Effect of indirect non-thermal plasma on particle size distribution and composition of diesel engine particles

Linbo GU (顾林波), Yixi CAI (蔡忆昔), Yunxi SHI (施蕴曦), Jing WANG (王静), Xiaoyu PU (濮晓宇), Jing TIAN (田晶) and Runlin FAN (樊润林)

School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, People’s Republic of China

E-mail: qc001@mail.ujs.edu.cn

Received 28 May 2017, revised 10 July 2017
Accepted for publication 12 July 2017
Published 15 September 2017

Abstract
To explore the effect of the gas source flow rate on the actual diesel exhaust particulate matter (PM), a test bench for diesel engine exhaust purification was constructed, using indirect non-thermal plasma technology. The effects of different gas source flow rates on the quantity concentration, composition, and apparent activation energy of PM were investigated, using an engine exhaust particle sizer and a thermo-gravimetric analyzer. The results show that when the gas source flow rate was large, not only the maximum peak quantity concentrations of particles had a large drop, but also the peak quantity concentrations shifted to smaller particle sizes from 100 nm to 80 nm. When the gas source flow rate was 10 L min\(^{-1}\), the total quantity concentration greatly decreased where the removal rate of particles was 79.2%, and the variation of the different mode particle proportion was obvious. Non-thermal plasma (NTP) improved the oxidation ability of volatile matter as well as that of solid carbon. However, the NTP gas source rate had little effects on oxidation activity of volatile matter, while it strongly influenced the oxidation activity of solid carbon. Considering the quantity concentration and oxidation activity of particles, a gas source flow rate of 10 L min\(^{-1}\) was more appropriate for the purification of particles.

Keywords: diesel engine, particulate matter, non-thermal plasma, gas source flow rate

(Some figures may appear in colour only in the online journal)

1. Introduction

Particulate matter (PM) emitted from diesel engine exhausts is one of the main causes of haze problems, which lead to inflammation, asthma, and heart disease [1–3]. In addition, polycyclic aromatic hydrocarbons (PAHs) produced by incomplete combustion of hydrocarbons in PM will increase the risk of carcinogenesis [4, 5]. Therefore, strict emission regulations have been established on a global level to limit the emission of pollutants from diesel engines. However, with increasingly stringent emission regulations, the technical approaches to reducing emissions by optimizing diesel engine combustion tends to be limited, only the installation of advanced post processors can enable PM to reach the emission standard [6, 7]. The advanced post processors of diesel engine mainly include a diesel particulate filter (DPF), diesel oxidation catalyst (DOC) and electrostatic trapping technology. However, these post processors have certain drawbacks. For example, DPF will be blocked with the deposition of PM in DPF which will affect the normal operation of the engine. DOC technology can reduce the soluble organic fraction adsorbed on the surface of carbon particles, but could have little effect on pure carbon particles. Electrostatic trapping technology also has the disadvantage of high cost and cannot automatically clear ash. Therefore, it is necessary to find a new after-treatment technology for diesel engine exhaust gas.

