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REVIEW ARTICLE

Diesel particulate filter regeneration mechanism of modern automobile engines and methods of reducing PM emissions: a review

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Abstract
Diesel particulate filter (DPF) is considered as an effective method to control particulate matter (PM) emissions from diesel engines, which is included in the mandatory installation list by more and more national/regional laws and regulations, such as CHINA VI, Euro VI, and EPA Tier3. Due to the limited capacity of DPF to contain PM, the manufacturer introduced a method of treating deposited PM by oxidation, which is called regeneration. This paper comprehensively summarizes the most advanced regeneration technology, including filter structure, new catalyst formula, accurate soot prediction, safe and reliable regeneration strategy, uncontrolled regeneration and its control methods. In addition, due to the change of working conditions in the regeneration process, the additional emissions during regeneration are discussed in this paper. The DPF is not only the aftertreatment device but also can be combined with diesel oxidation catalyst (DOC), selective catalytic reduction (SCR) and exhaust recirculation (EGR). In addition, the impact of DPF modification on the original system of some old models has been reasonably discussed in order to achieve emission targets.

Keywords Diesel particulate filter · Regeneration · Regeneration control · Pressure drop

Introduction

High concentration particulate matter (PM) in the air has always been one of the serious threats to human health and ecological environment (Zhang et al. 2016a) (Wang et al. 2020a). With the deepening of globalization, the proportion of transportation industry in PM emission is increasing (Zhao et al. 2021) (Zhao et al. 2019a). Although influenced by the trend of future transportation energy reform (electrification and hybrid), the diesel engines still occupy a considerable part of the market share by virtue of fuel economy, operation reliability and high stability (Zhao et al. 2018) (Zhang et al. 2022e) (Cai and Zhao 2022b) (Ji et al. 2014) (Cai and Zhao 2022e). At the national and regional levels, corresponding regulations have been issued on the characteristics of high pollution of diesel engines to urge researchers develop exhaust control technology and find alternative fuels (Tan et al. 2023) (Zhang et al. 2022a) (Zhang et al. 2022g).

By 2020, China has 372 million motor vehicles. Among them, PM emissions from diesel vehicles account for more than 99% of motor vehicle emissions, as shown in Fig. 1. People have begun to realize the importance of environmental protection (Cai et al. 2022d). In order to improve the ecological environment, China issued “Limits and measurement methods for emissions from light-duty vehicles” (CHINA VI) (Zhang et al. 2023). The new regulations not only improve the requirements for particle mass and quantity, but also introduce The Worldwide harmonized Light vehicles Test Cycles (WLTC) to replace New European Driving Cycle (NEDC). The new experimental cycle obtains more comprehensive test data in a larger test range (Ko et al. 2017).

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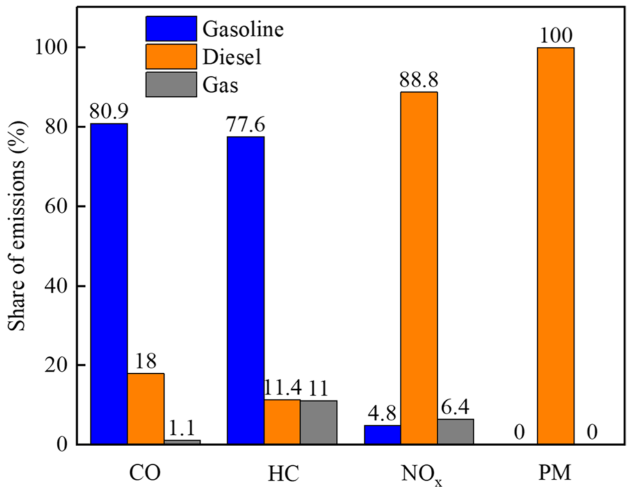

Fig. 1 Emission sharing rate of different fuel types of motor vehicles in China in 2020

In other major countries and regions, the control of diesel vehicles is also increasingly strict (Sartoretti et al. 2020). In Europe, since the introduction of motor vehicle emission limits in the 1990s, it has been updated to the sixth generation (Liu et al. 2020c). Compared with Euro V, the Euro VI standard controls the number of particles and enforces Real Driving Emissions (RDE) testing on the road using the Portable Emissions Measurement Systems (PEMS) (Ghaffarpasand et al. 2020). The United States is one of the countries with the most stringent emission requirements in the world. At the federal level, Tier 3 (2017–2025) requires manufacturers to prove that fleet emissions are gradually lower than 3mg / min (Orihuela et al. 2020). In addition to using strict emission standards, some local policy tools have also achieved certain results: tax incentives for alternative-energy car purchases, expanding the supply of alternative energy, low emission area setting, etc (Liu et al. 2020c).

As a by-product of diesel engine power, PM has obvious harm to human health. Especially during the epidemic period of COVID-19, the environment that exceeds the PM threshold may accelerate the spread of the virus (Magazzino et al. 2020). In the past literature, different methods have been proposed to control PM emission: fuel injection strategy (Liang et al. 2022), advanced combustion strategy (Yan et al. 2021), use of oxygenated fuel (Zhang et al. 2022b), exhaust aftertreatment system (Leskovjan et al. 2018), engine in cylinder technology for improving thermal efficiency (Yan et al. 2022), etc. However, the wall-flow diesel particulate filter (DPF) seems to be the only technical means to meet the current and future PM emission regulations (Tan et al. 2021). The basic appearance of DPF is an extruded cylinder, and the interior is composed of parallel cells (Zhang et al. 2016b) (Ye et al. 2023). Each cell is provided with a porous substrate wall in the axial direction, which can only allow the gas to pass through. The cell is square and blocked alternately at both ends. The exhaust is forced to enter from the inlet and discharged through the multi empty substrate wall to complete the mechanical capture.

The ability of DPF made of any material to contain particles is limited (Fang et al. 2019) (Orihuela et al. 2018). In order to obtain the lower pressure drop and longer service life, people introduce the technology of burning captured particles called regeneration. According to the mode of burning particulate matter, the regeneration is mainly divided into active regeneration, passive regeneration and mixed passive-active regeneration (hereinafter referred to as comprehensive regeneration). The traditional active regeneration is powered by an external device, and the captured particulate matter is oxidized by increasing the exhaust temperature. The specific heating technologies include fuel injection combustion (Fu et al. 2018), electric heating (Presti et al. 2013) and microwave (E et al. 2019b).

NO_2 is a much stronger oxidant than O_2 (E et al. 2016). Passive regeneration usually relies on NO_2 to catalyze soot oxidation at engine exhaust temperature. However, the NO_2 content in the engine exhaust is not enough to meet the requirements of smoke oxidation. The technology of oxidizing NO in exhaust and increasing exhaust temperature by using DOC is called continuously regenerating trap (CRT) (He et al. 2015). In addition, the catalyst supported on the fuel or the DPF wall can also reduce the reaction ignition temperature (Stępień et al. 2015) (Xu et al. 2021). However, the secondary pollution of ash and nonflammable metal particles generated therefrom is noteworthy.

Non-thermal plasma (NTP) is a new technology (Cui et al. 2018). When the NTP obtained by the reaction of the additional energy supply device is mixed with the soot, it can promote the reaction of the soot under normal exhaust temperature (Shi et al. 2022). Low temperature reaction can greatly prolong the service life of DPF and avoid uncontrolled regeneration.

The control of regeneration is facing challenges. The high temperature released during regeneration is detrimental to the normal operation of the DPF and even the vehicle (Peng et al. 2021). It is necessary to develop a reasonable and accurate regeneration control. Perfect regeneration control includes accurate soot load prediction and reasonable regeneration strategy. The traditional prediction method based on pressure drop model has achieved good results in laboratory environment (Wang et al. 2021a). In addition, considering the unstable factors such as cross regional driving of vehicles and ash deposition, the optimized model based on fuel consumption, temperature monitoring and ash parameter correction shows better prediction performance than the traditional model (Dawei et al. 2017) (Zhang et al. 2018).

The purpose of developing a reasonable regeneration strategy is to avoid unnecessary fuel consumption and DPF damage.

The inlet temperature and outlet pressure drop are controlled by the built-in program to form a closed-loop control (Bencherif et al. 2015). In addition to the additional energy supply device, the operation of regeneration strategy includes changing the DOC reaction temperature through adopting the fuel injection amount and changing the engine operation to increase the exhaust temperature (Sarkar et al. 2022) (Wang et al. 2020b).

DPF has limited or no effect on controlling other pollutants (such as NO_x) than PM. In order to meet the requirements of comprehensive control of pollutants, DPF is required to be used in combination with other aftertreatment devices. The influence of high temperature and high pressure generated by regeneration on the upstream and downstream systems is a factor that must be considered when selecting the collocation of aftertreatment devices. Through reasonable layout (Lao et al. 2020), integrated equipment (Millo et al. 2017), advanced control strategy (Sarkar et al. 2022) and structural improvement (Martinovic et al. 2020), the synergy between devices can be enhanced or the negative impact of regeneration can be reduced.

In the last decade, the researchers have done a lot of research on regeneration in order to meet the increasingly stringent emission regulations and the need of high-efficiency work of DPF. Because the regeneration is affected by working conditions and particle properties. A detailed description of various regeneration technologies is essential for manufacturers and vehicle owners to choose. In view of the insights provided by other previous review (Guan et al. 2015) on this topic, this review aims to introduce the latest development of regeneration technology in recent years.

In addition, this review discusses the specific impact of alternative fuels on soot reactivity, the source of ash and its impact on regeneration, the interaction between regeneration and other aftertreatment equipment, accurate soot prediction and reasonable regeneration control strategy. The specific structure of the review is shown in Fig. 2. The purpose of this review is to provide researchers, students, manufacturers and vehicle owners in relevant fields with an introduction to the latest features of various regeneration technologies.

Composition of particulate matter and its effect on regeneration

Composition particulate matter

PM is one of the by-products of diesel combustion. It is mainly composed of included solid particles、inorganic carbon and/or ash. Some liquid phase materials may be adsorbed on solid particles to form PM (Mohankumar and Senthilkumar 2017). The main components of PM are as follows: elemental carbon (EC) and organic carbon (OC), soluble organic component (SOF), sulfate, water and ash (Sarvi et al. 2011). The composition of PM is not constant and changes dynamically with engine structure, operating conditions, fuel type, lube oil, additives and control strategy (Liu et al. 2020c) (Chen et al. 2020a).

PM is divided into the following sizes according to particle diameter (d_p): $d_p < 10$ μm, PM_{10}; $d_p < 2.5$μm, fine particles; $d_p < 0.1$ μm, ultrafine particles; $d_p < 0.05$ μm, nanoparticles (Tan et al. 2020). It can be clearly observed that the contribution of small particle size PM in absolute quantity to the total mass is only 1–20% (Wang et al. 2019c). In the past regulations based on PM quality, DPF could only control large particles to reach the limit value (Peng et al. 2022a). According to CHINA VI, the introduced particle number limit enables manufacturers to reduce the filter hole diameter of the substrate. For the high temperature and high pressure produced by the regeneration process, higher requirements are put forward for the thermal shock resistance and anisotropy of the material under high porosity (Chen et al. 2020a).

Soot characteristics and diesel particulate filter regeneration

The oxidation reactivity of soot is an important factor affecting the regeneration process. According to the comparative experiments of Rodríguez-Fernández et al. (Rodríguez-Fernández et al. 2017), the trends were obtained by the two mainstream measurement methods. The first method is the actual DPF regeneration experiment. The second method is the thermal analysis of smoke and dust in the temperature-controlled laboratory. Both results are in good agreement, which prove the validity of the analysis.

Taking the most commonly used thermogravimetric analyzer (TGA) as an example, ignition temperature (T_i) and activation energy (E_a) were used to evaluate the oxidation reactivity of soot. T_i has different definitions in different literatures. In the research of Shimokawa et al. (2015), it was defined as the lowest temperature at which the soot began to lose mass and continued to react automatically. Readers can also find in other researches that it was defined as the temperature at which the CO_2 signal appears (Kimura et al. 2011), the temperature of Arrhenius-like plot of the CO_2 signal comparing with 1/T (Legutko et al. 2013), or the temperature at which the soot mass was lost by 5%/10% (Wei and Wang 2021) (Zhao et al. 2018). The specific needs shall be determined according to the specific circumstances. E_a can be obtained from the standard kinetic rate equation on the basis of Arrhenius law. The specific formula is as follow (Wei and Wang 2021):

$$\frac{d\alpha}{dt} = kf(\alpha) = A\exp(\frac{E_a}{RT})(1-\alpha)^n \tag{1}$$

where α is the conversion rate of PM mass; t is the time; k is the constant of Arrhenius; A is the frequency factor; T is thermodynamic temperature; R is the constant of gas; n is the reaction order ($n = 1$ for the PM from diesel engines).

