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# Effects of HHO Particulate Morphology from Diesel Engine Fueled with Bio-Diesel

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**Keywords**： bio-diesel, HHO, particles, morphological characteristics, fractal dimension.

## ABSTRACT

To provide a theoretical basis for reducing particulate pollutants from diesel engines fueled with bio-diesel, this paper examines the topographical characteristics of biodiesel combustion particulates, focusing on HHO (brown gas). A 186F trial diesel engine is run at the calibration conditions, and a particle size sampling device is used to collect particulate pollutants when the diesel engine burns biodiesel and conducts co-combustion of biodiesel and HHO. Scanning electron microscopy and transmission electron microscopy are applied to analyze the influence of co-combustion with HHO on the particle morphology and the equivalent area diameter, to examine the change law of the microstructures, such as the spacing of the particles and the crystallite size, with HHO co-combustion and to analyze the functional mechanism of HHO in the generation of particulates. The results show that when the diesel engine is fueled with biodiesel, the surface morphology of the particles is predominantly distributed in lumps, chains and branches, and so on; upon the blending combustion of HHO, the cluster structure is reduced, and the particulates are mostly in a linear and branched distribution. The soluble organic matter on the particle surface is reduced, and the number of particles per unit area is reduced. Co-combustion with HHO can decrease the average equivalent area diameter of the particles by approximately 71.1%, moving the particle diameter in the direction of a small particle size. The increased area of the microcrystalline carbon layer widens the basal advantageous for the process of particle oxidation, and the reduced microcrystalline dimension of the particles increases the curvature and weakens the ordering of the microcrystalline structure on the surface. When biodiesel is blended with HHO, the hydroxyl can accelerate the oxidation of soluble organic matter on the particle surface as well as of the carbon component, reducing the fractal dimension of the particles by 0.04, indicating that the combustion of an HHO blend can reduce the structural tightness of particles. HHO affects the topographical characteristics of biodiesel combustion particles and can effectively reduce the particulate contaminants of bio-diesel.

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## INTRODUCTION

The range of raw material sources for biodiesel is wide and rich, including oils from fruits, seeds, and animal fat or waste cooking oil, among other materials. These oxygen-containing molecules have high cetane value, no arene, very low sulfur content, and advantages such as innocuity, high biodegradability and renewability. The production and use of biodiesel do not produce a net accumulation of $CO_2$ in the atmosphere, helping to reduce the greenhouse effect and to maintain a virtuous ecological cycle. Thus, biodiesel is a true green fuel and has been widely used in many countries in recent years(Rakopoulos et al., 2015; Shekar and Purushothama, 2015; Rakopoulos, 2013; Xu et al., 2015).

Particulates discharged by diesel engines have become a major source of atmospheric haze. With increasingly stringent emission regulations, reducing the particulate emissions of diesel engines has become a major topic for researchers both at home and abroad. The combustion of gas blends containing both hydrogen and oxygen elements in a diesel engine helps to broaden the ignition limit, promote diffusion combustion, improve the combustion process, improve the combustion efficiency, reduce the formation of carbon nuclei and significantly reduce the particulate emissions of diesel engines(Qu et al., 2016).

HHO (brown gas) is a combination gas with a hydrogen-oxygen ratio of 2:1 and is mainly obtained through the electrolysis of electrolytic alkaline solutions. The electrolytic formation of HHO involves a certain amount of active substances, such as oxygen radicals (•O) and hydroxyl radicals (•OH), among others(Eckman, 2010; Baltacioglu et al., 2016; Durairaja et al., 2012; Santilli, 2006; Masjuki et al., 2016; Yilmaz et al., 2010; Park et al., 2011; Ramanjaneyulu and Rajakumar, 2015). When a diesel engine is fueled with an HHO blend, active radicals act as active intermediate vectors, participating in decomposition and oxidation processes to burn intermediate products such as $H_2O_2$ and $CH_2O$. When burned with biodiesel in diesel engines, HHO can promote combustion, promoting the oxidation of HC, CO and unburned particulate emissions (Ramanjaneyulu and Rajakumar, 2015). Scholars both at home and abroad have conducted many studies on the applications of HHO in diesel engines. The efficiency of a diesel engine was effectively improved by premixing diesel and HHO in the work of Bari and Esmaeil (Bari and Esmaeil, 2010). Birtas et al. (2011) showed that the emissions of CO and $CO_2$ can be effectively reduced and the PM intensity reduced by up to approximately 30 percent by using premixed HHO in a diesel engine. The intake premixing of HHO improved the cylinder combustion process of a diesel engine and accelerated the oxidation of cylinder particles in the work of Zhang (2014). The current literature shows that the work of researchers both at home and abroad is mainly focused on the influence of HHO on pollutant emissions in burning diesel oil, while there are fewer studies on the impact of burning biodiesel. Therefore, it is necessary to research the impact of HHO on the topographical characteristics of biodiesel particulates in diesel engine fuel.

