Effect of Oxyhydrogen Injection on Particulate Matter Characteristics in Ethanol-Fuelled Gasoline Direct Injection Engines

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Abstract. This research examines the influence of HHO gas, produced through electrolysis, on particulate matter emissions and combustion efficiency within a GDI engine under steady-state operational conditions. HHO, which consists of a composite of hydrogen and oxygen, was injected at varied concentrations (0.5%, 1%, and 2%) into the engine's intake system to optimize combustion attributes. The findings indicated that the incorporation of HHO resulted in a reduction of total particulate mass and a shift in the geometric mean diameter towards diminished values, thereby signifying enhanced combustion and decreased soot production. The categorisation of particles into nucleation and accumulation modes demonstrated a concentration-dependent behaviour, wherein lower concentrations of HHO facilitated the formation of ultrafine particles, while higher concentrations of HHO favoured oxidation processes and particle aggregation. The combustion efficiency, as determined from the concentrations of carbon monoxide and carbon dioxide, exhibited a significant increase with the addition of HHO, reaching a maximum of 96.24% at a concentration of 1% HHO. These results substantiate the hypothesis that HHO enrichment fosters cleaner combustion and presents a viable strategy for mitigating particulate matter emissions in GDI engines without necessitating substantial modifications.

1 Introduction

Particulate matter (PM) emissions originating from road transportation have emerged as a critical concern for both environmental integrity and public health, particularly in urban locales characterised by high population density and elevated vehicular activity. Fine ($PM_{2.5}$) and ultrafine particulate emissions are derived from both exhaust and non-exhaust mechanisms, with internal combustion engines (ICEs) being a predominant source due to the inefficiencies associated with fuel combustion and the generation of particulates related to lubricants. [1, 3] Ultrafine particles pose particularly severe health risks, as their diminutive size facilitates deep infiltration into the human respiratory tract, thereby increasing the likelihood of serious health complications such as cardiovascular and pulmonary disorders. [4] In light of accumulating scientific data that correlates PM exposure with detrimental health effects, regulatory bodies across the globe have instituted progressively stringent emission regulations. This trend has catalysed extensive research into methodologies for PM mitigation, encompassing advancements in fuel formulation, combustion chamber architecture, exhaust after-treatment technologies, and optimization of in-cylinder combustion processes, all intended to curtail emissions without compromising engine performance or operational efficiency.

Among the myriads of strategies aimed at emission reduction, hydrogen (H_2) supplementation has garnered significant scholarly interest due to its advantageous combustion properties. H_2 is characterised by a high laminar flame speed, extensive flammability limits, and the absence of carbon content, all of which facilitate more complete and efficient combustion processes. In Gasoline Direct Injection (GDI) engines, where stratified charge operation and fuel-rich zones frequently lead to localized incomplete combustion and soot generation, the incorporation of H_2 into the intake air has been demonstrated to diminish both PM mass and number concentrations. [5, 6] This phenomenon is attributed to the enhanced propagation of the flame and the improved oxidation of intermediate species, which collectively inhibit the genesis of soot precursors. A range of experimental investigations has substantiated that even

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minimal quantities of H_2, when accurately introduced, can result in substantial reductions in PM emissions without negatively impacting combustion stability or thermal efficiency.

H_2 produced through electrolysis presents additional benefits for automotive applications. Electrolysers facilitate the generation of H_2 and oxygen from water utilizing electrical energy, ideally sourced from renewable systems, thereby enabling the production of H_2 with zero carbon emissions at the point of generation.[7] The capacity to produce H_2 on-demand obviates the necessity for high-pressure storage or external refuelling infrastructure, rendering this methodology particularly appealing for decentralized, small-scale applications. Compact electrolyser units can be seamlessly integrated into vehicle architectures, allowing for real-time, continuous delivery of H_2 into the intake system. This capability enables dynamic regulation of the combustion process and offers a practical, sustainable avenue for the in-situ reduction of PM emissions.

