature of the DPF during regeneration experiments precisely. This furnace can maintain temperatures within a wide range, from 30°C to 3,000°C, ensuring that the DPF can be held at the desired exhaust gas temperature of 200°C during the regeneration. The blower features a 200 mm impeller diameter and is used to create and regulate the airflow throughout the experimental system. This ensured consistent gas flow rates for both ozone generation and DPF regeneration processes.

**Table 3.** The conditions for regeneration of DPF.

| Engine speed (rpm) | Engine load (%) | Flow rate to NTP (L/m) | Gas inlet | Voltage (kV) | Frequency (Hz) |
|---|---|---|---|---|---|
| 1,500 | 12 | 5 | $O_2$ | 20 | 50 |
| | | | | | 500 |
| | | | | | 1,000 |
| | | | Air | | 50 |
| | | | | | 500 |
| | | | | | 1,000 |

The NTP reactor was central to the ozone generation process. The principle of NTP involves electrical discharge to oxidize particles at low temperatures, a method chosen for its potential to extend DPF lifespan by avoiding high thermal stress. Specifically, the Indirect NTP (INTP) method was implemented to generate reactive chemical species for PM oxidation, thereby minimizing the production of secondary pollutants.

The commercial DPF used in this study was a silicon carbide (SiC) filter with modified a diameter to 23 mm and a length of 127 mm. Its specifications included a cell density of 200 cells per square inch (CPSI) and a wall thickness of 0.43 mm. Key properties for filtration performance were an average pore size of 11±5 µm and a porosity of 46±5%. The chemical composition of the SiC was measured to be 71±7%.

A Keysight model DSOX1204A oscilloscope was used for precise measurement and control of electrical signals, including voltage, frequency, and phase, within the NTP system.

An instrument capable of measuring pressure variations in the range of 0-25 kPa was installed at both the inlet and outlet of the DPF

Thermocouples type K were strategically placed to provide accurate temperature measurements throughout the system, within the DPF and the exhaust gas stream.

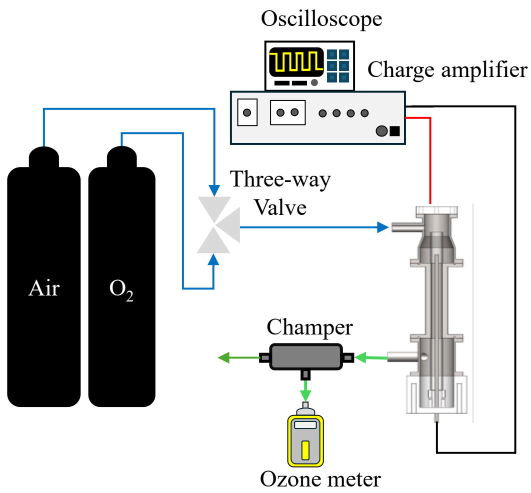


**Fig. 2.** Schematic diagram of the non-thermal plasma NTP system for ozone generation and measurement, with pure $O_2$ and air as feedstocks.

An ozone meter with a measurement range of 0-5,000 ppm was connected to the gas flow path to quantify the concentration of ozone produced by the NTP reactor in real-time. Ozone production was validated before initiating the engine experiments. The parameters and conditions governing ozone production are summarized in Table 2. In Figure 2, the diagram illustrates the system used to measure ozone concentration, featuring a three-way valve that allows for the selection of either pure $O_2$ or air. The selected gas was fed into the NTP reactor, where it generated ozone. The ozone meter then provided real-time measurements of the ozone concentration, enabling us to test various gas flow rates and frequencies to determine the optimal settings for ozone production.