In the field of diesel engine exhaust after-treatment, non-thermal plasma (NTP) technology has become a research focus with advantages of high conversion efficiency, simple installation, and lack of secondary pollution [8–10]. Many
studies that explore the use of NTP to purify PM emissions from diesel engines could be found in the literature. Babaie et al. [11, 12] studied the relationship between PM, ozone (O$_3$), and carbon dioxide (CO$_2$), and found that O$_3$ played a major role in the removal of PM. A PM removal efficiency of more than 50% was achieved during the experiments when the discharge power was high. Moreover, they also explored the effect of voltage on PM treatment via NTP, and the results showed that large particles were easily decomposed to small particles under high voltage, which was more harmful. In the study by Moket al. [13], NTP and a catalysis hybrid process were used to purify the exhaust from a stationary diesel engine. The results suggested that the removal of PM did not largely depend on the electrode structure, but was a strong function of the energy density. This study proved the NTP catalyst system process could be applied to simultaneously remove nitrogen oxides (NO$_x$) and PM. Chae et al. [14] used a new plasma/catalyst continuously regenerative hybrid system to reduce PM, NO$_x$ and carbon monoxide (CO). Catalyst temperature, plasma energy density, and exhaust gas characteristics were investigated in the study. It was reported that PM and CO were almost removed and NO$_x$ simultaneously reduced to 30% by the system. These studies mentioned above mainly use direct non-thermal plasma (DNTP) treatment for the diesel engine exhaust in which exhaust gas passes directly into the reactor for processing, and the treatment effect of DNTP is greatly affected by the fluctuation of exhaust gas. In recent years, some scholars use oxygen (O$_2$), nitrogen (N$_2$), or other gases as gas source and introduce them into the generator to produce active gas. Then, the active gas will be transferred into the diesel exhaust system for pollutant purification. This method is known as indirect non-thermal plasma (INTP) technology. Compared to DNTP technology, the working environment of INTP technology is cleaner and because the exhaust does not flow through the NTP reactor, the effect of treatment is less affected by exhaust fluctuations. Okubo, et al. [15–17] used air as the gas source, and active substances such as O$_3$ and NO$_2$ produced by the NTP generator were directly passed into the DPF, and the back pressure of DPF was reduced. Complete regeneration of DPF was achieved when the temperature was 250 °C, and the energy required for DPF regeneration was about 0.25% of the diesel engine power. In their study on simultaneously reducing PM and NO$_x$, BaTiO$_3$ worked as an absorber to absorb particles from engine exhaust as well as a barrier of dielectric barrier discharge (DBD). In their experiment, PM could still be removed under oxygen-lean conditions, but the adsorption of PM had an optimal threshold. When the threshold exceeded, the efficiency of PM and NO$_x$ simultaneously decreased. In our previous studies, structure optimization of a DBD type plasma reactor was implemented. According to the results, a discharge gap between positive and negative electrodes and cooling system had great impacts on the O$_3$ generation, discharge gap of 2 mm was appropriate, and both cooling water and a fan were adopted to cool the discharge surface. Based on the optimized plasma reactor, a series of experiments about DPF regeneration were conducted using INTP technology [18, 19]. The results of off-line regeneration of DPF indicated that test temperature of 80 °C and an engine load of 50% were more useful for DPF regeneration. In addition, gas source played a significant role in the INTP system because the gas type and gas flow influenced the generation of active substances from the start. Thus, experimental results of DPF regeneration showed differences. PM removal quality achieved via variable flow rate control strategy was about 1.8 times as much as that obtained via constant flow rate strategy [20]. Previous studies focused on DPF regeneration. This paper, however, provides an in-depth study about PM emitted directly from the diesel engine exhaust and explores the influence of gas flow of NTP on PM removal.

An experimental system was established dealing with actual diesel PM via INTP technology and an optimized NTP reactor was introduced. The effects of different gas source flow rates on the quantity concentration, composition, and apparent activation energy of diesel engine PM were investigated by using an engine exhaust particle sizer (EEPS) and a thermo-gravimetric analyzer (TGA). It can be conducted that considering the quantity concentration and oxidation activity of particles, a gas source flow rate of 10 L min$^{-1}$ was more appropriate for the purification of particles. For a small flow rate, the O$_3$ yield was not sufficient to remove the PM. When the gas source flow rate was large, the O$_3$ concentration was too small due to the deterioration of the discharge effect and the cost increased.

2. Test system and method

The schematic diagram of the test bench system for the INTP treatment of diesel engine PM is shown in figure 1, which includes an engine bench system, a NTP injection system, a sampling device, and analytical instruments. The engine is a YD480 diesel engine, and its technical parameters are shown in table 1. When the engine speed and load are 2500 r min$^{-1}$ and 100%, the total exhaust gas flow rate is about 3600 L min$^{-1}$. The exhaust pipe is installed with a reaction chamber and a flow meter. The reaction chamber is designed to make particles fully react with ozone. The main reaction was carried out in the reaction chamber, and a small amount of ozone generated by NTP injection system will continue to react with particles downstream the reaction chamber. The flow meter can accurately control the flow rate of the exhaust manifold and the control range of the flow meter is 10–100 L min$^{-1}$.