Although gasoline direct injection (GDI) engines are progressively adopted in contemporary automotive design due to their enhanced thermal efficiency, meticulous fuel metering capabilities, and elevated power output, they are intrinsically susceptible to increased particulate matter (PM) emissions in comparison to port fuel injection (PFI) systems. This phenomenon can be attributed mainly to the direct injection of fuel into the combustion chamber, which may result in suboptimal fuel–air mixing, particularly during transient operational conditions and cold start scenarios. To address these challenges, scholars have investigated the utilization of hydrogen (H_2) to improve combustion quality and diminish particulate matter formation. The incorporation of H_2, especially in the form of HHO gas (a synthesis of H_2 and oxygen) produced through electrolysis and introduced into the intake air, has exhibited promise in fostering a more uniform mixture formation and accelerating flame propagation, consequently mitigating soot production at its inception. Notably, this approach does not require extensive alterations to existing hardware, which resonates with broader initiatives aimed at promoting clean combustion through minimally invasive technological advancements.

The principal objective of this research endeavour is to examine the impact of electrolyser-generated HHO gas on the particulate matter emission characteristics emanating from a GDI engine. The investigation specifically concentrates on the way HHO supplementation influences particle size distribution, numerical concentration, and mass emissions under steady-state operational circumstances. Considering H_2's capability to enhance oxidation processes and decrease soot precursor formation, this study seeks to ascertain whether the introduction of HHO gas derived from electrolytic processes can effectively mitigate the particulate matter formation mechanisms that are intrinsic to GDI combustion.

2 Experimental Setup

2.1 Engine Test

The experimental configuration encompassed a four-cylinder, 1.3-litre Gasoline Direct Injection (GDI) engine, with detailed specifications delineated in Table 1, integrated with an eddy-current dynamometer (Hofmann Prüftechnik D3210 Elze) to facilitate accurate manipulation of engine load under steady-state operational conditions. All experimental trials were conducted at stoichiometric air–fuel ratios ($\lambda = 1$). Prior to the commencement of data collection, the engine was equilibrated at a coolant temperature of 310 K (±4 K), while the ambient relative humidity was sustained within a range of 60% to 80%. Emissions alongside fuel consumption metrics were meticulously recorded across a spectrum of steady-state speed and load conditions.

Table 1. Specification of GDI engine

Item	Value	Unit
Model	Mazda SKYACTIV G1.3	
Number of cylinders	4	Cylinders
Bore	71	mm
Stroke	82	mm
Displacement Volume	1298	cm^3
Compression Ratio	14:1	
Maximum Power	$62_{@5,400\ rpm}$	kW
Maximum Torque	$112_{@4,000\ rpm}$	Nm
Fuel System	Direct Injection	
Engine Aspirate	Naturally Aspirated	

In this investigation, HHO gas was synthesized utilizing an OH-series electrolyser system, as delineated in Table 2, which facilitates the generation of a composite of H_2 and oxygen through the electrolysis of water.[11] To enhance the conductivity and overall efficacy of the electrolysis process, the electrolyte solution consisted of water amalgamated with 37.5% Sodium Hydroxide (NaOH) by volume. This specific concentration was chosen to optimize H_2 output under consistent operational parameters. The resultant gas mixture is presented in Table 3.

Table 2. Specification of Electrolyser

Item	Value	Unit
Electrolyser Model	H180	
Electrolyte Composition	NaOH solution in Water	
Power	600	Watt
Capacity	1	Litre

In the present investigation, the experimental parameters entailed the modulation of the intake of the Gasoline Direct Injection (GDI) engine with diverse concentrations of Hydrogen-Hydrogen-Oxygen (HHO) gas generated through the process of electrolysis. The HHO gas, which is composed of a blend of diatomic hydrogen (H_2) and diatomic oxygen, was introduced at three distinct volumetric levels: 0.5%, 1%, and 2% of the intake air, as delineated in Table 3. The gas mixture was characterised by a composition of 63.36% H_2 and 18.55% oxygen by volume, with the residual fraction consisting of water vapor and minor trace gases. These gas mixtures were uniformly applied across all varying conditions of HHO blending. The principal aim of modifying the HHO concentration was to assess its impact on combustion behaviour, the formation of particulate matter, and combustion efficiency during steady-state engine operation, while ensuring a stoichiometric air-fuel ratio was preserved throughout all experimental trials.