## 2.3 The calculation of space velocity

The space velocity (SV, 1/h) is crucial for normalizing the gas flow rate relative to the volume of the catalyst or reactor, as follows:

$$SV = \dot{Q}/V \qquad (1)$$

Where Q represents the volumetric flow rate of the exhaust gas, and V denotes the volume of the reactor or catalyst.

$$V = \pi D^2 h/4 \quad (2)$$

DPF Volume Calculation: The volume of the DPF was calculated using the standard formula for the volume of a cylinder by following:

The volumetric flow rate of exhaust gas ($\dot{Q}$) produced by the engine was determined using the engine's cylinder volume ($V_e$) and the number of exhaust emissions per operating cycle, as follows:

$$\dot{Q} = V_e \times n \quad (3)$$

To ensure that the experimental conditions were scalable and comparable across different engine sizes, the space velocity was maintained consistently across various setups. This principle is expressed as:

$$SV_1 = SV_2 \quad (4)$$

$$\frac{\dot{Q}_1}{V_1} = \frac{\dot{Q}_2}{V_2} \quad (5)$$

The engine was running to its normal operating temperature, then exhaust gas was routed through the DPF for approximately 1 hour and 30 minutes to collect particulate matter. The collected particulate matter is deposited in the DPF, as illustrated in Figure 3. The DPF, now loaded with particulate matter, was then placed in the Cabolite oven and heated to the temperature of the exhaust gas. Ozone was generated using the NTP Reactor. The parameters and conditions of the experiment are shown in Table 3. To simulate real-world driving. The parameters of 1,500 rpm and 12% engine load are representative of a low-load, low-speed urban driving cycle [19]. A gas flow rate of 5 L/min was selected for testing. Experiments have shown that a lower flow rate results in a longer residence time for the gas within the NTP reactor. The extended residence time allows for more complete ozone formation, resulting in a higher overall ozone concentration and, consequently, a more effective regeneration performance.

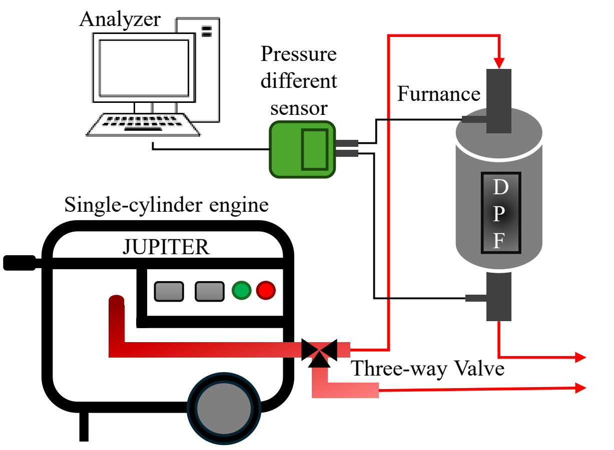


**Fig. 3.** Schematic diagram of the experimental setup of the engine for particulate matter collection.

## 3 Result and discussion

### 3.1 The comparative influence of air and oxygen on ozone production

When air is fed into the NTP reactor, the ozone production is significantly influenced by the frequency and flow rate. At a flow rate of 5 L/m, increasing the frequency substantially enhanced the ozone concentration, as indicated in Figure 4. Specifically, at 50 Hz, the ozone concentration was relatively low, ranging from 90 to 100 ppm. However, increasing the frequency to 500 Hz resulted in a notable increase to approximately 600 ppm, and further increasing it to 1,000 Hz yielded concentrations around 1,100 ppm.

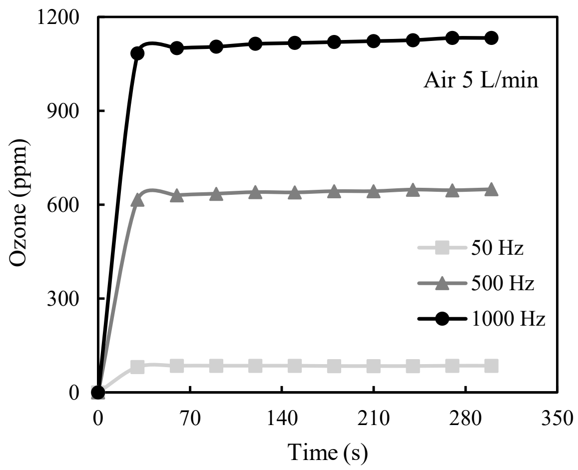


**Fig. 4.** Ozone production characteristics of the NTP reactor using an air inlet flow rate of 5 L/min at various frequencies.