Fig. 2 Article structure chart

The method of assisting DPF active regeneration by modifying engine parameters has been mentioned in the previous literature (Guan et al. 2015). However, the effects of these parameters on the oxidation reactivity of soot are not much. Zhao et al. (2019d) and Zhang et al. (2021a) analyzed the effect of the exhaust recirculation (EGR) on soot oxidation reactivity. They attributed the improvement of soot oxidation reactivity to the disorder of soot structure, the increase of active surface area and the increase of aliphatic C-H group concentration. These properties were directly related to the combined effects of heat, dilution and chemical action of EGR. On the other hand, Liang et al. (2022) evaluated the effect of injection strategy on soot oxidation reactivity of a four-cylinder diesel engine. Plus post injection (designed as M+Po) stand out among the three tested injection strategies. The comparison results are shown in Fig. 3. They believed that the M+Po strategy not only improved the exhaust temperature, but also promoted the disorder of soot structure.

Although the results obtained in the past literature are not consistent, the mainstream view is that the reactivity of soot is inversely proportional to the engine load (Wei et al. 2020a) (Zhao et al. 2015a) (Wang et al. 2019b) (Wei et al. 2020b). Zhang et al. (Zhang et al. 2021b) believed that this was because oxygen enrichment, fuel enrichment and high temperature optimize the combustion process under high load environment, resulting in more "mature" and orderly soot. This explanation was considered by Wei et al. (Wei et al. 2020b) as strong evidence to prove that the soot nanostructure determined the oxidation reactivity of soot. The effect of load on soot functional groups has also been revealed, although no rigorous linear relationship has been found in the research of Wei et al. (Wei et al. 2020a). For the difference of results produced by load, this may be attributed

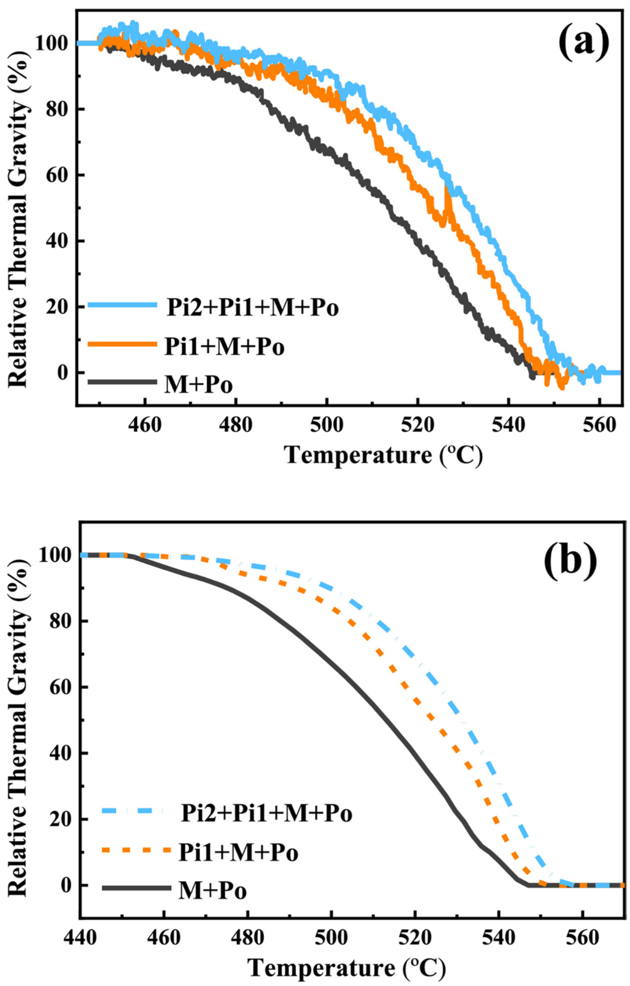

Fig. 3 Thermogravimetric analysis of soot samples produced by three injection strategies: (**a**) raw data; (**b**) Smoothed raw data (Liang et al. 2022)

to the difference of engine parameters, test methods, fuel characteristics and image processing procedures.

A consensus has been reached on the effects of fuel types on soot oxidation reactivity and regeneration process (Zhao and Li 2015b). In the research of Serkan et al. (Serhan et al. 2018), the soot produced by the tri-propylene glycol methyl ether/diesel blended fuel was more reactive than that produced by diesel. This was due to the structure with high porosity caused by devolatilization in the compound. So that the oxygen could penetrate and react with the internal surface area. The same conclusion appeared in the report of Du et al. (Du et al. 2022). They believed that the greater the porosity and specific surface area, the stronger the oxidation reactivity of soot. In addition to the effects of porosity and specific surface area, Luo et al. (Luo et al. 2018) claimed that the enhanced soot oxidation reactivity of acetone-butanol-ethanol (ABE) and diesel blended fuel was due to the increase of amorphous structure and oxygenated functional groups. Wei et al. (Wei et al. 2020b) and Hu et al. (Hu et al. 2022a) used Raman spectroscopy to characterize the disorder of the structure. In their conclusions, the good soot oxidation reactivity repeatedly emphasized three key structural parameters, namely, short fringe length (L_a), long fringe separation distance (D_s) and high curvature (T_f) (Hu et al. 2022b). However, in the experiment of Zhang et al. (Zhang et al. 2019a), the oxidation reactivity of soot did not show obvious linearity or correlation with the measured value of Raman spectrum. One possible explanation was that Raman parameters were limited by the heterogeneity of carbon materials and could not accurately describe the nanostructure of soot (Zhang et al. 2019b). Another explanation was that the oxidation reactivity of soot was determined by many factors, which was more convincing. Wang et al. (Wang et al. 2021d) (Wang et al. 2020c) supported this explanation by their research on the oxidation reactivity of aromatics to soot. For the mixed fuel of n-pentanol and diesel, the low content of aromatics reduces the generation of soot precursors and improves the reactivity of soot (Wang et al. 2021d). However, when aromatics are mixed with diesel, the soot produced also shows high oxidation reactivity due to the disorder of structure (Wang et al. 2020c). This showed that in addition to the joint determination of multiple factors, the influence weight of each factor on the oxidation reactivity of soot was also different. Pan et al. (Pan et al. 2022) and Wei et al. (Wei et al. 2022) got different conclusions on the distribution of weights. This indicated that the distribution weight of specific fuels needed to be discussed in detail.

A more extensive multifactor analysis was proposed in the research of Jafari et al. (Jafari et al. 2019). The conclusion is shown in Fig. 4. Blue indicates the correlation of the two parameters, red indicates the inverse correlation, and gray indicates no correlation (Peng et al. 2022b). The size of the circle describes the size of the pairwise correlation coefficient. The physical and chemical properties that affect soot shown a dependence on fuel oxygen content. In contrast, nanostructures were inversely correlated with engine parameters.

Table 1 summarizes the effects and causes of fuel types proposed in this section on soot oxidation reactivity.

As described in this section, the positive correlation between soot oxidation reactivity and DPF regeneration performance has been generally accepted. In most works, the results obtained by thermal analysis and real regeneration are in good agreement. It is worth noting that although the linear trend between soot oxidation reactivity and single factor has been proved, as a property jointly determined by multiple factors (such as engine parameters, load and fuel type), only a few literatures describe its multi factor sensitivity (Pan et al. 2022) (Wei et al. 2022) (Zhao et al. 2019b) (Jafari et al. 2019). The positive impact of soot oxidation

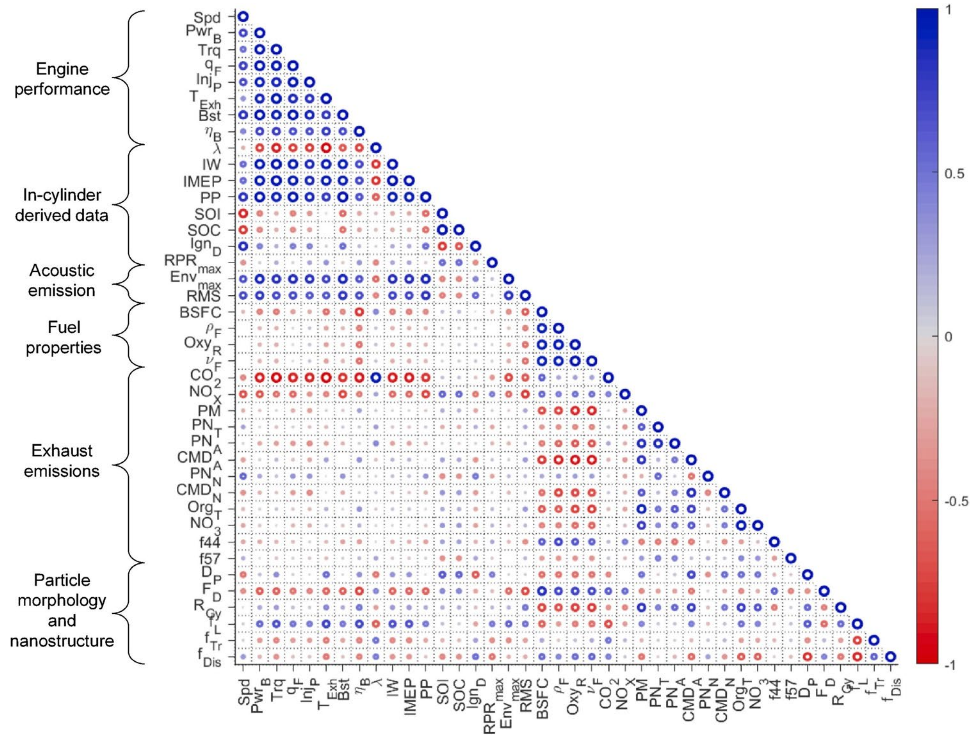

Fig. 4 Correlation matrix of biodiesel engine parameters and emission coefficient (Jafari et al. 2019)

reactivity on DPF service life and fuel consumption during regeneration will increase with future multi-objective optimization of engine management and fuel types. It is worth mentioning that the use of alternative fuels has not only improved the reactivity of soot, but also played a positive role in soot emission reduction (Zhang et al. 2022f). In addition, the pursuit of stable combustion technology will also help reduce soot emissions (Zhao et al. 2018).

Effect of ash deposition on diesel particulate filter regeneration

Compare with soot, ash is a non-combustible, non-evaporable solid residue that cannot be eliminated by regeneration. With periodic regeneration events, ash deposition will "permanently" block the cell. Because the composition of ash and soot is different, the blocked ash directly affects the regeneration performance of DPF.

Source and composition of ash

Energy discrete X-ray spectroscopy (EDS) and X-ray photoelectron spectroscopy (XPS) are powerful tools for analyzing ash elements. Elemental composition is very important to trace ash and quantify its contribution to regeneration. Elemental analysis of ash can also be used to provide candidate elements for fuel additives (fuel borne catalyst, FBC).

When determining the elements of the residuals after oxidation of PM, it was found that the elements that made up the ash range widely and did not have a fixed proportion. There are two main reasons for this phenomenon: Firstly, the experimental conditions of each experiment are different. Ash composition is affected by engine type, engine structure, fuel type, lubricating oil and its additives, operating parameters and engine wear. Secondly, different experimental methods and instruments with different resolutions are used. Table 2 summarizes ash element measurements from different researches (Liati and Dimopoulos Eggenschwiler 2010) (Bagi et al. 2018) (Bagi et al. 2020).

As shown in Table 2, the contribution of lubricating oil to ash is significant. Due to different experimental conditions, Zn, Mg, Ca, P, and S from lubricating oil account for 17–57% of the total weight. In addition, Fe and Al mainly come from engine wear. Generally, their proportion in ash is very small. It is worth noting that C also appears as an oxidizable element in each measurement result. The reasonable explanation is that the ambient air and oxidation residues pollute the experimental results.

Above all, the lubricants and their additives are the main source of ash, but not the only source. The specific composition of ash is affected by the engine type, engine structure, fuel type, lubricating oil and its additives, operating parameters, engine wear and other factors. When studying a specific fuel, it is necessary to control the consistency of experimental conditions to describe the characteristics of ash.

