Analysis of the effect of particle–wall collision process in DPF on the spatial structure of smoke cake layer

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Abstract
Based on the rebound model of particle–wall collision, the influence of adhesion force on the deposition process of particles on the smoke cake wall was studied by using atomic force microscopy (AFM) and automatic specific surface area (BET) and pore size distribution analyzer. The interaction between the deposition process and the spatial structure of smoke cake was analyzed. The results show that with the increase of diesel engine speed, Young’s modulus of particles decreases and the average particle size increases; the kinetic energy of particles impacting on the surface of smoke cake layer in diesel particle filter (DPF) increases; when the velocity of particles with the same particle size entering the wall increases, the maximum compression distance between particles and the surface of the smoke cake layer increases; and the adhesion force and adhesion energy increase. With the increase of diesel engine speed, the box counting dimension of smoke cake layer in DPF increases from 1.9478 to 1.996, the characteristic radius of pores decreases from 15.32 nm to 7.53 nm, the average pore diameter decreases, and the average pore volume increases. When the fractal dimension increases from 2.633 to 2.732, the deformation degree of particles increases, the smoke cake layer becomes more compact and dense, the internal structure of pores becomes more complex, the surface of pores is rougher, and particle adhesion requires overcoming larger adhesion barriers when particles adhere.

Keywords Particle · Collision · Smoke cake layer · Spatial structure · Pore

Introduction
Diesel vehicles have become an important power source of vehicles, but the particles emitted from combustion are the main cause of haze and environmental pollution (Nam et al. 2010; Xu et al. 2019; Yildiz et al. 2019). In addition, nanoparticles are easy to enter the human body (Guan et al. 2015; Yang et al. 2017), which poses a great threat to human health. Many countries in the world put forward strict requirements on the mass concentration and quantity concentration of diesel particulate matter emission (Ayodhya and Narayananappa 2018). In order to reduce the emission of particulate matter from diesel engine combustion, a lot of work has been done, such as optimizing diesel engine combustion (Wei et al. 2020; Jie et al. 2020), optimizing diesel engine control strategy (Yaopeng et al. 2020), and implementing diesel particulate filter (DPF) (Fang et al. 2017). At present, DPF is the main technical means to reduce diesel particulate emissions (Rodriguez-Fernandez et al. 2011; Pi-qiang et al. 2019).

The diesel particulate filter has a penetration window for trapping nuclear mode particles with a particle size of 20–30 nm and accumulated particles of about 60–100 nm, and the trapping effect on micro- and nanoparticles is reduced (Sun et al. 2016). With the increase of the thickness of the smoke cake layer formed on the surface of the DPF carrier, the trapping effect of micro- and nanoparticles will be enhanced, but at the same time, the back pressure in the exhaust pipe will increase, which will affect the fuel efficiency of the diesel engine (Chung et al. 2020; Meng et al. 2020). In order to prevent this, regeneration is usually used to remove the cake layer in DPF. However, in both active regeneration and passive regeneration, the pore structure of the smoke cake layer will affect the regeneration efficiency, so it is necessary to study the pore structure of the smoke cake layer. The collision process of particles in DPF directly affects the formation process of the smoke cake layer (Ulrich et al. 2018) and has an

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important influence on the pore structure, surface roughness, and other spatial structures of the smoke cake layer. Studying the relationship between the particle–wall collision process and the spatial structure characteristics of the smoke cake layer is of great significance to the discussion of the deposition process of particles in the DPF, and provides a certain theoretical basis for reducing pressure loss, improving the regeneration efficiency of DPF and the capture efficiency of DPF for particles (Pilar Orihuela et al. 2018; Tsuneyoshi and Yamamoto 2012; Zhang et al. 2019).

When the diesel exhaust particles enter the DPF, they collide with the surface of the cake layer, and gradually deposit on the surface of the DPF substrate and form a smoke cake layer. Liati et al. (2010) observed microscopic smoke cake layer deposited in the DPF by scanning electron microscopy and transmission electron microscopy (SEM/TEM), which showed that soot aggregates form an approximately 200–500-μm-thick, inhomogeneous porous cake consisting of several superposed layers corresponding to different soot generations. In a study on particle–wall collision process and pore structure characteristics of smoke cake layer, Meng et al. (2014, 2019) and Yuheng et al. (2019) used a two-dimensional laser displacement sensor and SEM to observe the formation process of the smoke cake layer. The results showed that with the increase of filtration speed, the packing density of particles increased, and the permeability coefficient and porosity of the particle layer decreased. Payri et al. (2011) proved that the pressure drop and filtration process depended on the pore structure properties (permeability, porosity, and pore size) of the cake layer. Wang et al. (2020) studied the morphology and fractal dimension of ash deposits in DPF. The study showed that the fractal dimension of the ash deposit pore surface calculated by the Avnir equation reflects the irregularity of the ash deposit pore surface.