To examine the influence of blending HHO with biodiesel on particle morphology and structure, a particle classification sampling device is employed to collect exhaust particles from a diesel engine, and scanning electron microscopy and transmission electron microscopy, combined with digital micrograph software, are used to analyze the characteristic parameters of particle morphology, equivalent area diameter of basic carbon particles, basal spacing, crystallite dimensions and so on, seeking to provide related basic data for reducing the particulate emissions of biodiesel.

## IMPACT OF HHO ON COMBUSTION

HHO is colorless and tasteless. The work of the Dublin Adsorption Laboratory showed that HHO is mainly made up of $H_2$ and $O_2$, with $H_2$ accounting for 60.79%, $O_2$ accounting for 30.39%, and a small amount of water vapor, O, OH and some other active substances accounting for the rest. The molar mass of HHO is 12.3 g/mol (Yilmaz et al., 2010). The energy stored in 1 L HHO is approximately 600 J (±34 J). HHO is unstable, and its life cycle is approximately 11 minutes (Li et al., 2015). After the active substance of HHO disappears, the rest is a combination of common $H_2$ and $O_2$, in a volumetric proportion of 2:1.

According to Eckman (2010), the common water molecule includes 2 hydrogen atoms and 1 oxygen atom. The hydrogen atom and oxygen atom connect to each other by bonding electrons, and meanwhile the molecule interacts with another two electron pairs, forming a tetrahedral structure in space, as shown below (Figure. 1). A Rydberg cluster can be formed by electrolyzing water. Its main ingredients are $H_2$ and $O_2$, and it also includes linear water molecules in a high-energy state with a trigonal bipyramidal shape, hydrogen atoms, free electrons, and several types of free radicals. As free radical research continues, the finding that OH can be generated by electrolyzing water also verifies that HHO includes a small quantity of free radicals (Lecour and Abdellah, 1998; Mccord, 1985).

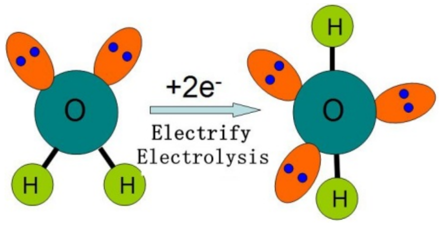



Fig. 1. A water molecule acquiring two electrons and becoming a linear water molecule.

OH is a type of nonselective oxide, and its oxidability is lower only than $F_2$. Of all reactive oxygen free radicals, OH is regarded as the one with the strongest activity, playing the main role (Birtas et al., 2011). It can easily oxidize almost all organic and inorganic pollutants with high oxidation efficiency and reaction speed. Although its life circle is short, its reaction is so powerful that the action radius is approximately 5-10 times the molecular diameter, even exerting great influence on adjacent molecules (White et al., 2005).

Introducing HHO into a diesel engine and kindling it causes an implosion effect, forming a vacuum and negative pressure with a ratio of 1860:1, thus improving the disturbance inside the diesel engine cylinder (Zhang et al., 2015). The HHO combustion process promotes the mixing of fuel and air and ignites nearby combustible mixtures, increasing the number of in-cylinder ignition points and leading to more complete fuel combustion. The trace amounts of OH free radical included in HHO have strong oxidizing properties, so that during the combustion process, HHO active radicals transfer oxygen into the fuel hydrocarbons and other substances, promoting the reaction of the C-H chains and increasing the quantity of OH free radical inside the cylinder. This catalytic effect accelerates the combustion process of hydroxyl (• OH), which can easily react with the soot precursor $C_2H_2$, which can inhibit the formation of soot but also promotes the oxidation of the particles, which has a greater effect on the particle morphology (Liu et al., 2016).