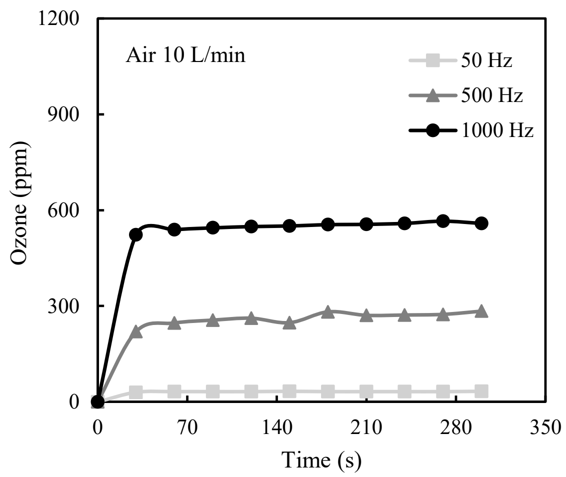


**Fig. 5.** Ozone production characteristics of the NTP reactor using an air inlet flow rate of 10 L/min at various frequencies.

This demonstrates a direct correlation between higher frequency and increased ozone output when using air. Conversely, when the flow rate of atmospheric air was increased to 10 L/m, as demonstrated in Figure 5, a substantial reduction in ozone concentration was observed across all frequencies compared to the 5 L/min condition. At 50 Hz, concentrations dropped to 30-40 ppm, at 500 Hz to 200 ppm, and at 1,000 Hz to 500 ppm. This reduction in ozone production at higher flow rates is attributed to a shorter residence time of the gas within the NTP reactor. With less time for plasma-induced reactions to occur, the efficiency of ozone formation decreases, resulting in lower ozone concentrations. This highlights that for optimal ozone generation, a balance between gas flow rate and reaction time within the plasma field is crucial. Utilizing pure oxygen as the feedstock improved the efficiency of ozone production. The Figure 6 illustrates that at a flow rate of 5 L/m, the ozone concentrations were significantly higher than those achieved with air. At 50 Hz, approximately 250 ppm of ozone was produced. At 500 Hz, the concentration surged to approximately 2,500 ppm, with production stabilizing after about 60 seconds. Notably, at 1,000 Hz, the ozone concentration exceeded the measurement range of the equipment, which has a maximum capacity of 5,000 ppm. This indicates that pure oxygen, being a more concentrated source of the reactant ($O_2$), allows for much higher ozone yields.

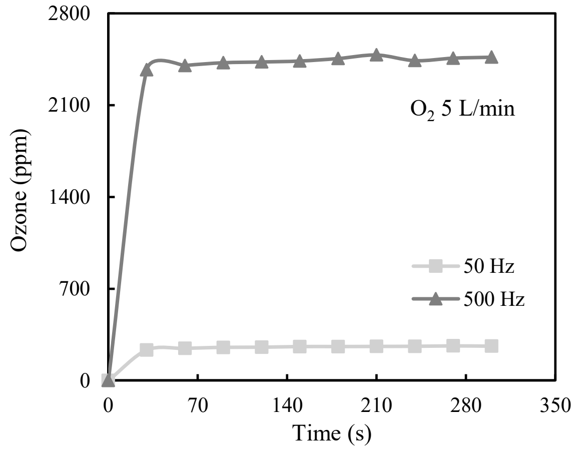


**Fig. 6.** Ozone production characteristics of the NTP reactor using an $O_2$ inlet flow rate of 5 L/min at various frequencies.

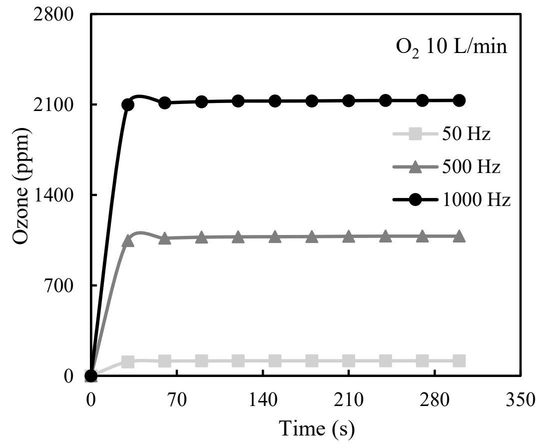


**Fig. 7.** Ozone production characteristics of the NTP reactor using an $O_2$ inlet flow rate of 10 L/min at various frequencies.