The above scholars have studied the formation process and pore structure characteristics of the smoke cake layer in DPF, which provides a good basis for optimizing the capture and regeneration performance of DPF. However, most of the studies neglect the influence of particle–wall collision on the particle deposition process and the pore structure characteristics of the smoke cake layer. Liu et al. (2011) believes that the critical adhesion velocity is important for filtration and surface deposition processes, as more attention is paid to the ability to trap particles than to how much energy is recovered after impact rebound.

To investigate the influence of critical adhesion velocity on filtration and surface deposition processes, a particle–wall impact model is required. Breure and Almohammed (2015) established an elastic particle wall collision model considering the effect of adhesion force, which shows that the model considering the adhesion force has a great influence on the particle wall collision. Ulrich et al. (2018) studied the effect of adhesion and rebound behavior on the deposition process of ash particles generated by coal and biomass combustion, and showed the particle kinetic energy, the substrate roughness, the substrate properties, and forces between particles and wall (adhesion or van der Waals forces) are the main factors that affect the deposition of ash particles.

In this work, the particle–wall collision model is first applied to analyze the formation process of smoke cake layer in DPF. Young’s modulus, adhesion force of particles, and the pore characteristics of smoke cake layer generated at different diesel engine speeds were measured by AFM or automatic specific surface area and pore size distribution analyzer. According to the dynamics of the collision and rebound of the particles and the wall, the influence of the characteristic parameters (such as adhesion and compression distance) and the pore characteristics of the smoke cake layer is analyzed.

**Materials and methods**

The test is carried out on a diesel engine test bench, using a 186FA diesel engine. The performance and structural parameters of the diesel engine are shown in Table 1. A particle trap with cordierite filter was installed at the exhaust outlet of the diesel engine. Figure 1 is a schematic diagram of the DPF structure and the smoke cake layer, and the structure parameters of the DPF are shown in Table 2. Through the NOVA3000e specific surface area and pore size distribution analyzer of Kangta Company of the USA, the pore distribution of the smoke cake layer generated in the DPF is measured; the morphology and microstructure of the smoke cake layer and particles deposited in the DPF are measured by SEM/TEM. Measurements were carried out using the Dimension Icon atomic force microscope of the American Bruker company, and the exhaust particles under different working conditions were selected to measure the adhesion between the particles and the surface of the cake layer.

During the test, the working condition is set to 100% load, and the speed is set to 1500 r/min, 2700 r/min, and 3600 r/min. Collecting diesel engine exhaust particles and DPF slices covered with smoke cake under different working conditions, when observing the shape of the smoke cake layer and particles on the DPF slice through SEM/TEM, gold spraying treatment is required. The pore structure parameters of the smoke cake layer were analyzed by DFT method to obtain pore-related parameters such as pore size distribution and average pore size of the smoke cake layer, and the isothermal adsorption data were processed by the FHH method to obtain the fractal dimension of the smoke cake layer (Hassan et al. 2020). The automatic specific surface area and pore size distribution analyzer is shown in Fig. 2.

In order to better understand the complex process of particle adhesion on the wall of the cake layer, atomic force microscopy (AFM) was used to measure the adhesion force
between the particles and the smoke cake layer (Wang et al. 2013). The force–displacement curve generated during the withdrawal phase during the measurement reflects the relationship between the adhesion force and the distance between the probe and the wall surface, as shown in Fig. 3, where point A is the maximum adhesion force received.

Mathematical model of collision

In order to consider the process of particle collision caused by the velocity of particle–wall collision, and obtain the continuous and dynamic change process of adhesion force, a particle–wall collision model was established.