## TEST DEVICE AND PROCEDURE

The test system shown in Figure 2 includes a dynamometer control system, HHO gas generator, diesel engine, MOUDI particle classification sampling device and dynamometer. A single-cylinder test diesel engine is employed in the test, with a rated speed of 3600r/min, rated power of 6.3kW and cylinder bore of 86mm. The flywheel end-connected dynamometer is operated by the diesel engine dynamometer control system. The main parameter of 186F diesel engine are shown in Table 1.

Table 1. The main parameter of 186F diesel engine.

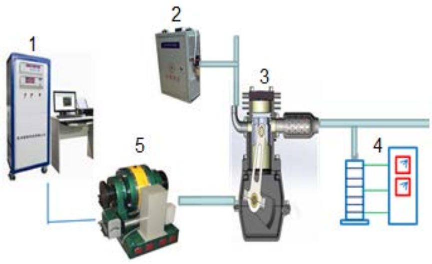
| Name | Parameter |
|---|---|
| Bore × stroke /mm×mm | 86×70 |
| Compression ratio | 19 |
| Rated power/kW | 5.7 |
| Rated speed/r·min$^{-1}$ | 3000 |

The HHO generator consists mainly of the electrolyzer, inert electrode and vapor filter element. The generation is provided by the core component of the cell electrode material, resulting in a greater impact on energy consumption during electrolysis. The working voltage is 12V, and the cathodic enrichment of H+ separates the hydrogen out when electrified. The anodic enrichment of OH- separates the oxygen out, and plate reaction area is changed by adjusting the immersion depth of the plate into the electrolyte to control the gas generation rate. $H_2O$ is very weak electrolyte. To improve the conductivity of the electrolyte, a strong electrolyte was added during the test in the form of 4% NaOH solution. The HHO gas generation process has maximum gas production of 8L/min, with the ongoing reaction maintained by continuously adding distilled water to the electrolyzer. The Physical-chemical properties of biodiesel are shown in Table 2.

Table 2. Physical-chemical properties of biodiesel.

| Parameters | Biodiesel |
|---|---|
| Chemical formula | $C_{18.64}H_{34.72}O_2$ |
| Cetane number | 50.0 |
| Oxygen content (wt %) | 11 |
| Carbon content (wt %) | 77 |
| Density (g·cm$^{-3}$ at 20℃)[a] | 0.88 |
| Kinetic viscosity (mm$^2$·s$^{-1}$ at 40℃) [a] | 4~6 |

Given the short survival time of free radicals in HHO, the reactivity of the blended HHO is maintained by using a blend premixed at the inlet. The blend ratio is controlled by a mass flow meter control valve, which adjusts the HHO supply. Depending on the external operation and load characteristics, the diesel exhaust gas generation is analyzed by measuring the combustion of NOx and PM using cylinder pressure sensors and a combustion analyzer, respectively.




1.Dynamometer control system; 2.HHO gas generator; 3.Diesel engine; 4.MOUDI particle classification sampling device; 5.Dynamometer
Fig. 2. Schematic diagram of test device.

The United States MPS micro-orifice uniform deposition impactor equipment includes vacuum pumps, flow meters, and a particulate collector. With three parts, it can achieve 8 fractioning samples. The impact parameter values are shown in Table 3.

Table 3. Particle size, nozzle number and average diameter of MOUDI

| Progression | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Nozzle diameter/mm | 17.10 | 8.89 | 3.80 | 2.47 | 1.37 | 0.72 | 0.41 | 0.13 | 0.10 |
| The average particle size/μm | ＞18 | 14 | 7.8 | 4.4 | 2.5 | 1.4 | 0.78 | 0.44 | 0.25 |

The MOUDI is connected to an exhaust pipe and used to collect particles before and after combustion of the HHO blend under the calibration conditions. The HHO has an intake gas flow rate of 1.9L/min, accounting for 0.25% of the total amount of intake gas. Under the effect of the vacuum pump, diluted engine exhaust enters the impactor at a constant volume flow of 30L/min; the sampling time is 20min; and the sampling filter paper is Φ = 47nm aluminum foil filter paper from the MPS company. To eliminate uncertainty during the test, multiple samples of the same operating conditions were collected and analyzed.