Table 3. Concentration of H_2 and O_2 mixture in HHO gas is contingent upon the specific conditions applied.

%HHO	%H_2	%O_2
0.5	63.36%	18.55
1		
2		

2.2 Apparatus

In the present investigation, the generation of H_2 from an oxy-H_2 generator was scrutinized through the application of the Hsense H_2 detection system, aimed at replicating the delivery of HHO gas to the intake manifold of a gasoline direct injection (GDI) engine. Considering that the flow rate of the electrolyser was inadequate to satisfy the engine's requirements under loaded operational conditions, the Hsense system was utilized to accurately quantify the volume of H_2 generated during the electrolysis process. Situated downstream of the electrolyser, the Hsense sensor facilitated real-time monitoring of H_2 concentration and flow rate, thereby enabling precise estimation of the HHO gas produced. These empirical measurements were subsequently employed to construct and simulate the regulated introduction of HHO upstream of the throttle valve, with the objective of enhancing mixture homogeneity while preserving stoichiometric combustion conditions.

Gaseous emissions emanating from the engine's tailpipe were quantified employing a HORIBA MEXA-584L automotive emissions analyser, distinguished for its exceptional precision in monitoring a comprehensive spectrum of exhaust gas constituents. The analyser provides measurement accuracies of ±0.3 %vol for carbon monoxide (CO) within the 0–10%vol range, ±0.4%vol for carbon dioxide (CO_2) within the 0–20 %vol range, ±10 ppm for hydrocarbons (HC) within the 0–10,000 ppm range, and ±25 ppm for nitric oxide (NO) within the 0–5000 ppm range. The system guarantees remarkable linearity and repeatability, thereby furnishing reliable and consistent data for the assessment of engine gaseous emissions across diverse testing conditions. Moreover, the concentrations of CO and CO_2 acquired from the MEXA-584L were employed to compute combustion efficiency as delineated in Equation 1, offering significant insights into the completeness of the combustion process and aiding the interpretation of particulate formation patterns observed during the experimental [13].

$$CE = \frac{[CO_2] + ([CO] \times 0.5)}{[CO_2] + [CO] + (n \times [HC])} \tag{1}$$

Within the combustion efficiency equation, each variable signifies a distinct exhaust gas component pertinent to carbon oxidation. $[CO_2]$ signifies the concentration of CO_2 present in the exhaust gas, articulated as a percentage by volume (vol%), which serves as an indicator of complete combustion. [CO] denotes the concentration of CO (also expressed in vol%), which arises from incomplete combustion and signifies partially oxidised carbon. The coefficient 0.5 corresponds to the oxidation level of CO, indicating that each CO molecule possesses only half the oxygen requisite for full conversion to CO_2. [HC] refers to the concentration of unburned hydrocarbons, initially quantified in parts per million (ppm) and subsequently converted to vol% by dividing by 10,000. This variable is contingent upon the number of carbon atoms within the hydrocarbon molecule based on the fuel type, typically 12 for gasoline (hexane), 3 for propane (LPG), and 1 for methane (CNG), thus quantifying the total unburned carbon content from hydrocarbons. Collectively, these variables facilitate the precise calculation of combustion efficiency through the evaluation of the extent of carbon oxidation within the exhaust stream.

In a concurrent manner, the characterization of particulate emissions was conducted utilizing a TSI Scanning Mobility Particle Sizer (SMPS), which quantified particle size distributions spanning from 7.50 to 294.3 nm, with a peak measurable concentration of 10^7 particles/cm³ attained through suitable dilution techniques.[14] Exhaust samples were channelled in a streamlined flow towards the SMPS for the purpose of real-time analysis, with the subsequent data processed employing Aerosol Instrument Manager software (version 10.3.1.0, TSI). Particle mass concentrations (µg/m³) along with size distributions were extracted for each experimental condition. The computation of particle mass was executed in accordance with the relationship articulated in Equation 2.

$$Particle\ Mass = \frac{\pi}{6} \times D_p \times N_p \times \rho_p \tag{2}$$

where denotes the particle diameter (nm), represents the number concentration (#/cm³), and indicates the particle density, which was presupposed to be 1.2×10^{-9} g/cm³. This methodology furnishes a robust assessment of particulate matter emitted from the exhaust system.