The particle normal collision equation (BD model) was proposed (Brach and Dunn 1995) as

\[
m \frac{\delta^2 \delta}{\delta t^2} = -F_H \left( 1 + C_H \frac{d\delta}{dt} \right) - F_A \left( 1 + C_A \frac{d\delta}{dt} \right)
\]

where \( F_A \) represents the Hertzian and adhesion forces, \( C_H \) and \( C_A \) are the damping coefficients of \( F_H \) and \( F_A \), \( \delta \) is the amount of overlap between two particles, \( t \) is the period of contact, and \( m \) is the particle mass. \( F_H \) is the classical Hertzian restoring force, which can be described as follows:

\[
F_H = K \sqrt{r} \delta^{3/2} \\
K = \frac{3\pi(k_1 + k_2)}{1 - \nu_i^2} \frac{1}{\pi E_i}
\]

where \( r \) is the particle radius, \( K \) is the Hertz stiffness, \( \nu_i \) is the Poisson ratio of the two surfaces, \( E_i \) is the Young modulus of the two surfaces.

The adhesion resistance during collision is as follows:

\[
\begin{align*}
F_A &= 2\pi a f_0 C_R \\
f_0 &= \left( \frac{9Kr\omega_A}{2\pi} \right)^{1/2}
\end{align*}
\]

where \( a \) is the contact radius between the particle and the wall; \( C_R \) is the surface roughness correction coefficient, which is generally 0.05–1 (Biryukov and Kadomtsev 2002; Cheng et al. 2002); and \( \omega_A \) is the surface energy of the system (Dong et al. 2019). In this paper, the surface energy of the particles is 2.7 J/m\(^2\) (Liu et al. 2015; Gilman 1960). The surface energy can also be regarded as a macroscopic characterization of van der Waals force interaction between molecules (Liu et al. 2009).

Kim and Dunn (2007) simplified the BD model. Algebraic approximations of the resulting equation’s integrals can be made to arrive at an explicit expression for the particle’s

| Parameter | Value or type |
|-----------|---------------|
| Type      | Wind cooling  |
| Bore × stroke (mm) | 86 × 72 |
| Compression ratio | 19 |
| Rated power (kW) | 6.3 |
| Rated speed of diesel engine (r/min) | 3600 |
| Maximum torque of diesel engine (N·m) | 20.1 |
| Speed corresponding to maximum torque condition (r·min\(^{-1}\)) | 2700 |

Table 1 Parameters of 186FA diesel engine

| Parameter                  | Value |
|----------------------------|-------|
| Material                  | Cordierite |
| Length (mm)               | 305   |
| Pore density (cpsi)       | 200   |
| Wall thickness (mm)       | 0.398 |
| Side length of inlet and outlet duct (mm) | 1.398 |
| Porosity (%)              | 040   |
| Micropore diameter (mm)   | 0.024 |

Table 2 Parameters of particle filter
The normal critical adhesion velocity (Haihang and Junfang 2016) is used to evaluate whether the particles adhere to the wall. When the particles reach the normal critical adhesion velocity, the normal recovery coefficient is 0, and the particles adhere to the surface. When the particle velocity is less than the velocity, the particles adhere to the surface.

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\[
\delta = \left( \frac{5mv^2}{4K} \right)^{\frac{5}{2}} \quad (4)
\]

\[
V_c = \left[ 2C_1 \rho f_0 \left( \frac{5}{4K} \right) \left( \frac{r}{m_0} \right)^{\frac{3}{5}} \right]^{1/5} r^{5/4} \quad (5)
\]

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Results and discussion

Particle characteristic parameters

Young’s modulus

Figure 4 shows the variation of Young’s modulus distribution of particles at different speeds. It can be seen from the figure that the distribution of Young’s modulus of particles presents a normal distribution, mainly concentrated in the range of 150–300 MPa, but the proportion of each Young’s modulus interval is not more than 15%. With the increase of diesel engine speed, the characteristic value of Young’s modulus decreases gradually.

Table 3 shows the calculated average Young’s modulus of exhaust particles at different speeds. It can be seen from the table that with the increase of diesel engine speed, diesel engine exhaust flow rate increased from 2.83 to 6.78 m/s, and the average Young’s modulus of particles increases from 190 to 306 MPa. The more rigid the exhaust particles are, the less likely they are to deform. When the particles collide with the wall, the deformation degree of the particles decreases, and it is easy to rebound. When the particles adhere to the wall, the contact area becomes smaller and the agglomeration degree decreases.