A Japan Seiko JSM-7001F Scanning Electron Microscope and JEM-2100 Transmission Electron Microscope are employed to image the particle morphology and structure of the particle sample before and after the HHO blend combustion. The Scanning Electron Microscope has a resolution of 1.2nm/3.0nm, a minimum resolution of 1nm and magnification of 10 to 800,000 fold. The Transmission Electron Microscope has magnification of 2000 to 1,500,000, a point resolution of 0.23nm and lattice resolution of 0.14nm. When observing, 20visual fields are arbitrarily selected to obtain a variety of particle projection images.

## TEST RESULTS AND ANALYSIS

To examine morphology and structure of exhaust particles of biodiesel fuel for diesel engines, researchers both at home and abroad have conducted numerous studies on morphological and structure parameters such as particle size, equivalent area diameter, basal spacing, fractal dimension, crystallite size and curvature (Lu et al., 2012), mainly using optical diagnostic techniques such as scanning/ transmission electron microscopy and atomic force microscopy (Ma et al., 2012; Zhang et al., 2010) as well as in-situ spectroscopic techniques such as infrared spectroscopy and small-angle scattering (Reff et al., 2005; Li et al., 2014). Using the Digital Micrograph software, the image is normalized according to uniform standards. The foreground and background regions of the image are segmented to obtain characteristic parameters of the particulate microstructure based on changes in the contrast of the gray image texture.

### Combustion process

Figure 3 shows the influence of HHO on the engine cylinder pressure and instantaneous heat release rate.

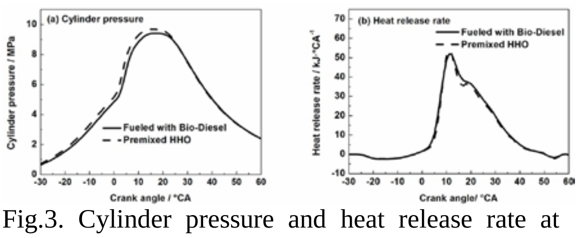



Fig.3. Cylinder pressure and heat release rate at rated condition.

As shown, the maximum explosion pressure of a cylinder in this diesel engine fueled with biodiesel is 9.41MPa, corresponding to a crank angle of 17°CA. Upon introducing the HHO blend, the HHO accelerates the burning rate of the combustible gas mixture in the cylinder, resulting in more thorough combustion of the mixed gas. The maximum cylinder pressure rises by 0.28MPa, ahead of the corresponding crank angle of 1°CA. For a crank angle of -5°CA, the engine begins to heat in the range of -5~8°CA. The introduction of blended HHO decreases the instantaneous heat release rate, indicating that the ignition delay stage prior to HHO combustion needs to absorb heat; within the range of 8~12°CA, blended HHO improves the instantaneous heat release rate of the engine, indicating an implosion effect as HHO promotes the mixing of biodiesel with air. The number of mixture ignition points in the cylinder increases, accelerating the diffusion combustion. For crank angles above 12°CA, introducing the HHO blend rapidly increases the diffusion rate of combustion of the combustible mixture, causing an instantaneous post-combustion heat release rate.

### NOx and PM

Figure 4 shows the variation of NOx and PM with the load and speed before and after adding HHO to a diesel engine fueled with biodiesel. As shown, when the load is small, the excess air ratio in the larger cylinder means that HHO's role in promoting combustion has little effect on NOx emissions; when the load is greater than 50%, the excess air ratio in the cylinder is reduced, and HHO promotes more complete biodiesel combustion. The in-cylinder combustion temperature and reduction of NOx emissions are more prominent. Under 100% load conditions, with increasing engine speed, the promotion of the combustion process by HHO shows a waning influence on decreased NOx emissions.