Table 1 Literature review on the effect of fuel type on oxidation reactivity of soot

Soot generator	Fuel	Compared with the oxidation reactivity of soot produced by diesel	Reason	Literature report
Diesel engine 1-cylinder	Tri-propylene glycol methyl ether di-propylene glycol methyl ether	better better	The formed soot had volatile matter, which formed a large number of pores in the process of volatilization and increased the active surface area. Oxygenated fuel promoted the disorder of soot and the increased of the number of carbon atoms at the edge	(Serhan et al. 2018)
Diesel engine,2.83L 4-cylinder	soybean oil methyl eater palm oil methyl ester waste cooking oil methyl ester	better better better	On the one hand, the high oxygen content of biodiesel inhibited the production of polycyclic aromatic hydrocarbons in soot. On the other hand, the high oxygen content contributes to the high porosity of soot, which reduced the activation energy required for soot oxidation	(Du et al. 2022)
ASTM D1322 burner	acetone-butanol-ethanol	better	The derived soot of ABE blended fuel contained more aliphatic compounds. These aliphatic chains at the edge of soot could attach more oxygen-containing functional groups to enhance the oxygen content of soot. In addition, the amorphous structure provided more activation points for soot oxidation	(Luo et al. 2018)
Diesel engine,1.99L 4-cylinder	Dimethyl carbonate (DMC)	better	DMC could reduce the formation of soot precursors, which was not conducive to the growth of graphene layer, leading to the disorder of soot particles	(Wei et al. 2020b)
Diesel engine,8.8L	Waste cooking oil (WCO)	better	The soot containing WCO showed a higher degree of disorder and a lower degree of graphitization. Due to the high oxygen content, the O/C ratio, sp^3/sp^2 ratio and oxygen-containing functional group content of WOC soot were higher than those of diesel	(Hu et al. 2022a)
Diesel engine,8L	biodiesel	-	Nanostructures was proved not to be the only factor affecting the structure of soot. It affected the oxidation reactivity of soot together with soot composition, oxygen content and surface functional groups	(Zhang et al. 2019a)

Table 1 (continued)

Soot generator	Fuel	Compared with the oxidation reactivity of soot produced by diesel	Reason	Literature report
Diesel engine,8L	Aref	better	Biodiesel derived soot aggregates had less chain orientation and were more disordered in structure than diesel derived soot	(Zhang et al. 2019b)
Diesel engine,2.77L 4-cylinder	N-pentanol	better	The addition of n-pentanol resulted in the decrease of graphitization and the increase of disorder degree of nanostructures	(Wang et al. 2021d)
Diesel engine 4-cylinder	Benzene M-xylene Tetralin	better better better	Compared with pure diesel, the soot nanostructures derived from aromatic mixed fuels become more disordered. Although the oxygen-containing functional groups of soot increase, the high oxygen concentration in the fuel improved the combustion environment, which would form more "mature" soot and reduce the reactivity of soot	(Wang et al. 2020c)
Diesel engine 4-cylinder	Dimethoxymethane	better	Oxygen content improved the purity of graphene and amorphous carbon in soot. In the multi factor sensitivity investigation, nanostructures were considered to play a more important role in the oxidation reactivity of soot than chemical properties	(Pan et al. 2022)
Diesel engine 4-cylinder	Methanol Dimethoxymethane	better worse	In the comparison between oxygen enriched fuel and pure diesel derived soot, it could be seen that the order of nanostructures was inversely proportional to the reactivity of soot	(Wei et al. 2022)

The fuel type includes pure alternative fuel and blend of alternative fuel and diesel. Specific types shall be subject to specific literatures

Catalytic activity of ash to soot

Figure 5 shows an investigation on the oxidation reactivity of lubricating oil-derived ash to soot and the TGA results of four soot mixtures (Ca, Zn-P, Ca-Zn-P, and Mo-P) at the mixing ratios of 1/5 and 1/10, respectively (Liang et al. 2021). It can be seen that the presence of metal elements in the ash reduced the characteristic temperature of soot oxidation. The authors explained that the enhancement might be due to the mechanism of oxygen storage and transfer, the electron donating effect and the increase of oxygen vacancy. It is worth noting that the physical barrier formed by P-containing compounds may play a negative role in the oxidation of soot. In other words, the catalytic effect of different components is different.

Compared with lubricating oil-derived ash, the catalytic effect of diesel derived ash on soot oxidation has not been experimentally verified until recently (Gao et al. 2022). Figure 6 shows TGA curves for PM and ash containing PM at different heating rates. It can be found that the ash derived from diesel fuel has a catalytic effect on PM, although the positive effect of this catalytic effect is limited at low temperatures. For a given situation, the ash could indeed reduce the burnout temperature of PM. However, the deposition caused by periodic regeneration makes the ash only contact with the bottom of PM, reducing the

Table 2 Constituent elements of different ash

Element	Weight Percentage (wt%)					
	Ash A (Liati and Dimopoulos Eggenschwiler 2010)	Ash B (Liati and Dimopoulos Eggenschwiler 2010)	Ash C (Bagi et al. 2018)	Ash D (Bagi et al. 2018)	Ash E (Bagi et al. 2020)	Ash F (Bagi et al. 2020)
Fe	0.90	18.90	5.09	8.05	5.28	12.46
Zn	2.80	2.50	14.08	12.61	6.44	16.00
Mg	10.90	3.20	5.05	4.54	0.41	3.58
Al	1.00	0.20	0.57	0.68	1.50	4.45
Si	1.70	1.90	0.63	0.61	3.70	0.35
P	2.10	4.90	8.22	8.22	2.04	7.09
S	10.90	1.40	5.33	7.19	2.65	10.78
K	-	-	0.27	0.31	1.93	0
Ca	3.30	5.60	22.56	21.78	9.78	20.32
Cu	-	-	0.70	0.79	0.10	0.79
C	9.50	7.30	5.88	5.61	36.30	7.58
Na	1.10	0.70	-	-	-	-
O	55.80	53.40	31.62	29.61	29.87	16.6

The existence of C may be due to the pollution of ambient air and a small amount of coexisting soot

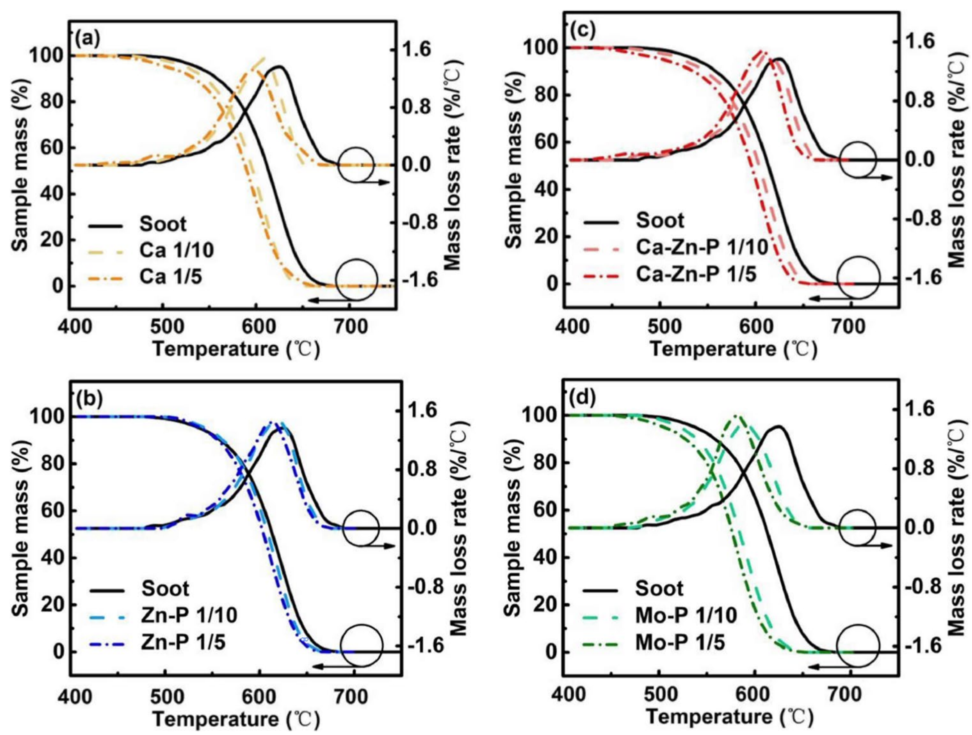

Fig. 5 Normalized mass and mass loss rate curves from isothermal oxidation of pure diesel soot and the four soot-ash mixtures with 1/5 and 1/10 mixture ratios: (**a**) Ca ash, (**b**) Zn-P ash; (**c**)Ca-Zn-P ash; (**d**) Mo-P ash (Liang et al. 2021)

temperature drop. In a word, due to the limitations of ash contact and diesel ash content, the catalytic effect of diesel derived ash is positive and limited.

Zhang et al. (Zhang et al. 2020b) evaluated the catalytic effect of ash (K, Na, P) from biodiesel impurities on soot. Figure 7 shows the temperature-programmed oxidation (TPO) curves of various ash-PM mixtures under characteristic conditions. It can be found that the introduction of sodium and potassium reduced the oxidation temperature of soot and had an obvious catalytic effect on soot. Phosphorus showed inhibition of soot oxidation. They explained that sodium and potassium promoted the disorder of soot structure, while phosphorus was just the opposite. The degree of catalysis depends on the disorder of the soot structure after doping.

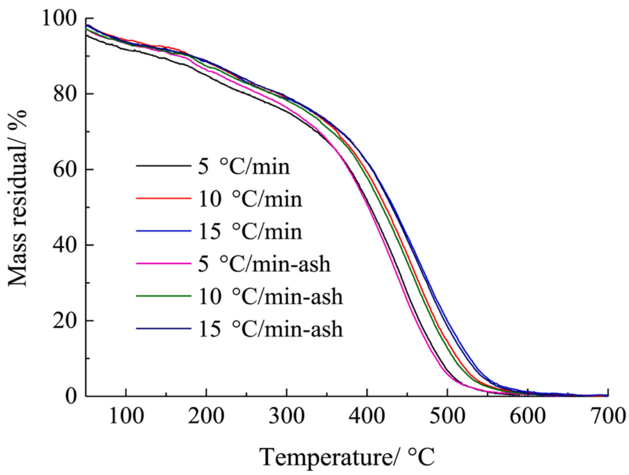

Fig. 6 TGA curves for PM and ash containing PM at different heating rates. (Gao et al. 2022)

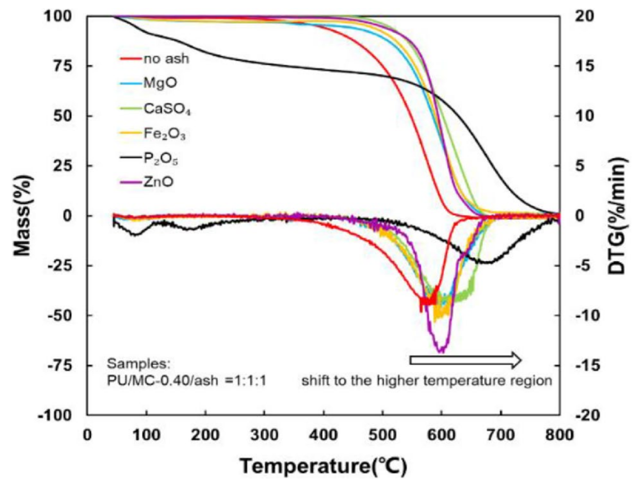

Fig. 8 TG-DTG curves of PU/MC-0.40/ash mixtures (Yang et al. 2022a)

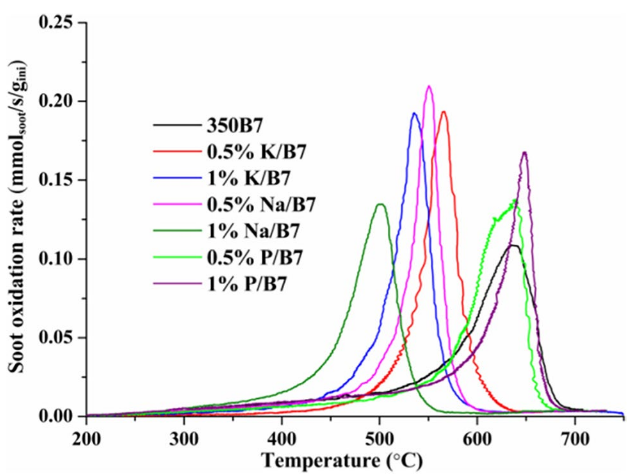

Fig. 7 TPO profiled of the doped soot samples under 400 ppm NO_2+9% O_2/Ar+5% H_2O. Two milligram soot and 80 mg SiC powder were mixed, heating rate was 10 °C/min (Zhang et al. 2020b)

In conclusion, the catalytic effect of soot catalyst mainly depends on the ash element. The influence trend of ash from different sources on regeneration is the same, but the specific value is closely related to the contact mode of ash and soot, regeneration environment and catalysis.

Catalyst deactivation

The potential effects of ash on the aftertreatment system are catalyst deactivation. For example, sulfur and phosphorus were reported to poison the catalyst, thus reducing the soot oxidation efficiency (Honkanen et al. 2021). In the catalytic regeneration experiment of Yang et al. (Yang et al. 2022a), the effects of different ash types on soot /catalyst are shown in Fig. 8. It can be seen from Fig. 8 that the TG-DTG (thermogravimetry-differential thermogravimetry) curve with added ash moves towards high temperature compared with the sample without ash. According to the description of the literature, the ash was divided into the ash containing metal elements (MgO, $CaSO_4$, Fe_2O_3, and ZnO) and the ash without metal elements (P_2O_5) according to the type of combustion inhibition. Although the former contains metal elements to increase oxygen adsorption, the catalyst and the blockage of the contact area between the active site and the soot sample had a negative impact on combustion. Compared with the former, the latter not only increased the ignition temperature, but also increased the reaction rate. The same explanation was that P could not provide good catalysis while blocking the active site, which further worsened the catalytic combustion. Above all, the negative effect of ash containing metal elements on catalysis was less than that of ash without metal elements due to the adsorption of metal on oxygen.

