Structure and Formation Mechanism of Methane Explosion Soot

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ABSTRACT: The bright spot phenomenon during the gas explosion was because of the soot particles of high heat radiation characteristics generated during the explosion process. The formation mechanism of soot and precursor polycyclic aromatic hydrocarbons (PAHs) of the methane explosion was numerically simulated using CHEMKIN-PRO. The methane explosion soot of the CH4−air premixed gas explosion experiments with volume concentrations of 8% was collected, and the pore size distribution and surface structure of the soot were analyzed by low-pressure nitrogen gas adsorption (LP-N2GA), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The results show that C2 and C3 play an important role in the formation of PAHs in the early stage of the explosion reaction. The LP-N2GA isotherms demonstrate that the pore type of the soot particles is mostly wedge-shaped, which was verified with SEM observations. The SEM analysis showed that the methane explosion soot is composed of a large number of spherical soot aggregates with diameters between 4 and 50 μm and the pores at the particle surface are well developed, some of the particles exhibit a melt sintering feature. Soot aggregates collide with each other with a chain-branched structure, and the diameters of the majority of the particles are of 100 nm according to TEM images. In addition, graphite-like lattice stripes can be clearly seen inside the particles when magnified to 8 nm. This work will provide the basis for further analysis of soot formation in the gas explosion process.

1. INTRODUCTION

Carbon black (CB) is a kind of carbon material whose microstructure, particle morphology, and surface properties are very special, it is the product of incomplete combustion. Industrial CB is mainly used in the rubber industry. According to the production method, there are furnace black, channel black, thermal black, lampblack, and so forth. CB resulting from combustion is harmful to the atmospheric environment and the human respiratory system and that coming from the internal combustion engine oil and exhaust gas is often referred to as soot. How to reduce the emission of CB from exhaust gas has always been a research hotspot. When representing the solid particles discharged from an internal combustion engine oil and exhaust gas, NBs is often referred to as soot. How to reduce the emission of CB from exhaust gas has always been a research hotspot. When representing the solid particles discharged from an internal combustion engine oil and exhaust gas, CB and NB are basically universal.

However, some scholars have proposed that the two concepts should be distinguished because CB is an industrial material produced under specific conditions, but soot is an undesirable product of the fuel combustion process. The carbon content, element type, and organic matter composition are different. Because the above controversy was raised when discussing CB or soot toxicity and carcinogenicity, both are universal in most cases.

CB as an additive can significantly improve the material properties, so scholars at home and abroad have conducted a lot of research on their physical and chemical structures. The performance indicators for the industrial CB include the surface structure, density, pH value, heating weight loss rate, ignition weight loss rate, Brunauer−Emmett−Teller (BET) specific surface area (SSA), diocyl phthalate oil absorption value, and so forth. The differences in the surface structure and chemical composition between the biomass oil soot (BS) particles and commercial CB were compared by Hu, they found that the average diameters of BS and CB particles were 50 and 40 nm, respectively. Alrefaai studied the effects of dicyclopentadiene (DCPD) addition on soot morphology and reactivity using different characterization techniques such as X-ray diffraction, high-resolution transmission electron microscopy (HRTEM), elemental analysis, thermogravimetric analysis, electron energy loss spectroscopy, and Fourier transform infrared spectroscopy. The soot formation and in-cylinder soot oxidation in an optically accessible direct injection spark ignition engine (DISI-engine) are analyzed for gasoline−ethanol and gasoline−butanol mixtures using the volumetric

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extinction measurement technique." Jung et al. used plane laser-induced fluorescence (PLIF) signals and soot scattering images to study the soot zone structure of inverse diffusion flames (IDFs).10 Clague studied the differences in the interplanar spacing and the length distribution of lattice fringes between diesel soot and commercial black and found that soot from engine oil and tail gas is very different from commercial CB in terms of chemical composition.11 Rockne analyzed the SSA, pore volume, pore size distribution (PSD), carbon/hydrogen ratio, and other parameters of n-dodecane flame soot, marine and automotive diesel soot, wood furnace, and fuel furnace soot by using liquid nitrogen and carbon dioxide adsorption methods.12 Gogoi used several experimental techniques to study the effects of 2,5-dimethylfurans additives on the sooting propensity of diesel, and the oxidative reactivity and characteristics of soot particles.13 HRTEM analysis showed the soot particles are irregular clusters with different sizes and compactness. The differences between the microstructure and reactivity of spark discharge (GKG), heavy duty engine diesel (EURO VI and IV) soot, and graphite powders before and after heat treatment are significant.14 A soot particle aerosol mass spectrometer was utilized by Fortner to study the chemical composition of refractory black carbon particles and the associated nonrefractory components.15 CB is usually present in the form of aggregates of primary particles and CB aggregates tend to agglomerate into larger aggregates.