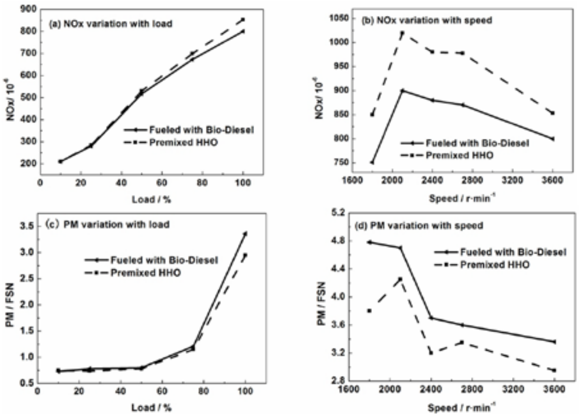



Fig. 4. The variation of NOx and PM with the load and speed.

When the engine load is small, due to the smaller amount of circulating oil, the impact of HHO on PM is not obvious. As the load increases, the HHO blend produces a stronger decline in PM. When the engine reaches 100% load, the HHO hydroxy (•OH; the highest reactive hydroxyl concentration occurs when the engine speed is 1800r/min) promotes the combustion reaction, and the higher in-cylinder combustion temperatures promote the oxidation of carbon particles. The most obvious role of HHO is to reduce PM oxidation inhibition and the generation of soot. Based on the comparison of PM test results obtained by the particle morphology analysis program, HHO is shown to affect a variety of calibration conditions.

**PM Appearance**

Several sets of scanning electron microscope images from collected particle test samples are selected for representative group analysis. Figure 5 shows the morphology and structure of particles from a diesel engine fueled with diesel and biodiesel, as well as after the combustion of an HHO blend. It can be observed that the particles are approximately spherical, and through collision and coagulation processes, the particles interact to form distribution patterns of flocculence, bulk and chains. Compared with diesel fuel, the diesel engine fueled with bio-diesel and bio-diesel containing O atoms promotes combustion, resulting in a smaller particle size. The biodiesel particle surface adsorption force is large, resulting in an increase in the number of particles. Compared with biodiesel particles, after the combustion of an HHO blend, fewer particles are in bulk and flocculence forms, instead being mainly distributed in chain and branch forms. Meshing is conducted by examining the combined scanning electron microscopy images of each sample to obtain the number of particles per square centimeter using the measurement capabilities in the Digital Micrograph software. The number of particles obtained is the average of 20 fields of view for each sample. The calculations show that before and after the combustion of the HHO blend, the number of particles per unit area is 16.9 and 13.2, respectively. Compared with biodiesel, the number of particles from HHO blend combustion is decreased by approximately 21.9%.

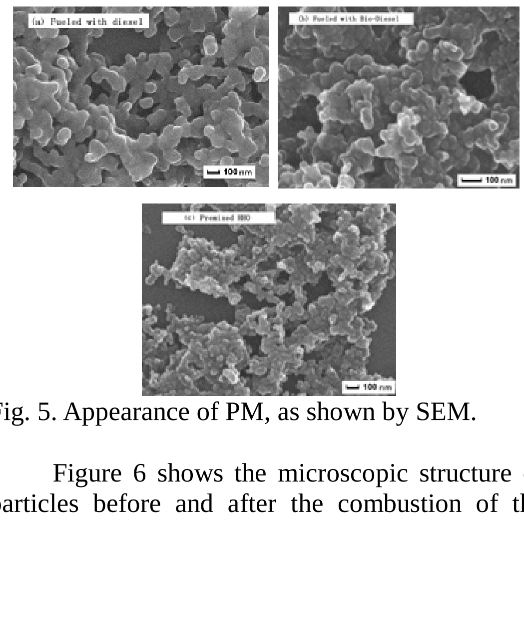



Fig. 5. Appearance of PM, as shown by SEM.