3 Result

3.1 Particle Size Distribution

The distribution of particle numbers (dN/dlogDp) ascertained under various HHO blending scenarios while maintaining a constant engine load and speed shown in fig. 1a. The baseline scenario (absence of HHO) displayed a preeminent particle mode in the range of 140–160 nm, with the particle number concentration consistently remaining beneath 1.0×10^6 #/cm³. The introduction of HHO resulted in notable alterations in particle number concentration. Specifically, at 0.5% and 1% HHO, the number concentration exhibited a modest increase yet migrated toward diminished particle sizes (~80–100 nm), signifying an enhancement in nucleation processes. Remarkably, the condition with 2% HHO manifested a pronounced peak at approximately 60 nm, with the number concentration surging to exceed 3.5×10^6 #/cm³. This significant escalation in the concentration of nucleation-mode particles implies that elevated HHO concentrations facilitate accelerated combustion and elevated flame temperatures, thereby promoting the generation of smaller particles, notwithstanding an overall improvement in combustion cleanliness. Figure 1b illustrates the distribution of particle mass, which exhibited an inverse relationship to the findings pertaining to particle number. The baseline condition displayed a prominent mass peak exceeding 700 µg/cm³ at approximately 160 nm, which is indicative of the accumulation mode. The incorporation of HHO gas at all concentrations resulted in a significant reduction in the overall particle mass, with the 2% HHO scenario demonstrating the most pronounced decrease. This finding suggests that while elevated concentrations of HHO may augment the quantity of nucleation-mode particles, they contribute minimally to the overall particulate mass owing to their reduced dimensions.

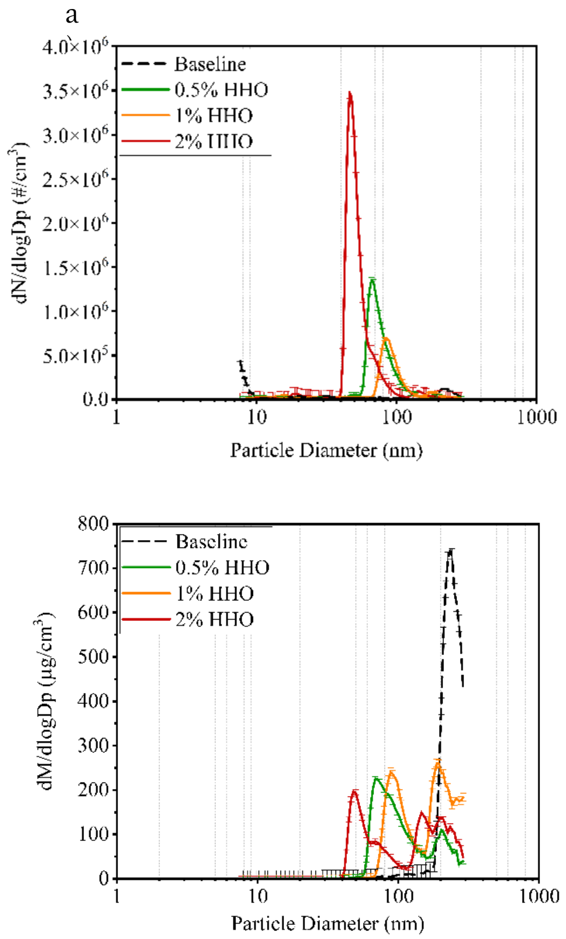

Fig. 1. An analysis of the distribution of a) particle Number and b) particle mass across each experimental condition.