In the NTP injection system, the gas source is O$_2$ of 99.99% concentration, and a flow meter with an accuracy of 0.01 L min$^{-1}$ is used to control the gas source flow. A coaxial cylindrical structure and the principle of dielectric barrier discharge are adopted by the reactor. The power supply device is composed of a CPT-2000K intelligent electronic impact machine and several capacitors. A TDS3034B digital oscilloscope can monitor the voltage and frequency in the
discharge process. Based on our previous optimization experiments, appropriate parameters where the discharge voltage and frequency were kept at 17 kV, and 7 kHz respectively is the best combination of reactor operating parameters. To ensure that the reactor is in a better working condition, the discharge surface temperature is cooled by air and water. A Mini-HiCon high-density ozone analyzer monitors the concentration of O$_3$ produced by the NTP injection system. The sampling device comprises a sampler, a sampling pump, and a sampling filter paper. The filter paper is a What Man’s QMA quartz fiber membrane with a diameter of 47 mm and a pore size of 2.2 μm, which is resistant to 900 ºC. The analytical instruments mainly include a United States TSI EEPS 3090 and METTLER TGA. EEPS3090 can measure the particle size distribution and the particle proportion of different modes. TGA is used to determine the composition and oxidation activity of PM, using the relationship between the change of sample mass and temperature. The experiment was divided into three parts. The first part was the original engine particle test. The diesel engine was open, the engine speed was set to 2500 r min$^{-1}$, and the load to 100% when the diesel engine was running stable. The exhaust flow rate was set to 60 L min$^{-1}$. The gas temperature at the reaction chamber was controlled at 180 ºC because ozone generated by the NTP injection system would be decomposed at higher temperature. The particle size distribution and quantity concentration of the particles were measured with EEPS. The sampling system was opened, the sampling flow rate was set to 5 L min$^{-1}$ and the sampling time to 25 min.

The second part was the emission test of PM under different gas source flow rates of the NTP injection system. The operating condition, exhaust flow rate and gas temperature at the reaction chamber were the same as that of the original engine particle test. The NTP injection system was opened, the gas source flow rate, discharge voltage and discharge frequency were adjusted to 3 L min$^{-1}$, 17 kV, and 7 kHz, respectively. The particle size distribution and quantity concentration of the particles were measured via EEPS and the sampling system was turned on for 25 min. Once the NTP injection system was switched on, the particles in the exhaust gas would react with ozone, and the reaction took at least 25 min. The gas source flow was adjusted to 5 L min$^{-1}$, 7 L min$^{-1}$, 10 L min$^{-1}$ and 15 L min$^{-1}$ and the operations were repeated.

The last part was the thermo-gravimetric(TG) test of the particles. The particle samples obtained in the first and second parts of the experiment were put into the crucible. The temperature during the test rose uniformly from 50 ºC to 800 ºC. During the experiment, air and nitrogen (N$_2$) were used as reaction gas and protective gas, respectively.

### 3. Results and discussion

#### 3.1. O$_3$ concentration and yield

The main component of active substances generated with the NTP injection system was O$_3$, which had a strong ability to oxidize PM from diesel engine exhaust gas. The chemical reactions in the NTP reactor are shown in Reaction (1)–Reaction (3) [21–23]. O$_3$ was formed via two main steps: the first step was shown in Reaction (1) and Reaction (2), where the oxygen molecules break the chemical bond to form oxygen atoms after discharge. The second step was the formation of O$_3$ via reactions between oxygen molecule radicals.
and ternary M, as shown in Reaction (3).

\[
e + O_2 \rightarrow e + O_2 \left( A \sum \frac{1}{u} \right) \rightarrow e + O(3P) + O(3P) \quad (1)
\]

\[
e + O_2 \rightarrow e + O_2 \left( B \sum \frac{1}{u} \right) \rightarrow e + O(3P) + O(1D) \quad (2)
\]

\[
O + O_2 + M \rightarrow O_3 + M. \quad (3)
\]

Figure 2 shows O₃ mass concentration and yield under different gas source flow rates. It can be found that the mass concentration of O₃ could reach 50–63 mg L⁻¹ for small gas source flow rates, which drastically decreased after the flow rate grew to 15 L min⁻¹. With the increase of gas source flow rates, the residence time of O₂ in the discharge region shortened, which led to the reduction of the discharge effect and the decrease of O₃ mass concentration. The yield of O₃ shows the opposite trend than the mass concentration of O₃. With the increase of gas flow, the yield of O₃ rose from 190 mg min⁻¹ to 555 mg min⁻¹. When the gas flow rate was small, the mass concentration of O₃ was higher; however, its yield was less due to the smaller flow rate. When the flow rate increased to 15 L min⁻¹, the sharp drop of O₃ mass concentration resulted in a slight increase of O₃ yield.