Figure 6 shows the microscopic structure of particles before and after the combustion of the HHO blend. It can be observed that under the action of liquid and solid bridges between the particles, the particle granules (i.e., secondary particles) are produced by mutual bonding and aggregation of the elementary particles at different sizes to form micelles with a fractal structure, showing different density levels at the junction. The darker area results from the superposition of a plurality of elementary particles, further amplified by particle agglomerates. The basic carbon particles consist of the core and the shell, and the carbon layer structure of the shell is strongly similar to the microcrystalline structure of multilayer graphite with high stability. Closer to the core is, the torsion and translation phenomena between carbon layers become more obvious, showing highly disordered topography. Compared with the biodiesel particles, the combustion of the HHO blend decreases the stacking of basic carbon particles, increases the gaps between basic carbon particles, and produces a looser aggregate structure. This change is mainly because in the combustion of HHO, on one hand, the active radicals such as OH promote the oxidation of soluble organic matter on the particle surface, reducing the stickiness of the particle surface and the probability of particle collision agglomeration; on the other hand, OH active radicals have the lowest reaction activation energy with particle precursors (benzene) and a fast reaction speed, thus suppressing particle nucleation and reducing particle generation.

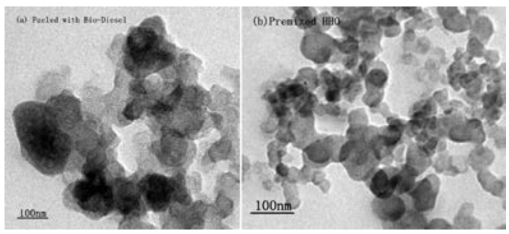



Fig. 6. Appearance of PM before and after the introduction of HHO, as observed by TEM.

**Average Equivalent Area Diameter**

To quantify the variation in particulate size before and after the combustion of the HHO blend, the average equivalent area diameter of the particles (the equivalent area diameter is the spherical particle diameter of the same material with the same projected area with the measured particles) is analyzed by image statistical methods. Figure 7 shows the distribution of the equivalent area diameter for particle samples before and after the combustion of the HHO blend. The equivalent area diameter of the bio-diesel particles is approximately normally distributed, mainly in the range of 150~500 nm, with an average equivalent area diameter of approximately 278.6nm. After HHO blend combustion, the equivalent area diameter of the particles ranges from 50~140 nm and 50~100nm, and the number of particles is larger; the average equivalent area diameter is 80.6nm. The HHO blend combustion moves the equivalent area size distribution of the particle samples in the direction of smaller particle size, decreasing the average equivalent area diameter by approximately 71.1%. Preliminary studies suggest that this change occurs mainly because the active radicals in HHO promote the oxidation of dissolved organic matter on the particle surface, decreasing the viscosity at the particle surface and reducing the probability of particle collision and agglomeration.

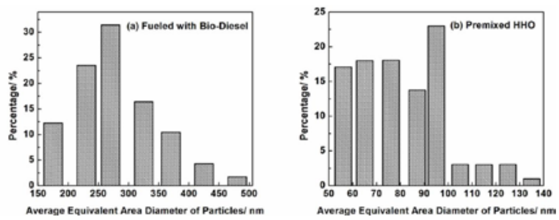



Fig. 7. PM equivalent diameter area before and after HHO blend combustion.

### Fringe Separation Distance

Basal spacing is the distance between two adjacent carbon layers in basic carbon particles. Figure 8 shows the distribution of the basal spacing of particles before and after the combustion of the HHO blending. The basal spacing of the basic carbon particles of biodiesel is mainly distributed in the range of 0.30~0.43 nm, and after the introduction of HHO, the basal spacing of the basic carbon particles is substantially increased, mainly in the range of 0.33~0.43 nm. The basal spacing of the basic carbon particles reflects the oxidation activity of basic carbon particle generation by Levy and Wong (1964). The smaller the basal spacing is, the smaller the contact area where the microcrystalline carbon layer reacts with oxygen will be. The difficulty of oxidation is increased, and the oxidation activity is decreased. After the combustion of the HHO blend in the diesel engine, the area of the particle microcrystalline carbon layer is increased, which is conducive to particle oxidation.