Average particle diameter

Figure 5 is the morphology of diesel exhaust particles captured by SEM. The geometric average diameter of carbon particles was analyzed by Nano Measurer software. It was found that when the diesel engine speed increased from 1500 to 3600 r/min, the average particle diameters of the exhaust particles are 26.14 nm, 25.05 nm, and 22.93 nm. This is mainly because, on the one hand, with the increase of the speed of the diesel engine, the combustion time in each cycle cylinder is shortened, and the soot generated by combustion does not have enough time to condense and grow, so that the number of particulate matter entering the exhaust pipe increases, the particle size dispersion is small, and the average particle size decreases; on the other hand, with the increase of the speed of the diesel engine, the time for the diesel exhaust particles to collide and condense in the exhaust pipe decreases, resulting in a reduction in particle size. The change of the particle size of diesel exhaust particles has an important impact on the collision motion of particles in the DPF.

Motion characteristic parameters

Adhesion

Figure 6 shows the AFM force curves of particles at different diesel engine speeds. The force measured away from the stage
is the adhesion. It can be seen from the measured results that with the increase of rotating speed, the adhesion force of particles increases from 12.76 to 23.56 nN, the adhesion between particles is enhanced, and it is easier to agglomerate.

The adhesion force model uses the JKR model in contact mechanics in this work. In the particle–wall contact process, the energy related to adhesion depends on the interface energy and elastic strain energy between the particle and the wall. Young’s modulus reflects the ability of particles to resist deformation and also affects the adhesion force during particle–wall collision (Derjaguin et al. 1975; Johnson et al. 1971). Surface energy is mainly related to particle size. Therefore, the adhesion force when particles collide with the wall under different Young’s modulus, particle size, and flow velocity is calculated and analyzed.

Figure 7 shows the relationship between particle adhesion and flow rate at different Young’s modulus and particle size. The experimental measurement value in the figure is the result of atomic force microscope measurement. In the model, the value of $C_R$ is 0.084. Comparing the adhesion obtained by the experiment with the value calculated by the model, it can be seen that the variation of the adhesion obtained by the model differs little from the results obtained by the atomic force measurement, which verifies the accuracy of the model.

In addition, Fig. 7 shows the dynamic change of adhesion force with velocity and particle size. At different particle sizes, the adhesion between the particles and the wall of the cake layer increases with the increase of the flow rate; with the increase of the Young’s modulus, the adhesion between the particles and the wall surface of the cake layer shows an increasing trend; the adhesion between the particles and the wall surface of the cake layer reflects the energy barrier of the particles detaching from the wall surface of the cake layer. Under the same compression distance, the larger the particle size of the particles, the greater the adhesion between the particles and the wall surface of the cake layer. When the attachment force is greater, the particles need to overcome a higher energy barrier to break away from the cake wall. The particles are easier to deposit on the wall of the cake layer, and the formed smoke cake wall is more compact.

### Compression distance

Figure 8 shows the effect of particle velocity, particle size, and Young’s modulus on the compression distance between the particles and the smoke cake layer. It can be seen from the figure that as the particle incidence speed and particle size increase, the compression distance between the particle and the smoke cake layer increases. This is because the large particles under high-speed motion have higher kinetic energy. When the particles collide with the wall surface of the cake layer, the kinetic energy is converted into potential energy. The more elastic potential energy the particles are subjected to, the greater the compression of the particles and the degree of deformation. At the same incident velocity and particle size, the larger the Young’s modulus of the particles, the smaller

| Speed (r/min) | Current speed (m s$^{-1}$) | Average Young’s modulus (MPa) |
|--------------|----------------------------|------------------------------|
| 1500         | 2.83                       | 190                          |
| 2700         | 5.08                       | 221                          |
| 3600         | 6.78                       | 306                          |
**Fig. 5** TEM images of exhaust particulates from diesel engines at different speeds: a 1500 r/min; b 2700 r/min; c 3600 r/min

**Fig. 6** Adhesion force–displacement curves of particles at different speeds: a 1500 r/min; b 2700 r/min; c 3600 r/min

**Fig. 7** Relationship between particle adhesion and flow velocity under different particle sizes and Young’s modulus: a $E_i = 190$ MPa; b $E_i = 221$ MPa; c $E_i = 306$ MPa
the compression distance between the particles and the smoke cake layer. This is because with the increase of Young’s modulus of the particles, the particles are not easy to deform and the compression distance decreases. With the low Young’s modulus, high-speed movement, and large-sized particles gradually colliding and adhering to the wall surface, the formed smoke cake layer will be more compact and the degree of agglomeration will be higher.