3.2. Effects of gas source flow rate on particle size distribution and quantity concentration of diesel particles

Particulate matter can be classified into different categories. Particles with a diameter below 100 nm are called nucleate particles, which are easily deposited in the lungs, causing strong inflammation [24]. Besides, particles can also be divided into nucleate particles and aggregated particles with a particle diameter less than or greater than 30 nm, respectively. The percentages of the total quantity concentration of the nucleate particles, aggregated particles, and ultrafine particles are called nucleate particle proportion, aggregated particle proportion, and ultrafine particle proportion, respectively.

The geometric mean diameter of particles is defined in Formula 4 and Formula 5.

\[
D_g = \exp \left( \frac{\sum (n_i \ln D_{gi})}{n_{total}} \right) \quad (4)
\]

\[
n_{total} = \sum n_i \quad (5)
\]

where \(D_g\) is the geometric mean diameter of the particles and \(n_i\) is the quantity concentration of the particles in the \(i\)th particle size interval. \(D_{gi}\) is the characteristic particle size of the particles in the \(i\)th particle size interval, and \(n_{total}\) is the total quantity concentration of the particles.

Particle size distributions under different gas source flow rates measured via EEPS are shown in Figure 3. During the experimental process, a gas source flow rate of 0 L/min represents the original situation without NTP injection. Particles were concentrated in two intervals. The first interval was 6–25 nm and the second interval was 60–300 nm where particle quantity concentration showed a normal distribution with a peak value of 5.28 × 10⁷ cm⁻³, accounting for 95.7% of the total quantity concentration. After NTP was introduced, the peak quantity concentration in the latter interval showed a different downward trend under different gas source flow rates, while the particle quantity concentration in the former interval presented a slight change. This indicates that O₃ generated from the NTP injection system trends to react with large rather than small particles. When the gas source flow rates were 3 L min⁻¹ and 5 L min⁻¹, only the peak quantity concentration of particles with a diameter of 60–300 nm decreased. Although the O₃ mass concentration was larger at 3 L min⁻¹ and 5 L min⁻¹, the NTP injection system produced a small O₃ yield of 200–300 mg min⁻¹. O₃ preferentially reacted with particles that had the largest quantity concentration with a diameter of about 100 nm, having less reactions with other particle sizes. When the gas source flow rates were 7 L min⁻¹, 10 L min⁻¹ and 15 L min⁻¹, not only the maximum peak quantity concentrations of particles had a large drop, but also the peak quantity concentrations shifted to the smaller particle size from 100 nm to 80 nm. O₃ yield was sufficient when the flow was large, the particles with larger
diameter were easier oxidized by O₃; therefore, their peak quantity concentration shifted to smaller size. Quantity concentration of particles in the range of 6–25 nm increased slightly at 10 L min⁻¹ because some of large size particles were decomposed into smaller diameter particles via oxidation reaction. With increasing gas source flow rates, particle peak quantity concentrations declined but appeared to follow a bounce phenomenon. This is probably due to insufficient reactions caused by excessive flow.

Figure 4 presents the quantity concentration and proportion of different types of particles under different gas source flow rates. The total quantity concentration of PM emitted from the original engine was 2.72 × 10⁸/cm³. Once NTP was injected, a slight decrease in the total quantity concentration was observed when the flow rates were 3 L min⁻¹ and 5 L min⁻¹. When the flow rates were 7 L min⁻¹ and 10 L min⁻¹, the total quantity concentration decreased greatly and the removal rates of particles were 55.8% and 79.2%, respectively. However, the total quantity concentration significantly jumped at 15 L min⁻¹ compared to 10 L min⁻¹. Simultaneously, aggregated particle quantity concentration and ultrafine particle quantity concentration experienced similar trends. The nucleate particle quantity concentration showed a slight fluctuation under different gas source flow rates among which it rose at 10 L min⁻¹ for the decomposition of large particles. The nucleate particles, aggregated particles, and ultrafine particles accounted for 4.3%, 95.7%, and 49% of total particles from original engine, respectively. The proportions of nucleate particles and aggregated particles were obviously changed at 10 L min⁻¹ and the proportion of ultrafine particles climbed to a peak at 10 L min⁻¹ and then decreased with increasing gas flow rates. When the gas source flow rate was 10 L min⁻¹, the variation of the different mode particle proportion was obvious, which was mainly caused by a 96.8% removal of particles with a diameter of 60–600 nm. The geometric mean diameter of particles under different gas source flow rates was calculated via Formula 4 and Formula 5 as shown in figure 5. The geometric mean particle diameter of original particles was 96 nm, and as the flow rate increased to 10 L min⁻¹, the geometric mean particle diameter had a larger drop to 37 nm.