In addition, the oxidation process of catalyst to soot was characterized according to the visualization method of Du et al. (Du et al. 2019). The “bottom-up” oxidation process was shown in Fig. 9. Soot, which was in contact with the catalyst at the bottom layer would be preferentially oxidized. However, when the incombustible ash was deposited on the catalyst layer after regeneration, which separated the contact between the catalyst and soot, the reverse diffusion of micro concentration oxygen molecules and the catalytic oxidation of soot would be inhibited.

For biofuels, Granestrand et al. (Granestrand et al. 2018) summarized the potential poisons (Na, K, Mg, Zn, S, and other compounds) from raw materials and production processes. They might lead to faster deactivation of the catalyst in the aftertreatment system. The inhibitory

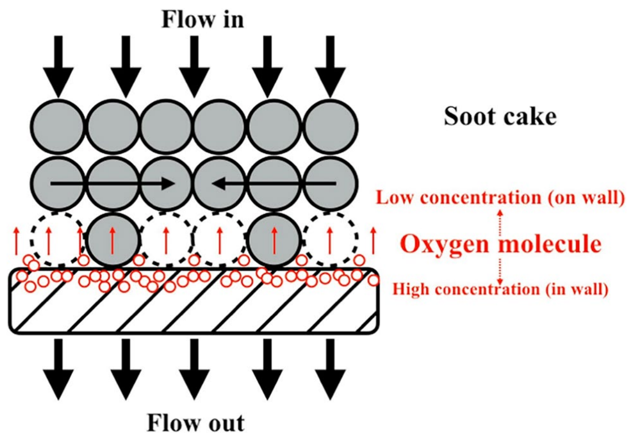

Fig. 9 Schematic diagram of catalytic oxidation of soot and reverse diffusion of oxygen molecules (Du et al. 2019)

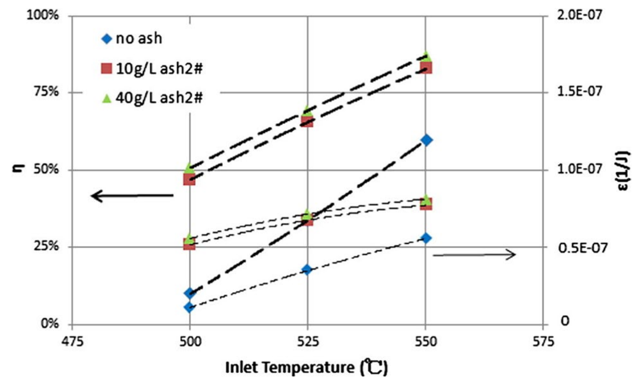

Fig. 10 The effect of ash loading on the regeneration efficiency and regeneration performance ratio on regeneration process (Fang et al. 2017)

effect of phosphorus on the catalytic reactivity was also reported in the research of Zhang et al. (Zhang et al. 2020b). Their explanation for this phenomenon was that phosphorus perfected the structural of soot. It should be noted that when NO_2 was used as the reaction gas, the soot samples doped with phosphorus could still show the improved reactivity. Schobing et al. (Schobing et al. 2018) observed that the generated phosphoric acid could even catalyze soot in a similar way to nitric acid when mixing water under the same conditions. This shows that the inhibition of inorganic elements on the catalyst also depends on the composition of the reaction gas. In a review of DOC, the effect of SO_2 on the conversion efficiency of NO_x affected the passive regeneration efficiency of downstream DPF (Zhang et al. 2022d). However, the proper desulfurization policy can completely restore the performance of the aftertreatment system (Millo et al. 2017).

Multicomponent catalysts have been shown to be very effective against sulfur. Although the additional catalyst made the composition of exhaust more complex, the advantages would become more obvious in the passive regeneration of high sulfur exhaust (Wang et al. 2021b). In Gao et al.'s review (Gao et al. 2018) on MnO_x - CeO_2 Catalysts, the method of using barium as a sacrificial agent to combat sulfur poisoning was involved. Although barium sulfate has the risk of accidental thermal deactivation, the idea of adding a catalyst that has no effect on regeneration to combat sulfur poisoning has a strong reference significance.

The effect of ash on catalysts is very complex. The same ash shows different results in different environments. However, the deactivation of catalysts by ash is becoming controllable. With the improvement of diesel quality control, ash management of lubricants and biofuels will become more stringent in the future.

Effect of ash deposition on regeneration

In addition to the catalytic effect of ash, the effect of ash deposition on regeneration is also significant.

Figure 10 presents the effect of ash load on regeneration efficiency and regeneration performance ratio (Fang et al. 2017). It can be seen that the regeneration efficiency and regeneration performance ratio increase with the increase of inlet temperature and ash load. Interestingly, although the regeneration performance was improved due to the presence of ash, the effect of the improvement did not seem to be load sensitive. Similar conclusions also appeared in the model of Chen et al. (2016). According to the simulation results, they proposed that the improvement of regeneration performance slowed down with the increase of ash load, and almost stagnated to the approximate maximum at 15g/L. In addition, the high ash loads were reported to reach pressure drop and soot load thresholds faster, requiring additional energy for more frequent active regeneration (Zhang et al. 2020a). This was detrimental to fuel consumption. Therefore, it is necessary to control the ash load below the boundary level.

In the further explanation, Fang et al. (2017) believed that the ash load improved the heat transfer and helped to generate local hot spots, thus improving the regeneration performance. This view was confirmed in an experiment on the regeneration performance of ash to NTP (Cui et al. 2018). In the experiment, due to the heat transfer improvement caused by ash deposition, the peak temperature increased with the increase of load.

Ash diameter is closely related to heat transfer efficiency. Fang et al. (Fang et al. 2017) believed that the smaller ash diameter not only enhanced heat transfer performance and heat capacity, but also had a better catalytic effect. As shown in Fig. 11, the soot with smaller diameter (ahs3#) tends to have higher regeneration efficiency. In their other researches, the relationship between small ash diameter and better

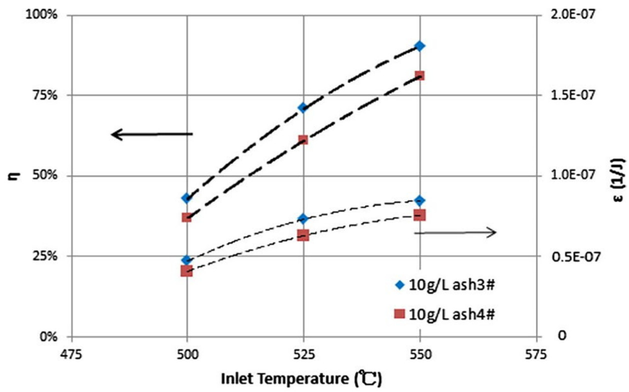

Fig. 11 The effect of ash diameter on the regeneration efficiency and regeneration performance ratio on regeneration process (Fang et al. 2017)

regeneration performance was interpreted as more contact area (Fang et al. 2020a).

The influence of ash on regeneration is a complex process controlled by many factors. According to the general literature description, the low load ash containing metal components is friendly to the regeneration performance. With the increase of ash load, the change of distribution pattern and the deactivation of catalyst, the influence of ash on regeneration changes from positive to negative. According to the quantitative estimation of ash accumulation on fuel consumption rate by Zhang et al. (Zhang et al. 2018), properly reducing the ash removal interval would help to improve the fuel saving potential of the vehicle. Therefore, it is necessary to make a further study on the optimal load and load threshold of ash in the future. In addition, ash generation in engines is a complex process. Although the pure ash used in the laboratory as the experimental object has strong operability, it still has errors with the ash produced by the real engine. It is necessary to develop more practical ash samples and experimental methods.

Diesel particulate filter regeneration

The capacity of all filter materials to hold PM is limited. As PM gradually blocks the pores, the exhaust back pressure continues to rise, worsening fuel consumption and engine power. This has a negative impact on the DPF device itself and engine operation (Wang et al. 2021a). Therefore, DPF provides a safe and reliable method to remove accumulated PM, restore its PM capture capability, and ensure accessible operations. This operation of removing deposited PM in DPF by oxidation is called DPF regeneration (Wang et al. 2021a). The timing of regeneration is very flexible, which can be carried out continuously during the operation of DPF, or it can be manually started by predicting the amount of accumulated soot (Huang et al. 2022).

As described in the "Composition of particulate matter and its effect on regeneration" section, the main component of PM is oxidizable soot. Maintaining the dynamic balance between DPF intercepted soot and oxidized soot is the most significant technical feature of regeneration (Ruehl et al. 2018) (E et al. 2020b). Regeneration efficiency is affected by filter temperature, inlet flow, exhaust and PM composition, soot/ash load, oxygen concentration, catalyst loading and other factors (Fang et al. 2017) (Meng et al. 2022) (Lapuerta et al. 2020) (Lisi et al. 2020). Among them, the filter temperature is the decisive factor for regeneration, because the soot can be oxidized only when the ignition temperature is reached (Meng et al. 2022). Since the engine exhaust temperature (200-400 °C) is not enough to oxidize the captured soot (the effective oxidation temperature with O_2 as the reaction gas needs to be maintained above 600 °C), it is necessary to increase the exhaust temperature additionally or use catalyst to reduce the ignition temperature to achieve the purpose of regeneration (Vernikovskaya et al. 2015) (Fino et al. 2016).

According to the technical characteristics, regeneration technology is mainly divided into two categories: active regeneration and passive regeneration. The former realizes the oxidation condition of capturing soot by supplying sufficient oxygen and using additional energy to raise the temperature of the filter (Zhang et al. 2016) (Fu et al. 2016). The latter uses catalyst to reduce the reaction temperature of soot to realize the oxidation reaction of soot under normal exhaust temperature (Lao et al. 2020) (Yamazaki et al. 2011). In addition, the integrated regeneration using the combination of active regeneration and passive regeneration is the favorite choice of most manufacturers today. Inserting passive regeneration in the active regeneration interval is conducive to reducing the frequency of active regeneration, which is friendly to fuel consumption (E et al. 2019a). It is worth noting that the use of NTP technology in DPF is becoming popular recently. PM can be oxidized at low temperature by electron collision (Shi et al. 2022). This is very beneficial to the improvement service life for the engine.

Active regeneration

Under the normal operation of diesel vehicles, the exhaust temperature (200–400°C) cannot meet the continuous oxidation of O_2/NO_2 to accumulated PM. At this time, the intervention of active regeneration can help the complete oxidation. The active regeneration is a heating technology that requires additional energy for power and/or driver operation (Rothe et al. 2015). Compared with the passive regeneration, the active regeneration has higher efficiency and lower requirements for the working environment. The active regeneration can be completed during vehicle driving and parking, which gives great flexibility to vehicle control (Ruehl et al.

2018) (Gupta et al. 2016). Without catalyst, the soot oxidation can be characterized by the following formula:

$$C + O_2 \overset{\sim 600^{\circ}C}{\rightarrow} CO_2 \Delta h_R = -393.51 kJ/mol \tag{2}$$

$$2C + O_2 \overset{\sim 600^{\circ}C}{\rightarrow} 2CO \Delta h_R = -110.51 kJ/mol \tag{3}$$

$$HC(SOF) + O_2 \overset{\sim 450^{\circ}C}{\rightarrow} H_2O + CO_2 \tag{4}$$

It must be noted that C in the formula represents the captured PM. CO_2 is the main gaseous product (Guan et al. 2015).

Active regeneration methods can be divided into two categories: fuel combustion (Fu et al. 2018) and electrical equipment (electric heating (Zhong et al. 2019) or microwave (Kurien et al. 2020a)). The most convenient choice is that the diesel is used as active renewable energy (Fu et al. 2018). The exhaust temperature will be increased by the additional fuel combustion. There are two technical routes for the development of fuel injection location: The first technology is that the fuel is sprayed at the DOC inlet (Liu et al. 2021a). The additional fuel enhances the reaction in the DOC, which in turn increases the temperature at the DOC outlet. The other technology is that the fuel was inject directly into the DPF and ignite additional fuel oxidation particles through the flame burner (Fu et al. 2018). Both methods need to accurately control the heat balance of regeneration. The use of electric heating is more flexible than fuel combustion. This is reflected in the various output forms of electric heating, such as microwave (E et al. 2019a) and resistance heating (Presti et al. 2013). However, the excessive cost of additional energy is where electric heating needs to be optimized.

However, in the process of active regeneration, the increase of pollutant emission (Beatrice et al. 2012) and fuel consumption (E et al. 2019a) makes frequent active regeneration not a reasonable choice. Cooperating with passive regeneration (Zuo et al. 2014) and scientific active regeneration strategy (Eck and Nakano 2017) are the way to solve the high pollution and high energy consumption. This section mainly describes the methods and characteristics of active regeneration.