**Critical adhesion velocity**

Figure 9 shows the effect of particle size and Young’s modulus on the critical adhesion speed. The normal critical adhesion velocity reflects the critical velocity at which particles can be trapped. This is of great significance to the study of DPF filtration and surface deposition processes because the research in this area focuses more on whether the particles can be trapped, not how much energy is recovered after the impact and rebound. It can be found from Fig. 9 that with the increase of particle size, the normal critical adhesion velocity of particles gradually decreases; with the increase of Young’s modulus of particles, the normal critical adhesion speed of particles gradually decreases; when the particle size is less than 40 nm, the normal critical adhesion speed of particles decreases rapidly with the increase of particle size; and when the particle size is greater than 40 nm, the normal critical adhesion speed of particles decreases with the increase of particle size. The main reason is that, according to the contact energy loss theory (Liu et al. 2011; Xie et al. 2015), the critical adhesion speed $V_c$ is related to the energy loss at the first contact, and is proportional to $R^{-5/6}$ and $E^{-1/3}$, which is related to the particle size and Young’s modulus. Therefore, the smaller the particle size, the greater the critical adhesion velocity, and the larger the Young’s modulus of the particles, the lower the critical adhesion velocity.

**Spatial structure analysis of smoke cake layer**

Smoke cake layer microstructure topography and box counting

Figure 10 shows the morphology of smoke cake layer and particles obtained by SEM. It can be seen from the figure that there are a large number of clusters formed by agglomeration of particles on the surface of DPF slice, and these clusters combine with each other to form a smoke cake layer. The surface of the smoke cake layer is irregular and rough. Under the influence of different temperatures and pressures, the particles or clusters in the cake layer are not completely in contact, thus forming a large number of intergranular pores. Such pores are the most common and most complex in the smoke cake layer, with strong heterogeneity. At the same time, there are micro-cracks in the smoke cake layer. There are two main types of micro-cracks in the DPF smoke cake layer, which are interlayer cracks and tensile cracks. The tensile cracks mainly form cracks in the smoke cake layer due to the influence of temperature and pressure. These micro-cracks can connect the large pores, improve the permeability of the...
smoke cake layer, and reduce the pressure drop of the DPF due to the smoke cake layer (Zhao et al. 2018).

According to the SEM pictures obtained, the fractal dimension of the smoke cake layer is calculated by the box dimension method (Yu et al. 2014). The box dimension method mainly covers the picture after the binarization process by gradually getting smaller boxes. The number of boxes in the black part is recorded as $N(r)$, and $r$ is the box side length. When $r$ approaches 0, the fractal dimension of the box dimension method is obtained:

$$D = \lim_{r \to 0} \frac{\log N(r)}{\log r}$$  \hspace{1cm} (6)

$D$ is the fractal dimension measured by box dimension method, but in practical application, it can only take a limited side length $r$. Generally, according to different sizes of $r$ and its corresponding $N(r)$, the following equation is fitted by the least squares method:

$$\log N(r) = Ds \times \log r + h$$  \hspace{1cm} (7)

The straight line slope $Ds$ is the fractal dimension value calculated by box dimension method.

The box counting dimension of SEM mainly reflects the characteristics of micropore structure on the surface of the smoke cake layer. The box counting dimension of particles is obtained by analyzing the distribution, quantity, and size of micropores in picture, which is used to evaluate the micropore structure of the smoke cake layer. The larger the box counting dimension of particles in the layer is, the smaller and more complex the pore structure is, and the more regular the distribution is. Table 4 shows the box counting dimensions of particles in the smoke cake layer at different rotational speeds. It can be seen from Table 4 that the box counting dimension of particles in the cake layer increases from 1.9478 to 1.996 with the speed increasing from 1500 to 3600 r/min. The reason for the increase of box counting dimension of smoke cake layer is that with the increase of diesel engine speed, the exhaust flow rate increases, the movement speed of particles increases, the maximum compression distance when particles collide with the layer surface becomes larger, the adhesion between the particles and the surface of the smoke cake layer becomes larger, and the particles become closer. At the same time, the newly formed smoke cake layer and the original smoke cake layer are also closer, and the interlayer cracks between the smoke cake layers are reduced. The other reason is that the particle distribution on the surface of the smoke cake layer is relatively uneven. The DPF material is mainly porous medium with a large number of pores. With the DPF continuously capturing particles, enough particles need to be deposited in

| Diesel engine speed (r/min) | $r$  | Box counting dimension |
|---------------------------|-----|------------------------|
| 1500                      | 0.997 | 1.9478                 |
| 2700                      | 0.998 | 1.964                  |
| 3600                      | 0.998 | 1.996                  |

**Fig. 10** SEM image of the smoke cake layer formed at different rotating speeds: a 1500 r/min; b 2700 r/min; c 3600 r/min

**Fig. 11** Pore distribution of smoke cake layer at different rotating speeds
the pores to form the smoke cake layer, which leads to the uneven distribution of the formed smoke cake layer. However, with the increase of the capture time, the thickness of the smoke cake layer increases, and the heterogeneity of the smoke cake layer will gradually decrease.