The physical and chemical structures of exhaust gas soot and commercial CB and their research methods have been discussed above, but there is less involvement of the formation of CB and its influencing factors during fuel combustion. Scholars in the field of internal combustion engines and combustion have conducted extensive research on the formation of CB and the CB precursor polycyclic aromatic hydrocarbons (PAHs) in both the forward and reverse diffusion flames. Beltrame found that changes in the oxygen concentration significantly changed the diffusion flame structure and the flame temperature, resulting in a large amount of soot generation.16 Merchán-Merchan studied the soot formation in coflow flames of fatty acid methyl esters using extinction/scattering techniques.17 As the oxygen concentration in the mixture increases from 21 to 35%, the soot volume fraction increases about 61%. The in-cylinder evolution of soot properties over the combustion cycle and as a function of exhaust gas recirculation was investigated in a modern heavy-duty diesel engine by Malmborg.18 Nakamura et al. used a microfluidic reactor to study the formation characteristics and formation process of PAHs at a certain temperature.19 Cuoci et al. studied the effects of unstable conditions on the formation of PAH and soot in propane countercurrent diffusion flames (IDFs).20 Qualitative and quantitative measurements of the soot volume concentration, OH, and PAHs were performed in vaporized liquid combustion experiments by using LIF and laser-induced laser techniques in a codirectional laminar flow burner.21 Franzelli et al. observed the spatiotemporal evolution of turbulent diffusion flame soot using image diagnostic methods, providing space-resolved information on turbulent flame surfaces and the interaction region of soot precursors.22 An and Bobba et al. studied the formation process and spatiotemporal evolution of soot precursor PAHs in an engine.23,24 Aizawa studied the PAH growth and the formation time of soot particles in a constant volume burner under similar conditions of a diesel engine.25 Zhang described the pyrolysis and oxidation of the fuel and the formation of PAHs by a numerical study to investigate the effects of n-propylbenzene addition to n-dodecane on soot formation in a laminar coflow diffusion flame.26

In the pipeline gas explosion experiment, the flame was shoot from an observation window through high-speed photography, a bright spot was often found in the flame, and its brightness was significantly different from the surrounding flame.27,28 Because of the strong absorption of soot particles, it has a strong heat radiation in the flame,29 which can promote heat conduction and heat radiation inside the combustion chamber. Thus, the bright spot is the soot aggregates produced in the gas explosion. It is not difficult to see that a great deal of results have been obtained on the commercial CB structure and on the formation of fuel combustion soot and its precursors. However, for such violent reactions (explosion), the research on the structure and formation mechanism of the soot produced during the process is still paid less attention. In this article, the surface microscopic structure of soot produced by gas explosion and the influence of the formation process on soot formation were analyzed to provide a basis for the formation mechanism of explosion soot and precursor research.

2. RESULTS AND DISCUSSION

2.1. Effects of CH4 Concentration on Soot Formation. The numerical simulation was carried out in a constant volume reactor with different concentrations in the explosion limit range (mole fraction 8, 9, 10, 11, 12, 13, and 14%, respectively). This study did not involve surface reactions, so surface dynamics and gas transfer data were not required. The initial conditions are shown in Table 1.

| no. | Y(CH4) | Y(O2) | Y(N2) | P (atm) | T (K) |
|-----|--------|-------|-------|---------|-------|
| 1   | 0.08   | 0.1932| 0.7268| 1       | 1200  |
| 2   | 0.09   | 0.1911| 0.7189| 1       | 1200  |
| 3   | 0.10   | 0.1890| 0.7110| 1       | 1200  |
| 4   | 0.11   | 0.1869| 0.7031| 1       | 1200  |
| 5   | 0.12   | 0.1848| 0.6952| 1       | 1200  |
| 6   | 0.13   | 0.1827| 0.6873| 1       | 1200  |
| 7   | 0.14   | 0.1806| 0.6794| 1       | 1200  |