In-exhaust fuel injection + diesel oxidation catalyst

For heavy duty applications, the high loads and infrequent engine oil changes can exacerbate engine oil dilution caused by post injection (PI) (Tormos et al. 2019). Therefore, for heavy duty engines, people tend to use in-exhaust fuel injection instead of PI. The syringe port is placed not far from the DOC inlet. The fuel can be directly injected into the exhaust channel and mixed with the exhaust, and the temperature of the exhaust can be increased through DOC oxidation (Rothe et al. 2015).

Due to the direct injection of fuel into the exhaust channel, the in-exhaust fuel injection avoids the problem of engine oil dilution and heat loss between the engine and the exhaust channel (Zhan et al. 2007). Interestingly, in some studies, the fuel injected was no longer limited to pure diesel. In the research of Chen et al. (2020b), the mixture of diesel and methanol was used as an energy source for active regeneration. The result showed that the active regeneration using mixed fuel had the lower PM, PN, NO_2, and CO_2 emissions and higher fuel utilization.

However, the fuel in the DOC cannot oxidized at low temperature and inaccurate temperature control are easy to cause the heat waste and bad fuel economy in the regeneration process. In Bai's research (Bai et al. 2017), the former could be solved by maintaining the exhaust temperature above 250 °C through active regeneration exhaust thermal management. The latter can predict the outlet temperature through a more accurate DOC model (Huang et al. 2021b).

Flame burner

For flame burners, the object of heating is the exhaust at the inlet of DPF. Nozzle is responsible for atomizing and spraying the fuel supplied by the fuel supply channel. These mixtures will be ignited by the ignition electrode in the combustion chamber. The exhaust enters the combustion chamber from the exhaust channel, heated by the flame generated by the mixture, and then flows into the DPF from the filter inlet. The regeneration process continues until the soot in the DPF is completely oxidized to CO or CO_2. Pressure sensors and temperature sensors monitor the regeneration process in real time, which is conducive to discovering abnormal regeneration phenomenon in time (Fu et al. 2018). The special sudden expansion structure can produce local reflux phenomenon, causing the combustible gas to roll into the flame, which is conducive to ignition stability. In Fu et al.'s simulation experiments (Fu et al. 2016), this special flow phenomenon occurs in four different models. The simulation results of four model speeds are shown in Fig. 12.

Flame burners can be adapted to any engine operating condition. In Europe and the USA, excellent adaptability allows the flame burner DPF to be used to retrofit diesel engines in service. However, combustion is a complex phenomenon. For the open system, the oil-air mixing and combustion are easily affected by the fluctuation of air supply and combustion, which is not conducive to the stability and continuity of regeneration. Although this phenomenon has been improved by geometric optimization (Fu et al. 2018) and the use of advanced nozzles (Yu et al. 2021). In addition, the low combustion peak of alternative fuels has a great potential in active regeneration. The development of flame

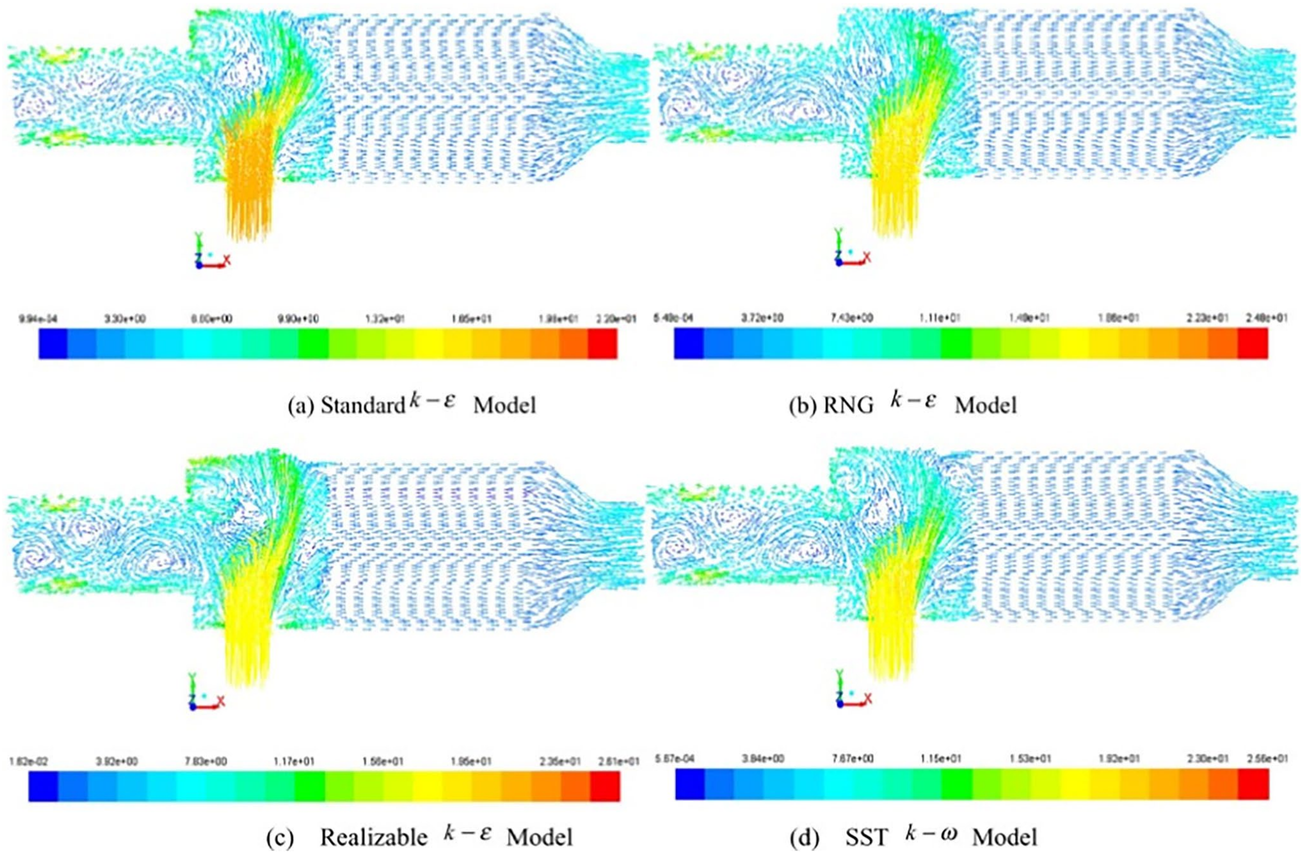

Fig. 12 Result diagrams of four speed simulation models (Fu et al. 2016)

burner in the future will benefit from the development of fuel, heat transfer and fluid dynamics.

Electric heating technology

Electrical heating is more direct than fuel injection. At present, there are two main regeneration methods of electric heating: electric heating wire and spiral heating wire. The return type electric heating wire is arranged upstream of the DPF and heats the exhaust flowing through it after the power supply is switched on. To further improve the heating efficiency, the spiral heating wire penetrates into the DPF cell. After the power supply is switched on, the spiral heating wire directly heats the exhaust and particulate matter from the inside for regeneration.

However, the price of convenient electric heating is very high energy consumption, which has a heavy load on the electrical system of the vehicle. The electrically heated catalyst developed by Presti et al. (2013) combined electrically heated regeneration with passive regeneration. The experimental results showed that the use of catalyst could reduce the regeneration ignition temperature and reduce energy consumption. Zhong et al. (Zhong et al. 2019) combined DOC assisted regeneration with electric heating regeneration. The new regeneration method plays a positive role in cold start. More combinations of electric heating regeneration are being explored.

Microwave heating technology

Microwave heating is a special regeneration technology powered by electricity. Compared with traditional resistance heating, microwave heating has the advantages of faster, more homogeneous and lower soot combustion temperature (Palma et al. 2015).

By selecting suitable materials that absorb microwave energy well, the microwave heating can easily produce the temperature required for DPF regeneration. The dielectric properties (especially dielectric constant ε′ and dielectric loss factor ε″) of materials are important indicators to measure the microwave absorption ability of materials. Table 3 shows the dielectric properties of common DPF materials. As can be seen that the SiC seems to be the most suitable material to meet the regeneration needs. This is supported by the literatures (Palma et al. 2015) (Meloni et al. 2017).

It is worth noting that although soot has shown good dielectric properties, catalysts (such as $CuFe_2o_4$ (Palma et al. 2015), $Cu_{0.95}K_{0.05}Fe_2O_4$ (Meloni et al. 2017), MnO_x-CeO_2

Table 3 Dielectric properties of various materials (Palma et al. 2015)

Material	Dielectric constant ε′	Dielectric loss factor ε″
Diesel soot	10.70	3.600
Quartz	3.80	0.001
Cordierite	2.90	0.140
Alumina ceramic Al_2O_3	8.90	0.009
Silicon carbide SiC	30.00	11.000

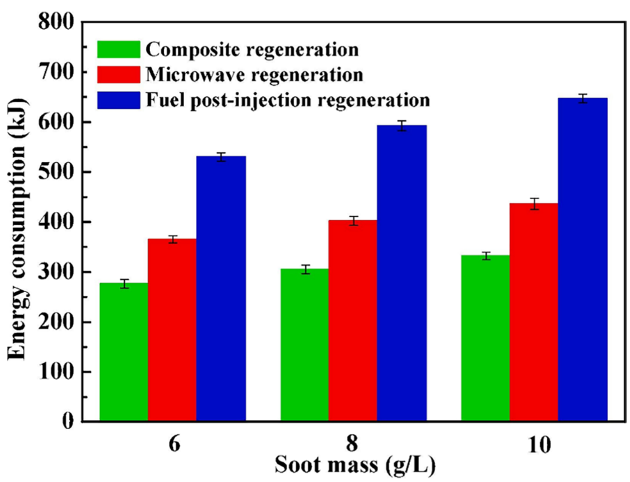

Fig. 13 Comparison of energy required for different regeneration modes (E et al. 2019a)

(E et al. 2019a) can be configured in some reports to further reduce soot oxidation temperature and improve regeneration efficiency. In an energy consumption assessment by E et al. (2019a), the microwave composite regeneration with 10 mg·L^{-1} MnO_x-CeO_2 catalyst reduced energy consumption by about 24% and 48% compared with microwave regeneration and fuel injection regeneration. The results are shown in Fig. 13. In addition, according to their team's previous research, regeneration performance had a good positive correlation with catalyst concentration and microwave power (Zhang et al. 2016). However, the specific weight of this positive correlation and the optimal concentration need to be further studied.

At present, some comprehensive analyses of wall-flow DPF based on the microwave regeneration have attracted extensive attention. Zuo et al. (Zuo et al. 2016) used the fuzzy gray correlation analysis to allocate the weight of the influencing factors of microwave composite regeneration. According to the model analysis, they believed that the regeneration time was the most critical factor to determine the overall performance. E et al. (2019b) established a three-dimensional mathematical model including different inlet velocity, inlet temperature and inlet pressure based on the field synergy theory and porous media theory. According to the simulation results, they found that when the inlet pressure was 0.08 MPa, the synergy between velocity vector and temperature gradient was the best. The simulation results are shown in Fig. 14. Zhang et al. (Zhang et al. 2016a) used multidisciplinary design optimization (MDO) based on adaptive mutative scale chaos optimization algorithm to optimize the DPF design. Compared with the non-optimized model, the optimized model reduced the pressure drop by 14.5%, improved the regeneration efficiency by 17.3%, reduced the microwave energy consumption by 17.6%, and reduced the thermal deformation by 25.3%. Although the use of comprehensive analysis has brought significant results to the optimization of DPF, there is still a lack of practical overall optimization strategy, which needs further research in the future.