The smaller geometric mean particle diameter means that large particles were oxidized or removed. Excessive flow rate above 10 L min⁻¹ leaded to bigger geometric mean particle diameter. Therefore, the purification effect of particles weakened with NTP treatment.

3.3. Effects of gas source flow rate on composition and apparent activation energy of diesel particles

The weight loss process of PM could be divided into two stages. The variation of mass loss with temperature was obtained via derivation of the TG curve and there were two peaks of mass loss rate curve corresponding to two weight loss stages, respectively. To further explore the effect of NTP on PM, four characteristic temperatures (T_s, T_{max1}, T_{max2}, and T_e) and apparent activation energy (E_a) were selected as the evaluation indexes for the PM oxidation activity.

(1) Starting ignition temperature T_s:
the temperature, at which the mass loss reached 10% of the initial sample mass during the oxidation process, was defined as the starting ignition temperature.

(2) The maximum oxidation rate temperature in the first stage T_{max1}:
the temperature corresponding to the first peak of the mass loss rate curve was the maximum oxidation rate temperature of the first stage.

(3) The maximum oxidation rate temperature in the second stage T_{max2}:
the temperature corresponding to the second peak of the mass loss rate curve was the maximum oxidation rate temperature of the second stage.

(4) The final burning temperature T_e:
the temperature at which the PM mass loss reached 99% was chosen as the final combustion temperature.

(5) Apparent activation energy E_a:
The Arrhenius method was used to calculate the apparent activation energy of PM via data obtained from TG analysis.
\[ \ln \left( -\frac{dm}{m dt} \right) = \ln(\text{AP}_2) - \frac{E_a}{RT} \]  

(6)

where \( m \) (g) is the mass of PM; \( t \) (s) is the time of the temperature rise process in the TG test; \( \text{PO}_2 \) (Pa) is the oxygen partial pressure; \( R \) is the gas constant, 8.314 J/K · mol; \( T \) (K) is the temperature in the TG test; \( A \) is the pre-exponential factor and \( E_a \) (kJ/mol) is the apparent activation energy.

The straight-line slope \( b \) was obtained via linear fitting with \( 1/ T \) and \( \ln \left( -\frac{dm}{m dt} \right) \) as the vertical and horizontal coordinates of the map and the apparent activation energy \( E_a \) is equal to \(-Rb\). Because the TG curve of PM is mainly divided into two stages which means the material composition of the two stages was different, the apparent activation energy in the two phases was also different. \( E_{a1} \) and \( E_{a2} \) represent the apparent activation energy of the substances in the first and second stages.

During the two stages of the TG process of PM, the temperature of the first weight loss stage ranged between 100 °C and 400 °C, which were the volatilization and oxidation of the volatile matter such as soluble organic fraction (SOF) and hydrocarbons. The temperature of the second weight loss stage ranged between 400 °C and 800 °C, which was mainly due to the oxidation of solid carbon in the samples [27]. Figure 6 illustrates the TG curves of the particles under different gas source flow rates. There were significant differences in the TG curves of the particles treated by NTP compared to the original engine. When the gas source flow rates were 3 L min \(^{-1}\) and 5 L min \(^{-1}\), the TG curve had obviously moved up, indicating that the composition of the particles had changed. When the gas source flow rates were 7 L min \(^{-1}\), 10 L min \(^{-1}\), and 15 L min \(^{-1}\), shapes of PM TG curve after NTP treatment differed from those of the original particles, which was caused by the change of the particle oxidizing activity.

The mass fraction of volatile matter and solid carbon in PM under different gas source flow rates is shown in figure 7. The proportion of volatile matter and solid carbon of the original particles were 67.2% and 32.8%, respectively. After NTP treatment, the proportion of volatile matter decreased, whereas the proportion of solid carbon increased. When the flow rates were 3 L min \(^{-1}\) and 5 L min \(^{-1}\), the yield of \( \text{O}_3 \) was small, volatile matter was easier to react with \( \text{O}_3 \). Therefore, volatile matter in the PM obviously decreased and component content changed greatly. When the flow rates were 7 L min \(^{-1}\), 10 L min \(^{-1}\), and 15 L min \(^{-1}\), the yield of \( \text{O}_3 \) was larger, and most of the large size particles were greatly reduced. Smaller size particles contained more volatile matter compared to larger size particles. As a result, the proportion of volatile matter in the sampled particles under large flow rates was much higher than that under small gas source flow rates [27].