In support of this observation, Figure 2 delineates the geometric mean diameter of the particles, which experienced a significant decline with HHO augmentation from 150.6 nm (baseline) to 81.5 nm (0.5% HHO), 103.5 nm (1% HHO), and 59.7 nm (2% HHO). This gradual transition towards smaller particle sizes underscores the impact of HHO on modifying combustion characteristics, culminating in enhanced fuel oxidation and diminished soot formation.

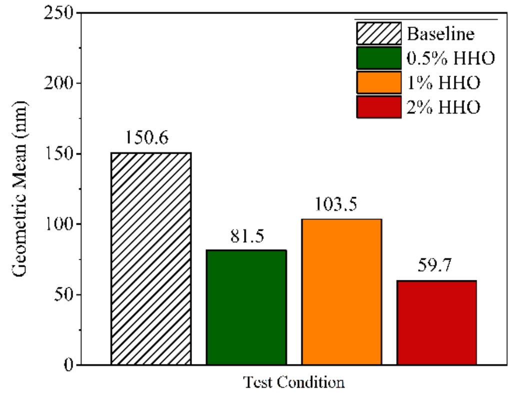

Fig. 2. Geometric Mean of Particle Diameter.

The categorisation of particles into nucleation mode (Dp ≤ 50 nm) and accumulation mode (Dp > 50 nm) elucidates the influence of HHO gas on particulate generation. As illustrated in Figure 3a, the concentration of particles within the accumulation mode exhibited a pronounced increase after the incorporation of HHO. The baseline condition recorded a total concentration of 1.56 $\times 10^6$ #/cm³. Following the introduction of 1% HHO and 0.5% HHO, the accumulation mode particles escalated significantly to 1.38×10^7 and 1.37×10^7 #/cm³, respectively. Notably, the condition with 2% HHO produced a moderate accumulation concentration of 7.53×10^6 #/cm³, which, although inferior to the concentrations observed with 1% and 0.5% HHO, still indicates a considerable enhancement relative to the baseline. This alteration may suggest particle enlargement through agglomeration or a modification in combustion dynamics that favours the formation of larger soot particles under these specific conditions.

Conversely, the particle behaviour in nucleation mode, depicted in Figure 3b, exhibited a distinct pattern. The baseline particle count within the nucleation mode was determined to be 2.58×10^6 #/cm³. The supplementation with HHO revealed a pronounced dependence on the blending ratio. The condition with 0.5% HHO resulted in a substantial increase in nucleation particles, reaching 1.63×10^7 #/cm³, indicative of vigorous ultrafine particle formation. In contrast, both the 1% and 2% HHO conditions led to a decrease in nucleation particle concentrations to 5.76×10^5 and 1.03×10^6 #/cm³, respectively. These findings imply that lower concentrations of HHO may facilitate nucleation through heightened combustion temperatures and the formation of reactive radicals, whereas higher concentrations may promote soot oxidation and particle coagulation, thereby diminishing the numbers of ultrafine particles. This classification accentuates the dual role of HHO in influencing both particle size modes contingent upon its dosage.