E et al. (2020b) introduced the rotating diesel particulate filter (R-DPF) to achieve continuous microwave regeneration. The specific structure is shown in Fig. 15. R-DPF is mainly cylindrical filter body divided into multiple filter units by equal radian. The exhaust flows out radially and

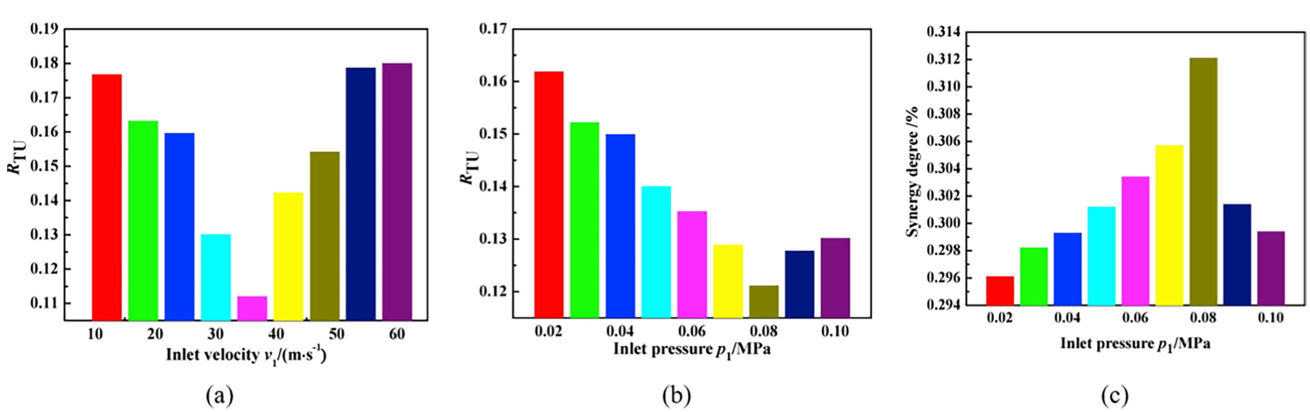

Fig. 14 Temperature uniformity coefficient under different inlet velocity (**a**) and inlet pressure (**b**); Degree of synergy under different pressures (**c**) (E et al. 2019b)

axially through the filter unit. When the R-DPF needs regeneration, the rotary filter units enter the microwave regeneration chamber in sequence. The fresh filter unit continues to complete the capture. According to the simulation results, when the number of filter units was 8–10, the oxygen content was 11–15%, the flow rate of exhaust was 0.3 m/s, the exhaust temperature was 327–477 °C, the microwave heating power was 800–1200W, and the soot concentration was 0.06–0.08, R-DPF obtained the best regeneration performance (E et al. 2020b) (E et al. 2020a). In further research, Pt-based catalyst and Pd-based catalyst were introduced into microwave R-DPF composite regeneration to further reduce the ignition temperature, 2% Pt-based catalyst was considered to be the best choice (E et al. 2021).

To sum up, the main methods of active regeneration are flame burner, electric energy heating and microwave. Among them, the microwave regeneration has the advantage in energy consumption (Kurien et al. 2020b). However, as the demand for renewable energy expands, the microwave regeneration does not perform well in the inlet exhaust with high oxygen content (E et al. 2020a). It is worth noting that the traditional fuel injection regeneration reduces the regeneration time and improves the regeneration efficiency after using biodiesel(Rodríguez-Fernández et al. 2017). In the pursuit of renewable energy and clean fuel, vehicles equipped with fuel injection regeneration only need to modify the pressure drop signal threshold in ECU to complete the transition from diesel to biodiesel. However, the active regeneration is not a normal operation behavior due to its high energy consumption and high exhaust pollution. Inserting passive regeneration during active regeneration is the choice of most DPF manufacturers. The good performances of electric heating and microwave assisted catalytic regenerations in the experiment laid the foundation for commercialization (Presti et al. 2013) (E et al. 2019a).

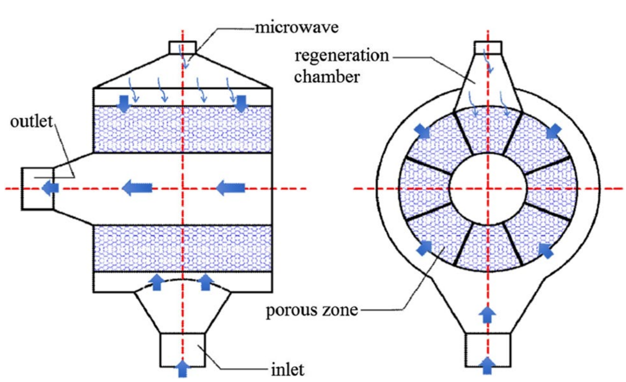

Fig. 15 Structure diagram of R-DPF (E et al. 2020b)

Passive regeneration

Compare with active regeneration, the passive regeneration does not require additional energy to heat the DPF. The chemical catalysis mode can be employed to reduce the reaction temperature. Thus, the particles can also complete oxidation at the exhaust emission temperature and convert them into harmless H_2O and CO_2. The advantage of passive regeneration is that no additional complex heating structure is required, and the lower reaction temperature can also prolong the service life of DPF (Ko et al. 2019). However, the passive regeneration requires the high engine operating conditions (Chen et al. 2020b). Therefore, the passive regeneration system is usually applied to long-distance vehicles with high exhaust temperature and long operation time (Rothe et al. 2015).

There are three kinds of common passive regeneration: catalyzed diesel particulate filter (CDPF), CRT or catalyzed continuously regenerating trap (CCRT) and fuel-borne catalysts (FBC). In the following sections, the characteristics and technical details of the three regeneration methods will be introduced in turn.

Catalyzed diesel particulate filter

CDPF is one of the most widely used technologies in DPF passive regeneration. Compare with the additional energy and sophisticated control required for thermal oxidation, CDPF oxidizes captured PM in the range of 250–550°C by coating the catalyst on the cell surface (Zhou et al. 2015) (Di Sarli et al. 2016). Although the regeneration efficiency and filtration efficiency of CDPF at low temperature are not as good as those at high temperature, they can also be maintained in a good range. At the same time, the low temperature can reduce the thermal shock to the material and prolong the service life of CDPF (Fang et al. 2019). The catalytic method is affected by several disadvantages: the reaction conditions are complex when driving, which is very different from the stable conditions in the laboratory; Poor contact of soot / catalyst, and the reaction speed cannot keep up with the deposition speed; The exhaust temperature range is wide, which requires high catalytic activity and heat resistance of the catalyst at low temperature (Zhang et al. 2020g). In order to achieve better filtration and regeneration performance, the composition and ratio of catalyst as well as PM to catalyst contact modes are key (Guo et al. 2013) (Sabet Sarvestani et al. 2020).

Ideal catalysts require the good catalytic performance, long-term durability and reasonable cost. In the past literature, the results had showed that the noble and base metals, rare earth elements, transition metals, and mixed oxides with perovskite and spinel structures had a positive catalytic effect on the oxidation of fumes (Sacco et al. 2022). The oxides of Pt, Ce, Pd, Zr, La, Pr, Mn, Cu, Ag, Ca, Y, Al, K, Ti, and other materials had been used as candidate materials for catalysts for DPF regeneration in the laboratory (Chen et al. 2022) (Zhou et al. 2015) (Ura et al. 2011) (Lee et al. 2021a) (Serve et al. 2019).

Noble metal oxides are the most common catalysts, which are loaded on the CDPF channel wall. Among them, Pt has become the most widely used noble metal catalyst due to its high and low temperature activity and long-term durability (Zhang et al. 2020c).In the experiment of Co et al. (Ko et al. 2019), Pt also showed the oxidation of NO in DPF and achieved the best efficiency at 350°C. This will facilitate the oxidation of retained PM. However, the high prices, volatile supply chains and high sensitivity to sulfur hinder Pt's further development in DPF in the presence of a single metal (Zhang et al. 2020c). Mixing two metals to make a new catalyst is a way to control the cost. Pd is also a transition metal with good catalytic oxidation effect on soot, and its price is slightly lower than Pt (Twigg 2011). It was reported in the literature that a new bimetallic mixed catalyst was prepared by mixing Pt and Pd in the ratio of 2:1, which was similar to the catalyst composed of single Pt in the catalytic oxidation of soot (Jung et al. 2019). However, Pt-Pd mixed metal catalyst is not satisfying at high temperature, which may lead to sintering if used with active regeneration (Wiebenga et al. 2012). In order to obtain good thermal stability, the researchers tried to mix other metals (Xu et al. 2022). It is worth noting that a large number of active oxygen participate in the oxidation of PM in the catalytic regeneration process. This active oxygen comes from the exchange of oxygen atoms between the metal oxide and the O-containing gas. These reactive oxygen species are transferred from the metal oxide surface to the soot and recombine to O_2. In the process of transfer, the catalyst will be in full contact with soot for catalytic oxidation. After the reactive oxygen species become O_2 or combine with soot to form CO/ CO_2, the free carbon sites formed on the surface will be further adsorbed and oxidized (Corro et al. 2019). Therefore, the materials with large oxygen storage (OCS) are paid more attention when doped (Masato Machida et al. 2008). CeO_2 is the most competitive catalyst. Due to the reduction of lattice oxygen, many vacant sites appear on the surface of CeO_2. These vacant sites facilitate the migration of oxygen to the oxidation reaction sites adjacent to the soot and facilitate the formation of oxygen species (Lee et al. 2021b). Yamazaki et al. (Yamazaki et al. 2011) synthesized CeO_2-Ag catalyst and found that it has unique “rice dough” morphology. Ag particles are encapsulated in CeO_2 as shown in Fig. 16(a). During oxidation processes, a large amount of movable active oxygen inside the catalyst migrates from the inside to the outside surface, effectively contacting the fume particles. This does not affect the catalyst's contact with soot and gives the CeO_2-Ag catalyst excellent catalytic oxidation. The process is shown in Fig. 16(b).

In order to obtain higher production performance of reactive oxygen species, doping appropriate levels of other elements is a feasible method (Seo et al. 2021).Recently, the doping elements of CeO_2 can be divided into Hf and rare earth metals (Uppara et al. 2021) (Sartoretti et al. 2022), transition metals (Andana et al. 2018), alkali metals and alkaline earth metals (Wang et al. 2021c). These doping elements enhance the activation of CeO_2 catalyst for fume oxidation. It is worth noting that the calculation of catalyst oxygen vacancy formation energy by density functional theory (DFT) method plays a key role in the description of catalyst. For example, Lee et al. (Lee et al. 2021a)

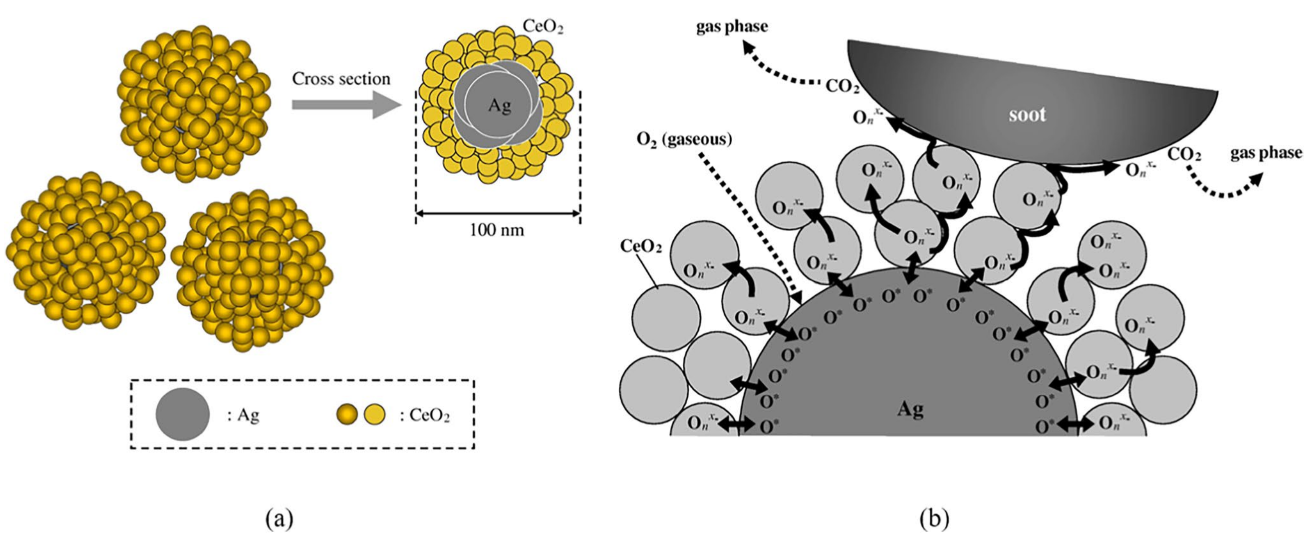

Fig. 16 (**a**) schematic diagram of catalyst structure, (**b**) schematic diagram of catalyst participation in PM oxidation process (Yamazaki et al. 2011)

introduced the generalized gradient approximation (GGA) of the Perdew Burke Ernzerhof (PBE) functional to determine the catalyst exchange correlation and used the projection enhanced wave (PAW) method to describe the core and valence electrons. DFT calculation confirmed that the interaction between Ag and La was weaker than that between Ag and Ce, and Ag adsorbed on La was easy to migrate to the Ce domain, while Ag and Ce were strongly bound. For structural loading, Zheng et al. (2022) used DFT to evaluate the interaction between Ru and CeO_2 nanocube. The calculation results showed that the high activity and stable catalytic performance of Ru/CeO_2 catalyst for soot oxidation were mainly attributed to the strong interaction between Ru and CeO_2, which was consistent with the experimental results.