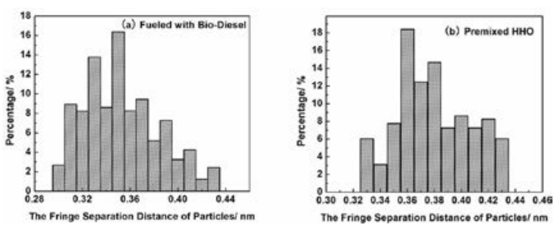



Fig. 8. Fringe separation distance of PM particles before and after HHO blend combustion.

### Average Fringe Length and Fringe Tortuosity

Crystallite size and curvature are important parameters in the physical composition and microstructure of the basic carbon particles. The transmission electron microscope images reflect the carbon layer structure with a certain length and curvature (Wang, 2012). Figures 9 and 10 show the distribution of the particle crystallite size and curvature before and after the combustion of the HHO blend. The particle crystallite size is mostly approximately 2nm, and the average crystallite size of the bio-diesel particulate is approximately 2.105 nm; the crystallite size of the particles from the HHO blend is reduced to approximately 1.912nm, a reduction of approximately 9.2%. The distribution of the curvature is the opposite of the distribution of crystallite size. Figure 8 shows that the average curvature of the bio-diesel particles is approximately 1.28 nm, while the curvature of the HHO blend particles is smaller, approximately 1.44 nm.

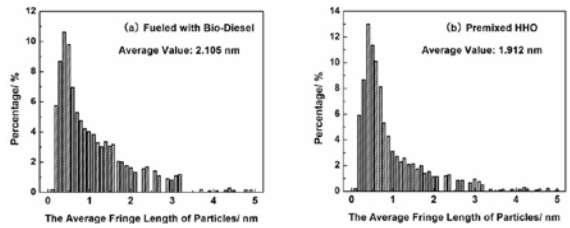



Fig. 9. Average fringe length of PM particles before and after HHO blend combustion.

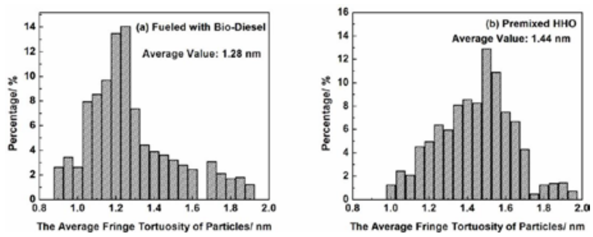



Fig. 10. Average fringe tortuosity of PM particles before and after combustion of HHO blend.

The longer the persistent febrile period of the cylinder flame is, the more orderly internal organizational structure of the bio-diesel particles tends to be, as determined by Wal and Tomasek (2012); the stronger the ordering of the microcrystalline structure, the higher the graphitization extent of the particles will be, leading to lower susceptibility to the oxidation activity. Compared with pure biodiesel, the combustion of an HHO blend has implosion and catalytic combustion effects that accelerate the cylinder combustion and shorten the persistent febrile period, lowering the electron resonance stability of the five ring structure. These effects lead to bending of the carbon layer, which increases the tension at the bending C-C bonds and weakens the bond energy. The HHO blend weakens the orderliness of the particle crystalline structure, reducing the degree of graphitization.

**Fractal Dimension**

Fractal dimension is an important parameter describing the degree of irregularity of objects. The Irregular combustion particles in chains, lumps and branches have typical characteristics of fractal structure, as described by Gulijk et al. (2004). The greater the fractal dimension is, the more compact the particle structure will be; the smaller the fractal dimension is, the looser the particle structure.

The scatter fitting of the lgN-lg($R_g/r_g$) values of the particles is plotted before and after the introduction of an HHO blend for combustion, as shown in Figure 11. The slope of the fitting curve is the fractal dimension of the particles, and the fractal dimension of the particles before and after the combustion of the HHO blend is 0.95 and 0.91, respectively. Compared with pure biodiesel, the overall particle structure after HHO blend combustion is loose, mainly because the hydroxyl in HHO accelerates the oxidation of soluble organic matter on the particle surface and of carbonaceous components. On the one hand, this process reduces the probability of particle collision and agglomeration, increasing the geometric mean distance between particles and reducing the tightness of the particle structure; on the other hand, it causes incomplete growth of the particle surfaces, resulting in increased particle surface defects and pores with non-uniform size and number, making the structure of the individual particles looser. The combustion of an HHO-biodiesel blend has the positive effect of reducing the number of particles.