The oxidation activity of PM represents the degree of difficulty of the PM oxidation. Figure 8 shows the characteristic temperatures of PM under different gas source flow rates. \( T_{max1} \) and \( T_{max2} \) indicate the temperatures corresponding to the maximum oxidation rates of volatile matter and solid carbon in the first and second stages, respectively.
system trended to react with the large rather than small ones particles.

(2) When the gas source flow rate was 10 L min\(^{-1}\), the total quantity concentration decreased strongly where the removal rate of particles was 79.2%, and the variation of the different mode particle proportion was obvious. The geometric mean particle diameter of the original engine was 96 nm, and as the flow rate increased to 10 L min\(^{-1}\), the geometric mean particle diameter had a larger drop to 37 nm.

(3) The volatile matter proportion and solid carbon proportion of the original particles were 67.2% and 32.8%, respectively. After NTP treatment, the proportion of volatile matter fell while the proportion of solid carbon increased. The proportion of volatile matter in the sampled particles under large gas source flow rates was much higher than under small flow rates.

(4) NTP could improve the oxidation abilities of volatile matter as well as those of solid carbon. However, the NTP gas source rate had little effect on the oxidation activity of volatile matter, while it strongly influenced the oxidation activity of solid carbon. Generally, a better effect was observed for a gas source flow rate of 10 L min\(^{-1}\).

(5) Considering the quantity concentration and oxidation activity of particles, a gas source flow rate of 10 L min\(^{-1}\) was more appropriate for the purification of particles. When the flow rate was small, the O\(_3\) yield was not enough to remove PM. The O\(_3\) concentration was too low due to the deterioration of the discharge effect and the cost increased at the large gas source flow rate.

Acknowledgments

This work is currently supported by National Natural Science Foundation of China (No. 51676089), the major projects of natural science research in colleges and universities in Jiangsu Province (No. 16KJA470002), and the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PADA).

ORCID iDs

Linbo GU (顾林波) @ https://orcid.org/0000-0002-6517-8104

Reference


4. Conclusions

(1) When the gas source flow rate was large, not only the maximum peak quantity concentrations of particles showed a large drop, but the peak quantity concentrations also shifted to smaller particle sizes, ranging from 100 nm to 80 nm. O\(_3\) generated via the NTP injection

Figure 8 shows that the starting ignition temperature \(T_0\) and \(T_{\text{max}}\) were about 135 °C and 181 °C respectively, and little fluctuations were caused by the change of the gas source flow rate. The final burning temperature \(T_f\) of the particles from the original engine was 623 °C and a slight fluctuation could be observed after NTP treatment. The fastest oxidation rate of solid carbon in original PM appeared at 592 °C. The oxidation temperatures of solid carbon decreased and the oxidation activity was enhanced with increasing gas source flow rates. The apparent activation energy of particles under different gas source flows is calculated via Formula 6 and results are shown in figure 9. The apparent activation energy of the volatile matter and solid carbon corresponding to the two stages of the PM TG process were quite different. For the original PM, \(E_{a1}\) and \(E_{a2}\) were 43.61 kJ mol\(^{-1}\) and 211.67 kJ mol\(^{-1}\), respectively, which means that volatile matter could be oxidized at a lower temperature compared to solid carbon. After NTP treatment, \(E_{a1}\) showed no significant difference to the change of gas source rates, dropping to 23.2 kJ mol\(^{-1}\) on average. \(E_{a2}\) however, continuously decreased before 10 L min\(^{-1}\), reaching the lowest point at 10 L min\(^{-1}\), after which it had a slight increase at 15 L min\(^{-1}\). This is consistent with the decrease in oxidation temperature of solid carbon after NTP treatment. The results indicate that NTP could improve the oxidation ability of volatile matter and solid carbon. However, the NTP gas source flow rate had little effect on the oxidation activity of volatile matter, while it considerably influenced the oxidation activity of solid carbon. Generally, a better effect could be achieved with a gas source flow rate of 10 L min\(^{-1}\).

Figure 9, Apparent activation energy of particulate matter under different gas source flow rates.
[20] Shi Y X et al 2016 J. Xi’an Jiaotong Univ. 50 74
[26] Li B 2013 Effects of fuel formulation on surface functional groups and oxidation reactivity of diesel engines particulate matters PhD Thesis Tianjin University, Tianjin, China (in Chinese)