Although the noble metal-based catalysts have good effects in controlling pollutants, the problems of secondary pollution, high-temperature sintering and high fuel requirements force people to find new catalysts. Composite metal oxides have attracted much attention because of their versatility. Compared with other catalysts, the perovskite catalysts are inexpensive, have good thermal stability and stable structure (Lee et al. 2016) (Shi et al. 2023). The common perovskite structures are ABO_3 and $A_2BB'O_6$, in which A represents rare earth or alkaline earth cations and B and B′ represent transition metals (Wang et al. 2019a). The cation at position B determines the catalytic ability of perovskite. Like position A, the cation at position B can be replaced by suitable metals (Shao et al. 2016). In order to obtain high catalytic activity, a small quantity of noble metals is usually doped into perovskite, but this will cause sintering. Guo et al. (Guo et al. 2013) proposed to use K to replace La ion at position A and Pd to replace Co ion at position B to make a new double substituted perovskite catalyst. The double substituted samples had better performance in surface area and catalytic activity and reduced the characteristic temperature and activation energy of soot combustion. This method has also been proved effective in the later in-depth research (Fang et al. 2014). Another advantage of using perovskite to load alkali metals is good stability, avoiding alkali metal volatilization. This is beneficial to long-term continuous regeneration (Pecchi et al. 2013). Changing the perovskite structure is also a method to enhance the activity of the catalyst. For example, three-dimensionally ordered macro-mesoporous (3DOMM) structure provided more active sites for soot oxidation (Zhao et al. 2020b). Figure 17 vividly shows the step-by-step cell of the model, which is beneficial to the contact between catalyst and soot.

Spinel, like perovskite, is a transition metal oxide with fixed structure. Spinel has the advantages of low price, simple preparation, good stability, low secondary pollution and strong catalytic activity, which makes it one of the most powerful competitors in CDPF potential catalysts (Xu et al. 2021). In spinel structure, there are different cations A and B

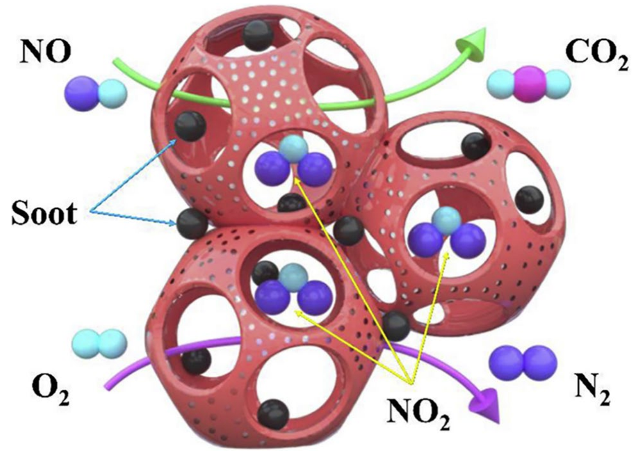

Fig. 17 3DOMM $La_{0.8}Ca_{0.2}FeO_3$ structure schematic diagram of perovskite-type oxides (Zhao et al. 2020b)

at the junction of tetrahedron and octahedron. The properties of A and B ions determine the catalytic activity of spinel (Xu et al. 2021). The synergistic effect between ions in multi-component composite metal spinel catalyst plays a positive role in the oxidation of soot. In Zhao's research (Zhao et al. 2017), the prepared $Cu_{1.5}Mn_{1.5}O_4$ spinel structure catalyst exhibited excellent soot oxidation properties. The rough microspheres well dispersed in Cu_1Mn_1 could improve the contact between soot and catalyst, and the accumulated pore in the microspheres was conducive to the diffusion of gas reactants or products. At the same time, metal cations and abundant adsorbent oxygen contributed to catalytic soot. In previous studies, Co-based spinel structure catalysts had been considered as the most outstanding case. The activity of the catalyst can be further improved by the active chemical composition (Álvarez-Docio et al. 2020b) and structure (Zhao et al. 2019c) of spinel. At the same time, the use of alkali metal doping to promote soot oxidation has also been reported in Li et al. (Li et al. 2022). Although alkali metal reduces the redox ability of the catalyst, the average grain size of the doped catalyst becomes smaller and oxygen vacancy increases. Thus, the doped catalyst has stronger catalytic activity. In the future, it may also be possible to mitigate the water poisoning problem that limits the actual use of spinel (excessive water will lead to catalyst deactivation and sintering) by changing the chemical composition and structure of spinel in practical applications (Neha et al. 2020). From the perspective of PM filtration and regeneration, the deposition of catalysts will affect the efficiency of the entire CDPF. According to Tandon et al. (2010), the FE of coated DPF under clean conditions is lower than that of bare DPF. The reason is that some pores are blocked up and the flow of remaining voids increases during coating. As shown in Fig. 18, with the deposition of PM, the coated DPF formed by soot cake shows higher filtration efficiency. More

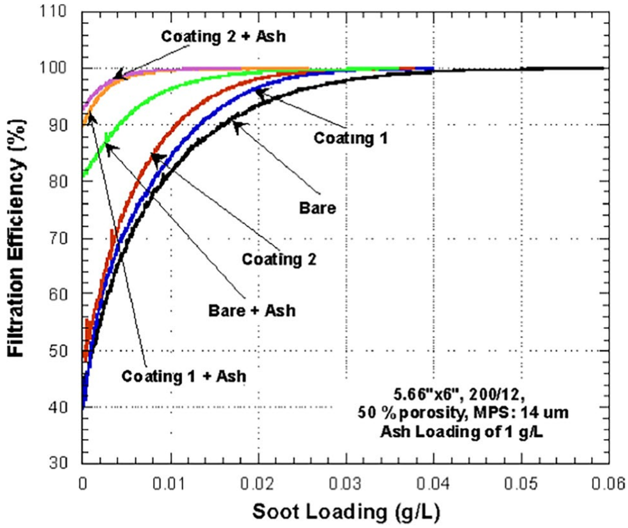

Fig. 18 Filtration efficiency sensitivity of bare DPF and coated DPF to PM load (Tandon et al. 2010)

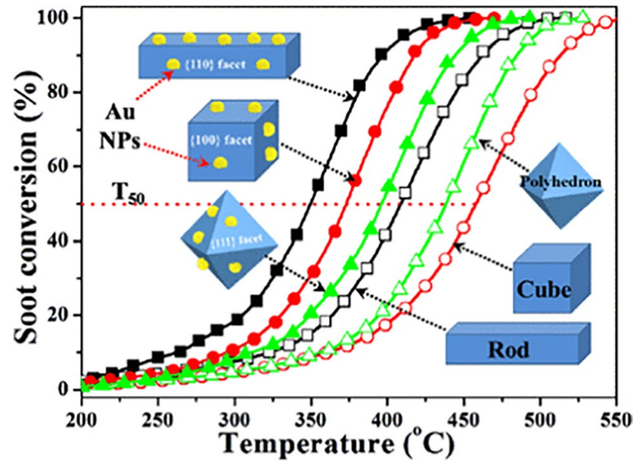

Fig. 19 PM removal efficiency of catalysts with different shapes at different temperatures (Wei et al. 2020c)

specifically, the contact between soot and catalytic particles is one of the key reasons affecting the filtration efficiency. In addition, this solid–solid contact also affects the regeneration efficiency of CDPF (Andana et al. 2019). This interaction increases with the tightness of the contact, which is measured by the number of contact points between PM and the catalyst. In general, this contact is considered as "loose" in the laboratory or in reality (Su et al. 2018). Based on the previous research, in order to increase the contact point between catalyst and PM, many catalysts with engineering form have been proposed to enhance the solid–solid interaction between catalyst and PM (Di Sarli et al. 2016). Fibers (Stegmayer et al. 2022), rods (Wei et al. 2020c), sheets (Yang et al. 2022b), cubes (Wei et al. 2020c), 3DOM (Zhao et al. 2020b), and star structures (Woźniak et al. 2020) had been shown that they had played a positive role in catalysis. Wei et al. (Wei et al. 2020c) investigated the soot removal efficiency of different exposed surfaces of CeO / Au and found that the rod catalyst can achieve the highest removal efficiency at the lowest temperature. Their experimental results are shown in Fig. 19.

However, the catalyst must be coated on the DPF cell surface. To make the catalyst cover more uniformly, new coating technologies have been invented, such as solution combustion synthesis (Fang et al. 2021), impregnation (Álvarez-Docio et al. 2020a), and wash-coating (Lisi et al. 2020).

The solution combustion synthesis is a method by which the aqueous solution of the catalyst precursor is put into the ceramic carrier and then heated at high temperature to form an active phase. The coating of perovskite (Fang et al. 2021) and spinel (Sabet Sarvestani et al. 2020) mainly depends on this method. The impregnation method is different from the solution combustion synthesis method and the catalyst precursor is deposited on DPF by impregnation. After immersion in its solution for several hours, it is dried and calcined to form a catalyst layer. This method has been applied in noble metal based catalysts (Álvarez-Docio et al. 2020a) and rare earth metal based catalysts (Zhao et al. 2020a). The washing coating immerses the DPF in a suspension containing the catalyst and then takes it out for drying. This method is commonly used for alumina or zirconia supported metals (Lisi et al. 2020).

The CDPF technology is a regeneration technology that can oxidize particles under normal exhaust temperature. Because of its harsh exhaust conditions, CDPF is more suitable for use in long-distance buses. Multicomponent catalysts (spinel and perovskite are outstanding in this respect) are gradually replacing single noble metal catalysts with low cost, low secondary pollution, good sulfur resistance and sintering resistance. Through the innovation of catalyst structure and loading mode, the contact between catalyst and particles can be improved. However, the activity of the catalyst is limited. The vehicle must periodically update the catalyst load and clean the ash to ensure good catalytic efficiency. Therefore, how to prolong the catalyst activity and reduce the ash generation becomes the next research hotspot of CDPF.

Continuously regenerating trap

CRT is a full-time passive regeneration system, which is mainly composed of two parts: DPF and DOC (He et al. 2015). When the exhaust enters DOC, the NO will be oxidized to NO_2, which can continuously promote the oxidation of soot captured by the downstream DPF at lower temperature (Tang et al. 2014). In the past literature, NO_2 has higher oxidation efficiency than O, and can react at 250 °C (Lizarraga et al. 2011). The regeneration reaction mechanism of CRT can be expressed as follow (E et al. 2016):

$$CO + NO + O_2 \rightarrow NO_2 + CO_2 \tag{5}$$

$$C + (1 - \frac{\alpha_1}{2})O_2 \rightarrow \alpha_1 CO + (1 - \alpha_1)CO_2 \tag{6}$$

$$C + \left(2 - \alpha_2\right)NO_2 \rightarrow \alpha_2 CO + \left(1 - \alpha_2\right)CO_2 + (2 - \alpha_2)NO \tag{7}$$

where α_1 is the selectivity coefficient of complete reaction between O_2 and soot, $\alpha_1 = 0.55–0.93$. α_2 is the selectivity coefficient of complete reaction between NO_2 and soot, $\alpha_2 = 1.2–1.8$.

In order to obtain stable and high concentration NO_2, catalysts (usually metal based, such as Pt and Pd) are introduced into DOC substrates (Jung et al. 2019). The NO, HC, and CO in the exhaust will also be oxidized into NO_2, H_2O, and CO_2 (Shah et al. 2012). Some literatures also showed that H_2O played a positive role in the oxidation of soot. Zouaoui et al. (Zouaoui et al. 2014) investigated the catalytic oxidation relationship between NOx, H_2O and soot. It was found that NO_2 and $C - NO_2 - O_2$ dominate the oxidation at 300–400 °C. Above 450 °C, H_2O begins to directly participate in soot oxidation. Finally, above 600 °C, O_2 direct oxidation will become dominant. The ideal CRT system has harsh working conditions, and the mass ratio of NO_x to C must be more than 8:1, preferably 20:1. In order to ensure the exhaust temperature above 260 °C, the engine duty cycle should be keep above 40% (Guan et al. 2015). In addition, CRT contributes to the formation of sulfate particles in fuel and lubricating oil sulfur (Chong et al. 2014). Therefore, when driving, the vehicles equipped with CRT system need to use ultra-low sulfur fuel. In order to optimize the regeneration capacity of the existing CRT system, the researchers changed the dimensions of DPF and DOC to a certain extent (Lao et al. 2020). In the literature, it has also been proved to be a feasible method to change the type of catalyst and the content of noble metals in the catalyst (Zuo et al. 2014) (Zhou et al. 2017).

CCRT is a combination of catalytic washcoat and catalytic soot filter (CSF), which is composed of CDPF and DOC. On the basis of the original DPF, the system is covered with a layer of catalyst, which is more favorable for the oxidation of soot. The CCRT system can reduce the CO and HC emissions by more than 60%, while the particle removal rate is more than 90% (Zhang et al. 2019e). The experiment was carried out by an off-road diesel engine, and it found that CCRT reduced more than 81% CO and 73% HC than a single CDPF device (Zhang et al. 2019c). Used CCRTs are difficult to be as efficient as new ones. CCRT aging is unavoidable due to high temperature, sintering of catalyst and pore plugging during use. All of these will affect the performance of CCRT and then whether it can complete regeneration (Gilpin et al. 2014). Wiebenga et al. (Wiebenga et al. 2012) proposed that the durability of the catalyst could be expressed from the flameout performance of the catalyst.