During the formation of soot particles, large amounts of PAH and small hydrocarbon molecules are produced.32 The mole fraction of small molecules such as C2 and C3 rapidly reached the peak concentration in the process of methane explosion, and basically stabilized at 0.03–0.04 s, and then the concentration gradually decreased and flowed to the rear zone with a certain stable value (Figure 1), indicating that C2 and C3 components play an important role in the formation of PAHs in the early stage of the explosion reaction. With the increase of the methane concentration, the reaction time for each component to reach its maximum is delayed, but the maximum amount of methane is increased. Therefore, the methane concentration has an accelerating effect on the formation of intermediate components, thus increasing the amount of PAHs. PAHs are usually formed in fuel-rich combustion. Under fuel-rich conditions, many acetylene molecules will be formed. The acetylene molecules will react with PAHs and lead to further growth of PAHs and particles in the flue gas.33 From Figure 2, it can be seen that with the
increase of methane concentration, the maximum production of multiring aromatic PAHs such as PAHs (A1, C6H6) and methyl C6H5 (A1-), produced by the explosion increases, this result is consistent with the previous research studies.32−34 Therefore, the larger the methane concentration, the greater the generation of PAHs and the formation of soot.

2.2. Particle Size Distributions and Surface Area. The hysteresis loop shape of the porous media adsorption isothermal curve can reflect the pore type. The pores in porous media are divided into four types: cylindrical, slit-shaped, wedge-shaped, and bottleneck.35 On the basis of multiple adsorption theories,36−39 pore structure parameters were automatically calculated using computer software. BET, Barrett–Joyner–Halenda (BJH), and Dubinin–Radushkevich (DR) methods are used for calculating SSA, BJH and D−R equations for calculating the pore volume, and Dubinin–Astakhov (DA) and density functional theory (DFT) approaches for PSD, the results are presented in Table 2.

The SSA in micropores is significantly larger than that in mesopores, illustrating that the micropores have a greater contribution to SSA than mesopores, thus, micropores determine the adsorption capacity to a large extent. However, the micropore volume is much smaller than the mesopore volume. According to the isothermal adsorption and desorption curves of soot particles in Figure 3, the predominantly wedge-shaped pores in the soot particles can be determined, which is consistent with the pores in the particles in the scanning electron microscopy (SEM) image. Figure 4 shows the PSD and cumulative pore volume of soot particles. It can be seen from Figure 5 that the PSD of most pores ranges from 3 to 15 nm and the peak value is about 4

Table 2. Pore Structure Parameters of Gas Explosion Soot

| Sample | SSA/m² g⁻¹ | pore volume/cm³ g⁻¹ | pore size/nm |
|--------|------------|---------------------|--------------|
| Soot   | 1.989      | 6.519 × 10⁻³        | 1.083 × 10⁻³ |

Figure 1. Effects of the gas concentration on C2 and C3.

Figure 2. Effects of the gas concentration on the PAHs.

Figure 3. Low-Pressure Nitrogen Gas Adsorption (LP-N₂GA) isotherms of soot particulates.

Figure 4. Mesopore PSD of the soot particulates (DFT).
nm, that is, the pores with a diameter of about 4 nm in the soot particles are the most. Figure 5 shows the DA microporous distribution of soot particles with a peak value at 2.5 nm, with most of the pore sizes ranging from 1.4 to 3.5 nm. The extremely small pore size, large SSA, and pore volume have a considerable ability to adsorb and store pollutants. Considering the huge amount of soot particles discharged into the atmosphere every year, when these particulate pollutants enter the atmosphere, the soot particles can absorb a large amount of sunlight energy and adsorb and store a large amount of atmospheric pollutants.40,41

2.3. SEM Analysis. It can be seen from Figure 6a that the soot aggregates are mainly of spherical and lumpy shape in the SEM image with a magnification of 1000. The surface is rough, and the diameter ranges from 4 to 50 μm. According to the ambient air quality standard (GB 3095-2012) and according to the size of the particle size, particulate matter can be divided into total suspended particulates (TSPs, particulate matter less than 100 μm in aerodynamic diameter) and particulate matter (PM10, particulate matter less than 10 μm in aerodynamic diameter). Soot has a wide range of particle size distribution, the particle size of soot particles floating in the atmosphere is generally 0.01–20 μm.42 The particle size range of interest in air pollution is 0.01–10 μm.43 From Figure 6a, it can be easily observed that half of the soot particles have a diameter less than 10 μm. These particles can be deposited in the lungs with human breathing, and can even enter the alveoli and blood.