When the flow rate of pure oxygen was increased to 10 L/m, as shown in Figure 7, a similar trend of reduced efficiency due to shorter reaction time was observed. However, the absolute concentration remained higher than those from the air. At 50 Hz, approximately 115 ppm of ozone was produced. At 500 Hz, the concentration reached about 1,000 ppm, and at 1,000 Hz, it was around 2,000 ppm, also stabilizing after approximately 60 seconds. The results show the average ozone concentration achieved under various conditions of gas type, flow rate, and frequency.

The ozone production tests indicate that the gas flow rate has a direct impact on the efficiency of ozone generation. A flow rate of 5 L/m consistently produced higher ozone concentrations than 10 L/m, primarily because the lower flow rate allowed for a longer reaction time within the NTP reactor. This extended residence time facilitated the formation of more complete ozone. Furthermore, ozone production generally stabilized after approximately 60 seconds of operation, indicating a steady-state condition for the NTP system. The superior performance with pure oxygen highlights the importance of feedstock purity in maximizing ozone yield, particularly at higher frequencies.

### 3.2 The regeneration of DPF utilizing ozone under varying gas inlet compositions

The effectiveness of DPF regeneration was primarily assessed by monitoring the differential pressure across the filter, which directly correlates with the accumulation of particulate matter. A reduction in differential pressure indicates successful soot removal.

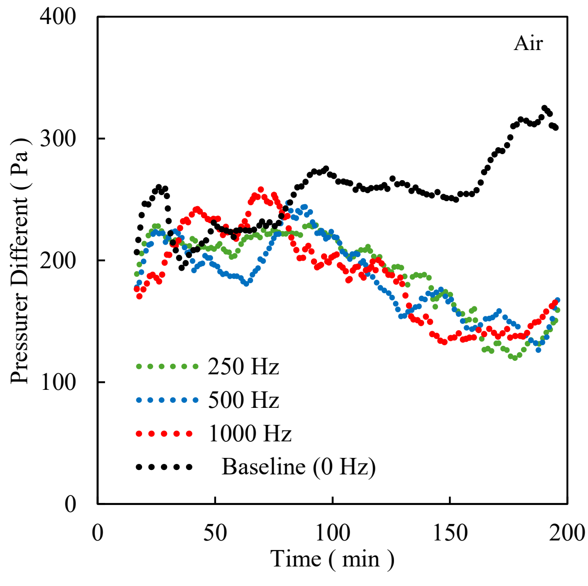


**Fig. 8.** Comparison of DPF regeneration using ozone generated from the air inlet to NTP.

The experiments involving ozone generated from atmospheric air demonstrated clear regeneration capabilities. The baseline shows the initial increase in differential pressure as soot was collected in the DPF during the first 60 minutes. After this soot loading phase, ozone injection commenced at a DPF temperature of 200°C for 2 hours. The results indicated that the differential pressure began to decrease noticeably around the 80-minute mark and eventually returned to a nearnormal state by 180 minutes, as illustrated in Figure 8. This trend confirms the efficacy of ozone produced from atmospheric air in regenerating the DPF, with higher frequencies and thus higher ozone concentrations, generally leading to more effective regeneration. The ability to achieve regeneration at 200°C, significantly lower than the 600°C required for conventional thermal regeneration, highlights a key advantage for applications in low-temperature exhaust environments, such as urban driving.