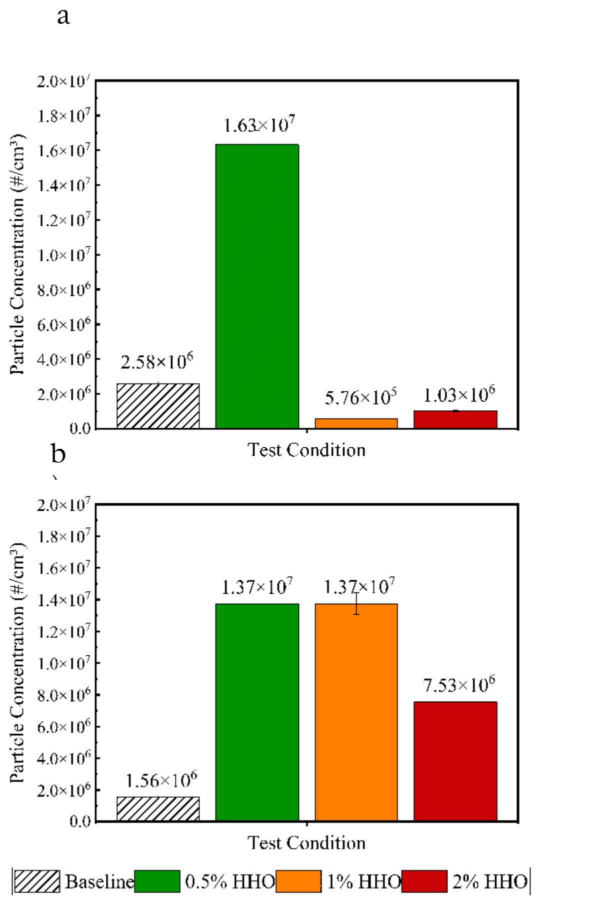

Fig. 3. Total particle number concentration for a) Nucleation Mode and b) Accumulation mode

3.2 Combustion Efficiency

The combustion efficiency outcomes, derived from the analysis of CO and CO_2 concentrations, furnish compelling corroborative evidence for the alterations observed in particle characteristics as measured by the SMPS. As illustrated in Figure 6, the baseline condition manifested a combustion efficiency of 88.35%, which reflects significant incomplete combustion, correlating with an increased particle mass and geometric mean diameter noted in the accumulation mode. The incorporation of HHO resulted in a notable enhancement in combustion efficiency, achieving a pinnacle of 96.24% at a concentration of 1% HHO, indicative of more thorough oxidation of carbonaceous materials and a concomitant reduction in CO emissions. This augmented efficiency is consistent with the pronounced decrease in particle mass and the transition towards smaller particle dimensions (as substantiated by the observed reduction in geometric mean diameter), thereby validating the hypothesis that HHO facilitates cleaner combustion processes. Even at a concentration of 2% HHO, notwithstanding a slight decline to 95.81% efficiency, the prevailing trend of diminished particle mass and diameter persisted, implying that the enhancement of combustion quality is instrumental in mitigating soot formation and reorganizing particle size distribution.

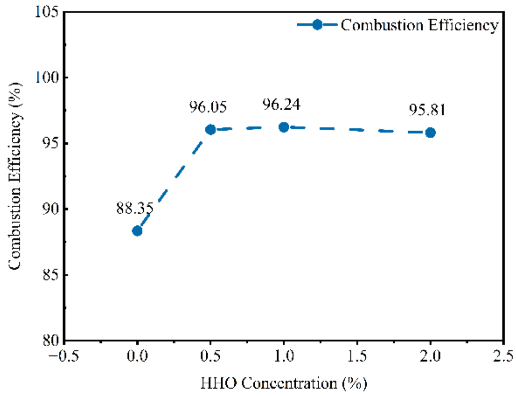

Fig. 4. The combustion efficiency associated with varying concentrations of HHO (hydrogen and oxygen)

4 Conclusion

This comprehensive investigation elucidated that the incorporation of HHO gas, which is generated through an on-demand electrolysis process, into a GDI engine system can profoundly affect both the emissions of particulate matter and the overall efficiency of combustion processes. The introduction of HHO into the combustion chamber was associated with a significant reduction in the mass of particulate emissions, alongside an observable transition towards smaller geometric mean diameters of these particles, which serves as a compelling indicator of more complete combustion processes and a concomitant suppression of soot formation in the exhaust. A meticulous classification of the emitted particles into distinct nucleation and accumulation modes has revealed that lower concentrations of HHO tend to promote the formation of ultrafine particulate matter, whereas elevated concentrations tend to enhance the oxidation of soot and facilitate the agglomeration of particles, leading to a more efficient combustion environment. Simultaneously, the combustion efficiency, which was quantitatively assessed through the analysis of CO and CO_2 concentrations in the exhaust, exhibited a remarkable improvement, achieving a peak efficiency of 96.24% when 1% HHO was supplemented, thereby providing substantial corroboration for the findings derived from the SMPS measurements. These insightful findings serve to affirm the considerable potential that HHO supplementation holds as a practical and minimally invasive methodology aimed at reducing particulate emissions while concurrently enhancing the quality of combustion in contemporary GDI engine technologies.

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