Spatial pore structure

Figure 11 shows the pore distribution of the smoke cake layer formed at different rotational speeds. It can be seen that the pore radius of the smoke cake layer formed at 1500 r/min, 2700 r/min, and 3600 r/min speeds is mainly concentrated at 15.32 nm, 13.25 nm, and 7.53 nm. The results show that the pore radius of the smoke cake layer formed by high speed is more concentrated on the smaller radius than that at low speed, the smoke cake layer formed by high speed is more compact, and the pore between particles is smaller. In addition, the effect of rotating speed on the number of pores with radius greater than 20 nm is relatively small and the number of pores decreases with the increase of pore size.

Figure 12 shows the relationship between the cumulative pore volume and the average pore diameter with the speed of the diesel engine. As the speed of the diesel engine increases, the average pore size of the particles decreases and the cumulative pore volume increases. There is no obvious correlation between cumulative pore volume and average pore diameter. It can be seen from the figure that although the average pore size of the smoke cake layer formed at a high rotation speed of 3600 r/min is small, the cumulative pore volume is very large. The permeability of the smoke cake layer is stronger than that of the smoke cake layer formed at low speed. This is mainly because, as the speed of the diesel engine increases, the exhaust gas flow rate increases, the smoke cake layer formed in the DPF withstands greater pressure, and a larger pore volume is required to pass through the airflow.

In order to further understand the fractal characteristics of the pores of the smoke cake layer on the three-dimensional level, the fractal dimension is introduced to quantitatively analyze the pore structure formed in the smoke cake layer. Through the FHH equation in the nitrogen adsorption method, the fractal dimension of the smoke cake layer is obtained. The fractal dimension is usually between 2 and 3 (Liu et al. 2020; Yang et al. 2019). The larger the fractal dimension value, the rougher the surface of the solid adsorbent, and the smoother conversely.

Figure 13 shows the isotherm adsorption data and fitting curve of the smoke cake layer particles at different diesel engine speeds. Table 5 shows some parameters and fractal dimensions of the curve obtained by fitting at different diesel engine speeds. It can be seen from Table 5 and Figure 13 that the fitting result obtained by using the FHH equation has little deviation from the measured data, and the calculated fractal dimension has a high accuracy, and the fractal dimension increases from 2.633 to 2.732 as the speed increases from 1500 to 3600 r/min. It shows that the pore surface of the smoke cake layer in DPF is rougher at high speed. Combined with other pore characteristics, it can be found that with the increase of rotating speed, the average pore diameter decreases, the average pore volume increases, the fractal dimension increases, the pore structure becomes more complex, and the pores become narrower, longer, and smaller. It is found that with the increase of surface roughness, the adhesion between particles and the wall decreases gradually. With the increase of pore surface roughness, the adhesion force decreases, the normal recovery coefficient increases, and the normal critical adhesion velocity decreases.

Conclusions

The atomic force microscope and pore size distribution analyzer were used to study the relationship and mutual influence of the
adhesion force on the collision process of diesel engine exhaust particles in the DPF and the spatial structure of the smoke cake layer. The relationships between the adhesion force and Young’s modulus, and the critical trapping velocity and the pore distribution of the smoke cake layer were analyzed.

1. As the speed of diesel engine increases, the average Young’s modulus of diesel exhaust particles increases from 185 to 306 MPa. The rigidity of exhaust particles increases and it is easier to rebound when particles collide with the wall of the cake layer.

2. As the speed of diesel engine increases, the compression distance between particles and wall increases, the adhesion force and energy increase, the adhesion between particles and wall increases, and the energy barrier increases. When particles with the same incident speed and particle size collide with wall, the adhesion force decreases, the normal recovery coefficient increases, and the normal critical adhesion speed increases. As critical adhesion rate decreases, the particles are more difficult to adhere to the pore surface.