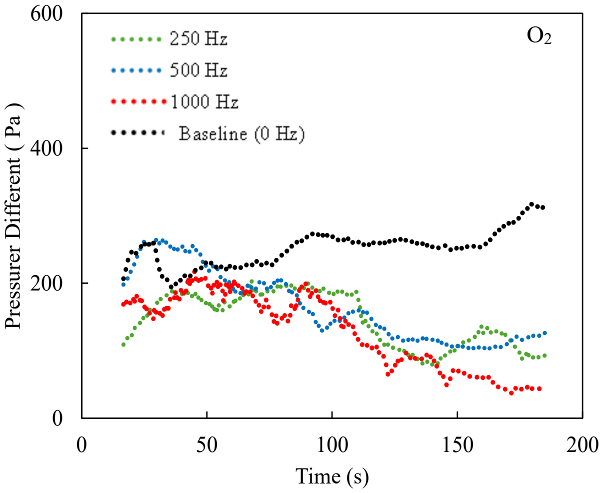


**Fig. 9.** Comparison of DPF regeneration using ozone generated from the air inlet to NTP.

Regeneration experiments using ozone generated from pure oxygen were expected to show superior performance due to higher ozone concentrations. Figure 9. illustrates these results. While the overall trend for regeneration was positive, some inconsistencies were observed in the differential pressure readings at 250 Hz and 1,000 Hz. These anomalies are hypothesized to stem from variations in the modified DPF devices used for each test or potentially from the presence of water within the exhaust system. The latter could be a consequence of experimental conditions, particularly if hydrogen were introduced in preliminary or subsequent tests that might have influenced the system. Despite these irregularities, the general pattern indicated that the DPF's pressure differential returned to normal levels within the 180-minute regeneration period, suggesting effective soot oxidation by ozone from pure oxygen.

The experimental investigation into the use of ozone and hydrogen for DPF regeneration has yielded several important conclusions regarding their efficacy and potential applications. The primary measurement, based on the differential pressure across the DPF, unequivocally indicates that ozone is highly effective in regenerating the DPF by reducing the accumulation of soot. This is particularly evident when ozone is generated from pure oxygen at higher frequencies, such as 1,000 Hz, which yields higher concentrations of ozone. The mechanism underlying this effectiveness lies in ozone's inherent instability, which leads to its decomposition into highly reactive free oxygen atoms. These atoms possess a strong oxidizing capability, enabling them to react directly with the carbonaceous particulate matter and soot in the DPF, converting it into gaseous products, such as carbon monoxide or carbon dioxide. Crucially, this ozone-driven oxidation occurs at significantly lower temperatures, typically around 200-300°C, compared to the approximately 600°C required for conventional DPF self-regeneration. This low-temperature capability represents a substantial advantage, making ozone a promising low-energy solution for DPF regeneration, especially suitable for operating conditions where exhaust temperatures are typically insufficient for passive regeneration, such as in urban driving cycles.

## 4 Conclusion

The experimental investigation into the use of ozone for DPF regeneration has yielded several important conclusions regarding its efficacy and potential applications. The experiment, which measures the differential pressure across the DPF, indicates that ozone is highly effective in regenerating the DPF by reducing the accumulation of soot. This is particularly evident when ozone is generated from pure oxygen at higher frequencies, such as 1,000 Hz, which yields higher concentrations of ozone. This study confirmed that higher frequencies of the power supply to the NTP system at 250, 500, and 1,000 Hz directly result in increased ozone production, which in turn leads to improved DPF regeneration performance. This oxidation occurs at significantly lower temperatures, typically around 200-300°C, compared to the approximately 600°C required for conventional DPF self-regeneration. This low-temperature capability represents a substantial advantage, making ozone a promising low-energy solution for DPF regeneration, especially suitable for operating conditions where exhaust temperatures are typically insufficient for passive regeneration, such as in urban driving cycles.

The future work, including further optimization of the NTP reactor parameters, particularly focusing on energy efficiency for ozone generation from pure oxygen, could be explored. Investigations into the long-term effects of ozone regeneration on DPF material degradation and catalyst durability would also be beneficial. Additionally, exploring alternative methods for low-temperature soot oxidation that do not introduce additional system complexities or by-products could be considered. The findings from this research provide a strong foundation for developing more energy-efficient and environmentally sound diesel exhaust after-treatment technologies.

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