In Figure 6b,d,e, it can be seen that the surface has highly developed pores in the honeycomb form, which is consistent with the results predicted using the isothermal adsorption–desorption curves. The spherical surface is uneven, with spherical particles of smaller diameter attached to the surface. From Figure 6d,e, it can be found that soot aggregates with relatively smooth surfaces have fewer soot particles attached to them. Conversely, relatively coarse surfaces or particles with high-developed porosity tend to bind soot particles more easily, and such soot aggregates are generally larger in diameter. Figure 6f shows that the surface of the soot aggregate has a pit with a diameter of about 4 μm. The surface of the pit is surrounded by a large number of spherical particles with a diameter of less than 1 μm. During the growth, collision, and oxidation process of soot particles, the surface structure will be destroyed, and new soot particles will be attached to the surface, thus this incomplete sphere structure was formed. With further reactions, small soot particles continue to accumulate on the surface of the spherical particles, causing the spherical soot particles to continuously grow and condense to form blocks(Figure 6g–i). On the surface, it can be seen that large aggregates are tightly bound

Figure 5. DA micropore size distribution of soot particulates.

Figure 6. SEM images of the soot particulates. (a) Mag 1000X, (b) mag 7000X, (c) mag 5000X, (d) mag 15,000X, (e) mag 14,000X, (f) mag 15,422X, (g) mag 15,000X, (h) mag 15,999X, and (i) mag 11,974X.
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TEM images shown in Figure 7, it can be seen that most of the
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condensation between the smaller particles that makes up
The soot internal crystal structure con
This phenomenon is consistent with the simulation results.
agglomeration, indicating that the soot formation process is a
result of the competition of soot particle growth, agglomera-
tion, fusion sintering, and surface oxidation.

2.4. TEM Analysis. The internal crystal structure of the
sample can be observed in the TEM image. Soot aggregates are
composed of primary particles, and primary particles are
generally spherical-like irregular polyhedrons. 10 From the soot
TEM images shown in Figure 7, it can be seen that most of the
soot particles have a diameter of about 100 nm (Figure 7a).
There are some relatively dispersed particles with a diameter of
about 200 nm, the surface of the particles is not smooth, and
there are bonds between the particles (Figure 7b). Clague made a comparison of diesel engine soot with select
commercial CBs and found that the soot and commercial CBs have different particle sizes. 11 Primary particle sizes of
commercial CBs range from 30 to 50 nm, and they have
agglomerated into large clusters (agglomerates) with the mean
particle sizes between 150 and 350 nm. Through comparison,
it was found that the shape characteristics of the soot produced
by methane explosion are basically the same as those of
commercial CB, and there is a strong tendency of
condensation between the smaller particles that makes up
the soot agglomerates. In terms of the particle size, the mean
particle size of the methane explosion soot is generally larger
than that of commercial CB. It can be seen that the smaller
particle units are partially melted and combined, and it is
possible for the sintering fusion of high-temperature or the
primary particle growth position to occur at the contact point
between the particles. 10 The chain structure formed by these
polyfused soot particles is called a primary structure or a
permanent structure. The crystal nuclei are connected by
strong chemical bonds and have a strong cohesive strength.
The interaction between aggregates is mainly van der Waals
forces rather than chemical bonds, 44–46 and the structure
formed is called the secondary structure. The aggregates are
also connected in a chain structure but the structure is easily
destroyed and the process is reversible.

It is known from the simulation that the formation process
of soot includes formation and growth of carbon nuclei. The
chain structure of the methane explosion soot shows that the
growth process of the soot aggregates is the reaction of small
molecules on the carbon surface core to form smaller particles.
This phenomenon is consistent with the simulation results.
The soot internal crystal structure confirms the results of the
numerical simulations. The surface of these smaller particles is
not smooth, and the particles collide and condense with each
other (Figure 7c). Under high-temperature conditions, the
oxidation reaction occurs on the surface of the particles,
resulting in a large number of pore structures on the surface of
the formed soot aggregates. From Figure 7d, it can be seen that
similar to the primary particles of commercial CB, the methane
explosion soot is also composed of concentric graphite layers,
showing a graphite-like lattice fringe.

3. CONCLUSIONS
The formation mechanism of soot and precursor PAHs of
the methane explosion was numerically simulated using CHEM-
KIN-PRO. The samples of soot produced by the CH₄–air
premixed gas explosion were collected and analyzed by
cryogenic liquid nitrogen adsorption, SEM, and TEM.