3. With the increase of diesel engine speed, the fractal dimension of the cigar layer increases, the pore surface roughness increases, the box counting dimension of particles in the cigar layer increases from 1.9478 to 1.996, the average pore diameter decreases, the average pore volume increases, the particle and particle layers become more compact, the interlayer cracks between the cigar layers decrease, and the final cigar layer agglomeration degree becomes higher.

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| Diesel engine speed (r/min) | 1500         | 2700         | 3600         |
|-----------------------------|--------------|--------------|--------------|
| Intercept                   | 2.65077 ± 0.00937 | 2.94798 ± 0.00245 | 3.38368 ± 0.00404 |
| Slope                       | −0.36756 ± 0.00669 | −0.31049 ± 0.00168 | −0.26805 ± 0.00286 |
| Pearson’s $r$               | −0.99713               | −0.99858               | −0.99955               |
| $R^2$ (COD)                 | 0.99427               | 0.99715               | 0.9991               |
| Fractal dimension           | 2.633               | 2.690               | 2.732               |

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**Data availability** All relevant data are within the manuscript and available from the corresponding author on request.

**Compliance with ethical standards**

**Consent to participate** All authors have given consent to their contribution.

**Consent to publish** All authors have agreed with the content and all have given explicit consent to publish.

**Competing interests** The authors declare that they have no conflict of interest.

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**References**

Ayodhya AS, Narayanappa KG (2018) An overview of after-treatment systems for diesel engines. Environ Sci Pollut Res 25:35034–35047

Biryukov DG, Kadomtsev IG (2002) Dynamic elastoplastic interaction between an impactor and a spherical shell. J Appl Mech Tech Phys 43:777–781

Brach RM, Dunn PF (1995) Macrodynamics of microparticles. Aerosol Sci Technol 23(1):51–71

Breure M, Almohammed N (2015) Modeling and simulation of particle agglomeration in turbulent flows using a hard-sphere model with deterministic collision detection and enhanced structure models. Int J Multiphase Flow 73:171–206

Cheng W, Dunn PF, Brach RM (2002) Surface roughness effects on microparticle adhesion. J Adhes 78(11):929–965

Chung TL, Akroyd J, Eaves N (2020) Investigation of the impact of the configuration of exhaust after-treatment system for diesel engines. Appl Energy 267:114844