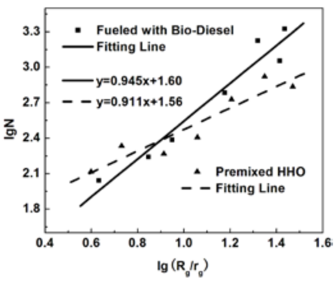



Fig. 11. Scatter fitting diagrams for lgN-lg(Rg/rg) of PM particles before and after HHO blend combustion.

## CONCLUSIONS

This paper focuses on the impact of HHO on the morphology and structure of biodiesel particles in diesel engine fuel, analyzing the morphology of particles collected by a classification sampling unit by scanning electron microscopy and transmission electron microscopy, using the Digital Micrograph software. This paper explores the influence of HHO on characteristic parameters such as the equivalent area diameter of basic carbon particles, basal spacing and crystallite dimensions and the variation of fractal dimension, seeking to provide relevant basic data to reduce biodiesel particulate emissions. The conclusions are as follows:

When the engine is running under low load conditions, the influence of HHO on NOx and PM HHO is smaller. As the load increases, the influence gradually increases. For an engine at 100% load conditions, the impact of HHO on NOx and PM is gradually weakened with increasing speed.

When a diesel engine is fueled with biodiesel, the surface morphology distribution of the particles consists predominantly of lump, chain and branched structures, among other structures. The combustion of an HHO blend reduces the lumps, leaving the particles mostly distributed in chains and branches, and the number of particles per unit area is reduced.

When a biodiesel-fueled diesel engine operates under the described working conditions, the average equivalent area diameter of the particles is significantly reduced upon combustion of an HHO blend, and the particle size is decreased.

HHO can increase the basal spacing of basic carbon particles, subsequently increasing the area of the microcrystalline carbon layer, which is conducive to the particle oxidation process; the crystallite size of the particles is reduced, while the curvature is increased and the orderliness of the crystalline structure on the surface is weakened.

Upon combustion of an HHO blend with biodiesel, hydroxyl accelerates the oxidation of the soluble organic matter on the particle surface and of the carbonaceous components, reducing the fractal dimension of the particles by 0.04, which indicates that the combustion of an HHO blend can reduce the tightness of the particle structure.

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# 布朗氣對柴油機燃用生物柴油顆粒形貌特徵的影響研究

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## 摘 要

為了為降低柴油機燃用生物柴油的顆粒污染物提供理論依據，論文圍繞 HHO（布朗氣）對生物柴油燃燒顆粒的形貌特徵進行了研究。針對一臺 186F 試驗柴油機，柴油機在標定工況運行，採用顆粒分級採樣裝置，採集柴油機燃燒生物柴油和生物柴油摻燒 HHO 的顆粒污染物。分別使用掃描電鏡和透射電鏡分析摻燒 HHO 對顆粒形貌和等效面積徑的影響規律，研究顆粒的層面間距和微晶尺寸等微觀結構隨 HHO 摻燒的變化規律，分析 HHO 對顆粒物生成的作用機理。結果表明，柴油機燃用生物柴油時，顆粒物的表面形貌主要呈團狀、鏈狀和枝狀等狀態分佈，摻燒 HHO 後，團狀結構減少，顆粒物多呈鏈狀和枝狀分佈，顆粒表面的可溶性有機物減少，組織面積內的顆粒數量減少；摻燒 HHO 可以使顆粒的平均等效面積徑降低約 71.1%，顆粒粒徑向小粒徑方向移動；微晶碳層的面積增大，使得基本碳粒子層面間距有所增加，對顆粒氧化過程的進行有利；顆粒的微晶尺寸減小，彎曲度增大，錶面微晶結構的有序性減弱；生物柴油摻燒 HHO 後，羥基加速了對顆粒表面可溶有機物以及碳質組分的氧化，導致顆粒的分形維數降低了 0.04，表明摻燒 HHO 可以降低顆粒的結構緊密程度；HHO 影響生物柴油燃燒顆粒的形貌特徵，可以有效降低生物柴油的顆粒污染物。