(1) During the methane explosion process, the components
of C₂ and C₃ play an important role in the formation of
PAHs in the early stage of the explosion reaction. The
production of PAHs increases with the increase of the
methane concentration, but the overall generation trend
is basically the same.

(2) Soot particles in methane explosions are porous
particles, and the pore type is mostly wedge-shaped,
which was verified with SEM observation. The pore size
is mainly in the range of 3–15 nm, and the pore
diameter of 4 nm is the largest, and the PSD of most
pores ranges from 3 to 15 nm and the peak value is
about 4 nm.

(3) The methane explosion soot particles are composed of a
large number of spherical soot aggregates, and the
particles are bound to each other or small particles are
attached to the surface of the larger particles. The
particle surface has the characteristics of melt sintering,
which leads to the further development of pores on the
surface of the particles. This characteristic results from
competition and coordination between surface oxidation
and soot particle growth, agglomeration, and fusion
sintering during the formation process.

(4) TEM shows that the surface of most of the soot particles
is not smooth but convex, and the particles collide with
each other and coalesce to form an aggregate with a
chain-branched structure. Graphite-like lattice stripes
can be clearly seen inside the particles when magnified
to 8 nm.

4. NUMERICAL SIMULATIONS OF SOOT
GENERATION
The formation process of CB (soot) is very complex, involving
a variety of physical and chemical reactions, including the
gas-phase reaction, phase transition from the gas phase to solid
phase, and formation and growth carbon nuclei. The
nucleation process involves the dehydrogenation, polymer-
ization, and cyclization of small molecules of hydrocarbons

together by small particles, some undergo a process of melting
and sintering, and the surface of the most soot particles has
highly developed pores, this is because the temperature in the
explosion process rapidly increases, causing the soot particles
to continuously ablate in the process of growth and agglomera-
tion, indicating that the soot formation process is a
result of the competition of soot particle growth, agglomera-
tion, fusion sintering, and surface oxidation.

Figure 7. TEM images of soot particulates (a) mag 15,000×, (b) mag 15,000×, (c) mag 100,000×, and (d) mag 375,000×.
generate cyclic hydrocarbons; the process of growth is from PAHs to small CB particles, then the small CB particles grow into large CB particles through mutual collision and polymerization during the reaction. The formation process of CB from cyclic hydrocarbons to particle aggregates can be summarized as five processes: (a) pyrolysis, hydrocarbon fuels undergo high-grade pyrolysis reactions to form small molecule radicals such as C2 and C3, which can be further developed into cyclic aromatic hydrocarbons. (b) Precursor generation, a series of elementary reactions will be used to generate a benzene ring after pyrolysis, which is a small molecule aromatic hydrocarbon, and the small molecule aromatic hydrocarbon will generate a macromolecule PAH through the recombination or polymerization reaction. (c) Nucleation process, the PAHs continue to grow and begin to transform into the initial soot particles, namely the carbon nuclei with the size between 1.5 and 2 nm. (d) Soot particle growth process, this process is mainly a growth process of carbon nucleus mass and volume, including surface growth and agglomeration. The viscous carbon nucleus particles collide with each other to form irregular clusters by the aggregation reaction. Because of that the soot particles decrease and the size of the soot increases. However, the total mass does not change and a large soot particle is eventually formed. (e) Oxidation process, PAHs and soot particles are oxidized to produce CO and CO2, thereby reducing the mass of PAHs and CB particles. The important role of aromatic hydrocarbons can be seen from the soot production process. Studying the aromatic hydrocarbon formation during combustion can help to understand the formation of soot particles.

4.1. Gas Explosion Model. The numerical simulation used the closed homogeneous batch reactor model in CHEMKIN. This model is a 0-D adiabatic model. The gas in the reactor is completely in a highly diffused state. The following basic assumptions were made: (a) the gas in the reactor is inviscid and satisfies the ideal gas state equation; (b) the wall is considered as a rigid body, there is no the viscous friction, and (c) the system is isolated from the exterior (adiabatic).

The mechanism of methane oxidation is calculated using the WF mechanism (proposed by Wang and Frenklach) including 99 species and 531 reactions, including not only the thermal decomposition of C1 and C2 components and the formation of higher-order linear hydrocarbons including C6 components, but also the formation and oxidation of benzene, aromatic hydrocarbons, and PAHs. In addition, the thermal-cracking reaction mechanism of small-molecular-weight hydrocarbons used GRI-Mech 3.0 of 325 reactions and 53 species, and the chemical composition thermodynamic data required for numerical simulation were taken from the CHEMKIN thermodynamic database. The numerical simulations mainly include three reaction processes: (1) methane thermal decomposition process; (2) the formation and oxidation of intermediate products such as C2 and C3; (3) the formation and oxidation of PAHs.