Derjaguin B, Muller V, Toporov Y (1975) Effect of contact deformations on the adhesion of particles. J Colloid Interface Sci 53(2):314–326
Dong M, Li JY, Yan S, Sufen Li (2019) Numerical investigation on deposition process of submicron particles in collision with a single cylindrical fiber. J Aerosol Sci 129:1–15
Fang J, Meng ZW, Li J, Pu Y, du Y, Li J, Jin Z, Chen C, G. Chase G (2017) The influence of ash on soot deposition and regeneration processes in diesel particular filter. Appl Therm Eng 124:633–640
Gilman J (1960) Direct measurements of the surface energies of crystals. J Appl Phys 31(12):2208–2218
Guann B, Zhan R, Lin H, Huang Z (2015) Review of the state-of-the-art of exhaust particulate filter technology in internal combustion engines. J Environ Manag 154:225–258
Haihang C, Junfang L (2016) CFD simulation of the dynamic ultrafiltration process based on the foulant critical adhesion force. Acta entiae Circumstantiae 36(10):3636–3642
Hassan NM, Yan D, Nayima H (2020) Pore structure characteristics and fractal dimension analysis of low rank coal in the Lower Indus Basin, SE Pakistan. J Nat Gas Sci Eng 77:103231
Jie L, Ma B, Zhao H (2020) Combustion parameters optimization of a diesel/natural gas dual fuel engine using genetic algorithm. Fuel 260:116365
Johnson KL, Kendall K, Roberts AD (1971) Surface energy and the micro-, macro- and nano-scales. Combust Flame 157(9):1658–1670
Liu T, Song R, H, et al. (2015) Effect of surface properties of fuel soot deposited in catalyst diesel particulate filter. Environ Sci Pollut Res 22(1):16–26
Meng ZW, Pu Y, Yan Y et al (2014) Experimental investigation on the influence of filtration velocity on particulate deposition characteristics in DPF. Chin Intern Combust Eng 35(5):12–16
Meng ZW, Du Y, Li JS et al (2019) Experimental investigation on characterization of simulation soot deposited on diesel particulate filter. Trans CSICE 37(03):257–264
Meng ZW, Li JS, Fang J et al (2020) Experimental study on regeneration performance and particle emission characteristics of DPF with different inlet transition sections lengths. Fuel 262:116487
Nam E, Kishan S, Baldauf RW, Fulper CR, Sabisch M, Warila J (2010) Temperature effects on particulate matter emissions from light-duty, gasoline-powered motor vehicles. Environ Sci Technol 44(12):4672–4682
Payri F, Broatch A, Serrano JR, Piqueras P (2011) Experimental–theoretical methodology for determination of inertial pressure drop distribution and pore structure properties in wall-flow diesel particulate filters (DPFs). Energy 36(12):6731–6744
Pilar Orihuela M, Gómez-Martin A, Miceli P, Fino D et al (2018) Experimental measurement of the filtration efficiency and pressure drop of wall-flow diesel particulate filters (DPF) made of biomorphic silicon carbide using laboratory generated particles. Appl Therm Eng 131:41–53. https://doi.org/10.1016/j.applthermaleng.2020.120863
Pi-qi ang T, Cao C-y, Hu Z-y, Lou D-m (2019) Modeling of soot fragmentation that proceeds in a catalyzed diesel particulate filter of a diesel engine. Chem Eng J 375:122110
Rodriguez-Fernandez J, Oliva F, Vazquez RA (2011) Characterization of the diesel soot oxidation process through an optimized thermogravimetric method. Energy Fuel 25:2039–2048
Sun W, Liu G, Guo L et al (2016) Efficiency of DPF on ultrafine particles in a common-rail diesel engine. J Jinlin Univ (Engineering and Technology Edition) 46(01):133–139
Tsuneyoshi K, Yamamoto K (2012) A study on the cell structure and the performances of wall-flow diesel particulate filter. Energy 48(1):492–499
Ulrich K, Wieland C, Frandsen FJ, Splei thoff H (2018) Ash formation and deposition in coal and biomass fired combustion systems: progress and challenges in the field of ash particle sticking and rebound behavior. Prog Energy Combust Sci 68:65–168
Wang J, Li Y, Lian X et al (2013) Research of adhesion force between dust particles and insulator surface using atomic force microscope. High Voltage Eng 6:1352–1359
Wang H, Tan J, Ge Y et al (2020) Pore morphology and fractal dimension of ash deposited in catalyst diesel particulate filter. Environ Sci Pollut Res 27:11026–11037
Wei C, Pan J, Zuo Q, Zhang J, Wang Z, Zhang B, Zhu G, Fan B (2020) Combustion performance improvement of a diesel fueled Wankel stratified-charge combustion engine by optimizing assisted ignition strategy. Energy Convers Manag 205:112324
Xie J, Dong M, Li S F, et al. (2015) Experimental research on the effect of incident velocity on particle/surface collisions. J Eng Thermophys (05):1033–1037.
Xu C, Zhao J, Pan L (2019) A geographically weighted regression approach to investigate the effects of traffic conditions and road characteristics on air pollutant emissions. J Clean Prod 239:118084
Yang CQ, Wang YM, Wu LG, Li WS (2017) Preparation and application of the HCA catalyst materials. Rare Metal Mater Eng 46:2423–2427
Yang Y, Liu S, Zhao W, Wang L (2019) Intrinsic relationship between Langmuir sorption volume and pressure for coal: experimental and thermodynamic modeling study. Fuel 1:105–117
Yaopeng L, Jia M, Xu L, Bai X-S (2020) Multiple-objective optimization of ethanol/diesel dual-fuel engine at low loads: a comparison of reactivity controlled compression ignition (RCCI) and direct dual fuel stratification (DDFS) strategies. Fuel 262:116673
Yildiz I, Acikkalp E, Caliskan H et al (2019) Environmental pollution cost analyses of biodiesel and diesel fuels for a diesel engine. J Environ Manag 243(AUG.1):218–226
Yu Z, Lijian Z, Fanhao M et al (2014) Calculating SEM fractal dimension of concrete by MATLAB. Cement Eng 000(005):59–62
Yuheng D, Meng Z, Fang J et al (2019) Characterization of soot deposition and oxidation process on catalytic diesel particulate filter with ash loading through an optimized visualized method. Fuel 243:251–261
Zhang Y, Lou D, Tan P, Hu Z (2019) Experimental study on the emission characteristics of a non-road diesel engine equipped with different after-treatment devices. Environ Sci Pollut Res 26:26617–26627
Zhao J, Junk Y, Lei Z et al (2018) Effects of micro-fractures on gas flow in tight porous media. J China Univ Pet (Edition of Natural Science) 42(1):90–98

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