4.2. Governing Equations. The species equation is as follows

\[ \frac{dX_i}{dt} = v_i \quad (i = 1, 2, ..., N) \]

\[ v_i = \sum_{k=1}^{n} v_{ik} \prod_{i=1}^{N} X_i^{v_{ik}} \quad (i = 1, 2, ..., N) \]  

\[ S_k = A_k T^{b_k} \exp\left(-\frac{E_{ak}}{RT}\right) \quad (k = 1, 2, ..., n) \]

where \( X_i \) is the molality of the ith species, \( \text{mol/mol} \); \( v_i \) represents the time, \( \text{mol}/(\text{mol-s}) \); \( N \) is the number of species, \( n \) is the number of reaction steps. \( S_k \) is the forward reaction rate constant of the kth reaction step, \( v_{ik} \) and \( v_{ik} \) are the stoichiometric coefficients of the forward reaction and the reverse reaction of the ith species in the kth elementary reaction step, respectively. \( A_k \) denotes the pre-exponential factors. \( b_k \) is the temperature index. \( E_{ak} \) is the activation energy of the kth reaction, \( \text{kJ/mol} \). \( T \) is the gas temperature, \( \text{K} \). \( R \) is the gas constant, \( \text{kJ/(mol-K)} \).

Energy equation

\[ \rho \frac{dT}{dt} + \sum_{i=1}^{N} u_i v_i = 0 \]

where \( \rho \) is the gas density, \( c_i \) is the specific heat at constant volume, \( \text{J/(kg-K)} \), and \( u_i \) is the reaction heat of the ith species, \( \text{J/mol} \).

5. EXPERIMENTAL SECTION

5.1. Sample Preparation. The gas explosion experiment system is composed of five parts: an explosion pipeline, a gas distribution system, an ignition system, a data acquisition and analysis system, and a pressure measuring system. The explosion test pipeline (Figure 8) is 40 m long with an internal diameter of 35 cm. It consists of four long pipes of 9 m and two short pipes of 2 m that are connected by flanges. The pipeline wall thickness reaches 0.02 m and the strength is 20 MPa. The high-voltage electric spark releases 40 J energy to supply the ignition energy in the experiments. The experiment was carried out under the condition that the front end is ignited, the back end is confined. The inner wall of the pipe was cleaned before conducting the experiment to ensure that no other residues were attached to the inner surface, and then conducted the CH4-air premixed gas explosion experiment with a volume concentration of 8% and collected the soot on the inner wall and stored it in a sealed bag. Because little solid products generated in one explosion, the soot was collected by
conducting multiple explosion experiments. The information on CH₄ is shown in Table 3.

Table 3. Sample Information

| chemical name | CAS no. | source                        | initial purity | purification method |
|---------------|---------|-------------------------------|----------------|---------------------|
| methane       | 74-82-8 | Beijing Yanan Weiyi Gas Co., Ltd. | ≥99.998        | supplier            |

5.2. Low-Pressure Nitrogen Gas Adsorption. The soot samples were dried before testing. The SSA and pore volume of soot particles tests were conducted in accordance with the SY/T6154-1995 standard by using the Quantachrome Autosorb-iQ analyzer from Contac Corporation based on the isothermal physical adsorption static capacity method. The liquid nitrogen adsorption was performed at a temperature of 77 K and the relative pressure was 0.050–0.995.

5.3. Scanning Electron Microscopy and Transmission Electron Microscopy. Soot surface structure morphology was qualitatively observed by using a JSM (5600 lv) scanning electron microscope. A transmission electron microscope can be used to accurately observe the arrangement patterns of different kinds of materials inside the micron-sized soot particles and the way of molecular arrangement, so that the microscopic molecular structure morphology of soot particles can be analyzed. The soot particles are ground first and then continued to crush to a particle size of less than 1 μm using an ultrasonic dispersion method. After sampling using a special configuration, the sample is placed in an absolute ethanol solution, and after a period of time, it is shaken uniformly using an ultrasonic disperser, then TEM observations were performed after drying.

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Notes

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