Zhong et al. (Zhong et al. 2021) tested the performance of CDPF, DPF, CRT and CCRT. It was found that CCRT system performed best in the catalytic generation, consumption and outflow of NO_2 in hot start and high-speed cycle under the limited installation space condition. Schejbal et al. (Schejbal et al. 2010) used simulation software to simulate various regeneration modes and found that the regeneration performance of CCRT was better than CRT or single CDPF. Tan et al. (2017) tested various aftertreatment devices with biodiesel and found that CCRT system had the best filtration effect on particle mass, PN and SOF. Compared with DOC, DPF, CDPF and CRT, it could further reduce sulfate emission.

Fuel borne catalyst

The FBC technology makes the soot produced be oxidized at the normal exhaust temperature by adding additional catalyst (especially metal catalyst) (Zuo et al. 2014). These additives produce new catalysts when the additives are burned in the combustion chamber. These catalysts are doped into PM and trapped together as exhaust pass through DPF. These catalysts reduce the chemical activity of PM, allowing it to oxidize at lower temperatures. So FBC technology can remove unnecessary heating from the vehicle structure and extend DPF life.

Inorganic metals are the core of these additives, but they are not soluble. In order to blend these inorganic metals better with diesel fuel, the use of organic dispersants can transform inorganic metals into soluble complex compounds. From a micro-perspective, long chain molecules of additives surround the metal core and coordinate the metal by using free electron pairs or double bonds (Stępień et al. 2015). The suitable metal additives have also been a hot topic for FBC. Fe, Pt, Ce, Cu, K, Na, Mn, K, Co, Ni, and Cs are FBC materials which have been experimented or applied in recent years (Zhang et al. 2020b) (Huang et al. 2020) (Zhao et al. 2014) (Cheng et al. 2017), and there are many interesting researches:

Previous researches had shown that Fe-based additives were generally used as a method to optimize engine emissions (Lee et al. 2010). The successful application of Ferrocene and other Fe compounds in engine combustion, as well as the low price of Fe, good thermal stability and low requirements for fuel, attracted researchers to use Fe-based FBC in DPF (Zhao et al. 2014). Recently, Liu et al. (2021b) tested its effect on soot oxidation with 4% Fe_2O_3 additive solution. According to the experiment, the initial oxidation temperature of soot was decreased by 75.1°C and 107.3°C respectively under the condition of Fe content of 200mg/kg and 400mg/kg. There are two reasons why Fe can catalyze soot oxidation: (1) Fe can hinder the growth of PM during combustion, resulting in the reduction of particle size and the increase of contact area with the catalyst; (2) the addition of Fe makes the particles produce a unique lattice, increases the curvature of the particle micro carbon layer, and makes the particles easier to participate in the oxidation reaction (Liu et al. 2020a). In another study, through the experiment of the oxidation temperature of soot by the mixture of Fe / Ce FBC and perovskite, it was found that the mixture could effectively reduce the oxidation temperature of PM (Lee et al. 2010). In Stelmachowski's experiment (Stelmachowski et al. 2016), the stable solvent of Fe oxide surrounded by various long-chain methacrylic acid (C4), undecanoic acid (C11), oleic acid (C18), and erucic acid (C22) carboxylic acids could reduce the oxidation temperature of soot from 700-500°C to below 500°C.

Ce-based FBC is also an excellent catalyst type. Liu et al. (2020b) found that the ignition and maximum temperature of PM decreased with the increase of catalyst mixing ratio. This proves that Ce-based catalytic fuel can promote PM oxidation at low temperature. They suggested that 150mg / kg was the best mixing ratio. In addition, the oxidation temperature will fluctuate up and down with diesel of different quality. For example, when Ce-based additives are added to the diesel of Euro IV, V and VI, the oxidation peak temperature decreases by 114.9°C, 146.2°C, and 153.7°C, respectively compared with the original diesel (Liu et al. 2020c). The use of nano CeO_2 catalyst can not only reduce the oxidation temperature of soot, but also inhibit the generation of soot in the early stage of fuel combustion and improve engine emission at medium and high loads (Liu et al. 2018).

Although metal-based FBC has excellent performance in experiment process, some metal additives have been abandoned in DPF regeneration applications. Because the metal core cannot be decomposed, it may cause air pollution due to secondary emission, and some metals are also toxic to human body. For example, Cu plays a positive role in the production of dioxins in exhaust, which has been proved by researchers. Therefore, the use of Cu containing compounds is prohibited in FBC (Heeb et al. 2015). In addition, since the temperature of the DPF melts the metal core, those catalysts that do not escape will be left in the DPF to block the pores. After accumulation to a certain extent, it may affect DPF FE and fuel economy.

To sum up, FBC technology is easy to operate and low-cost, which is suitable for popularization in gas stations through policy tools. Some metal catalysts can not only reduce the ignition time of soot combustion, but also improve the engine combustion (Liu et al. 2021b). But the metal additive is nonflammable. It is worth noting that compared with CDPF, the injection amount of metal additives is continuous. Most of these nonflammable metal particles will accumulate in the cells and cause more serious blockage (Wang et al. 2020d). Therefore, FBC requires more frequent off board regeneration than the other two passive regeneration methods. In addition, the potential threat of escaping metal particles to the environment and human health makes the government have to put forward restrictions on the use of FBC (Nash et al. 2013). The use of FBC needs to be more careful than the other two regeneration methods. Although the initial reaction temperature of CDPF is lower than that of FBC under the same conditions according to the experiment of Tourlonias et al. (Tourlonias and Koltsakis 2011), the fuel consumption of CDPF is superior to that of FBC. At the same time, the innovations of catalyst formula, structure and loading mode have greatly reduced the cost of catalyst. Therefore, the CDPF has stronger economic advantages than FBC. However, both CDPF and FBC are essentially solid contact between soot and catalyst. When too much ash is piled up, the regeneration rate will drop or even become invalid completely (Fang et al. 2020b). Although the efficiency of NO_2 catalysis adopted by CRT is not as high as that of CDPF and FBC, it can directly contact with soot for oxidation (Schejbal et al. 2010).

In addition, the three passive regeneration methods all need to face a common problem, that is, the minimum catalyst temperature. Because the engine cannot always maintain a standard passive regeneration environment, such as idle speed and low load low-speed operation. Therefore, it is necessary to monitor the pressure drop in the passive regeneration process. When the passive regeneration cannot keep DPF clean, the active regeneration is required to oxidize the deposited soot at high temperature.

Non-thermal plasma

The NTP technology provides a new idea for the regeneration of DPF. Energy is selectively transferred to electrons by the discharge reaction. The free radicals generated by the collision of electrons can oxidize particles at low temperature (Zhu et al. 2021). The complex chemical reaction of this active substance cannot be realized under normal conditions (Shi et al. 2019b). Compared with other regeneration technologies, NTP technology uses external energy, but its oxidation reaction temperature is extremely low. Under the action of catalyst, the regeneration can be carried out at 17°C (Shi et al. 2022). Which is friendly to filter life. According to the arrangement, NTP can be divided into direct non-thermal plasma (DNTP) and indirect nonthermal plasma (INTP).

DNTP is to directly enter the exhaust into the reactor and discharge it at intervals. Shi et al. (Shi et al. 2019b) carried out experiments on the oxidation process of PM by NTP and found that the oxidation of PM by NTP could be divided into two stages. The two stages were mainly oxidized SOF and soot. After NTP oxidation, the proportion of soot increased from 18–36% to 29–52%. In the experiment of Zhu et al. (Zhu et al. 2021), the SOF after NTP treatment showed different components under different engine loads. At the low and medium loads, there were more low-carbon atoms in the SOF. At the high load, the content of low carbon atoms decreased, and the content of high carbon atoms increased relatively. The efficiency of particle treatment by DNTP is greatly affected by reactor parameters such as dielectric material, discharge gap, voltage and frequency (Guo et al. 2020).

The active substances will be produced by the INTP and enter DPF with exhaust. Thus, the PM oxidation at low temperature will improved due to the active substance (Yao et al. 2006). Compared with DNTP, the INTP reacts with air or oxygen and will not produce secondary pollution and excess particles (Okubo et al. 2008). The DPF has a longer working time. In Okubo's experiment (Okubo et al. 2007), PM can be continuously burned and removed at 245°C through NTP injection, and DPF can be regenerated at 280°C. Shi et al. (Shi et al. 2016) used the oxygen supply NTP injection system to study the effects of PM composition and temperature on DPF regeneration efficiency after NTP reaction under different loads. The optimum regeneration temperature and PM composition were obtained under NTP conditions. Gu et al. (Gu et al. 2017) optimized the operating conditions of NTP injection regeneration and proved that the number and quality of particles would be significantly reduced after using NTP. Moreover, NTP had the ability to change the properties of particles, which could make the captured PM begin to oxidize at a lower temperature. This point has been pointed out in previous studies. The number of surface hydrocarbon functional groups in PM were decreased, while the proportion of oxygen-containing functional groups increased (Shi et al. 2019a). As NTP technology was used, the ozone was generated by dielectric barrier discharge (DBD) reactor. It had been proved to have a positive effect on the oxidation of PM (Babaie et al. 2015). Pu et al. (Pu et al. 2018) had investigated the effects of different O_2 concentrations and flow rates on the regeneration of DPF injected through the DBD reactor. It had been proved by experiments that the excessive O_2 concentration and flow rate would stagnate the growth of NTP. They pointed out that SOF had the higher oxidation activity than soot and would be oxidized firstly during regeneration.

At present, the NTP performance of DPF regeneration technology is satisfactory in the laboratory. Its characteristics of low temperature and low energy consumption are very prominent in the continuous oxidation processes of smoke and dust. However, the NTP technology is very capable of completely oxidizing particles (including the deposited aging particles), which remains to be discussed. Future experiments will focus on the soot and SOF. The NTP technology with catalyst coordination also faces the problems of ash deposition, secondary pollution of metal particles, sulfur poisoning and sintering. The applicability of the existing catalyst formulation and structure optimization in NTP technology needs to be discussed.

Uncontrolled regeneration

Uncontrolled regeneration of DPF will produce excessive thermal stress. Excessive temperature may cause damage to the substrate, even melting and cracking, and permanent failure of DPF (Chen et al. 2011a). In addition, in Mertzis's research (Mertzis et al. 2017), uncontrolled DPF regeneration will seriously weaken the operating performance of DPF, as shown in Fig. 20. However, it is undeniable that uncontrolled DPF regeneration can eliminate ash from lubricants. These ashes cannot be eliminated during normal regeneration and are considered to be a factor that permanently blocks pores during the service life of DPF (Chen et al. 2016). Therefore, the industry will complete safe regeneration in any case as the research direction (Millo et al. 2015). Although uncontrolled regeneration of DPF has been observed, there is still no unified solution on how to prevent uncontrolled regeneration. Taking China's latest emission regulations as an example, the demand of trucks for DPF is necessary, and the price of DPF is high (the cost of DPF for 8L emission is about 1500 yuan). It is particularly important to control uncontrolled regeneration and complete safe and complete active regeneration under any conditions.

Now it is known that the causes of DPF uncontrolled regeneration are mainly divided into three categories, as follows (Chong et al. 2011) (Chen et al. 2011c) (Chen et al. 2011c) (Chen and Sun 2013):

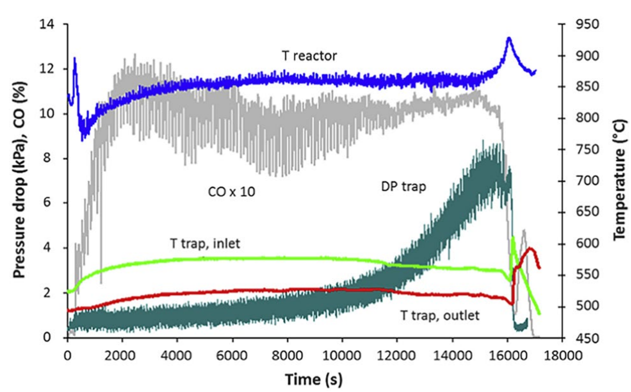

Fig. 20 Evolution of gasification conditions in the bench scale gasifier. CO is expressed as volume fraction (Mertzis et al. 2017)

(1) If the content of SOF in the components of PM is too high, it will enhance the oxidation effect of regeneration. In addition, feed temperature and unreasonable temperature rise control will also lead to rapid temperature rise in the initial stage of regeneration.
(2) The traditional runaway regeneration occurs when the operating mode is quickly switched to drops-to-idle (DTI). Excessive PM load, high O_2 concentration and low exhaust flow rate at idle will deteriorate the regeneration environment. Low convective heat transfer efficiency and exhaust volume cause excess heat, which leads to the rapid rise of local temperature and thermal stress of DPF and the cracking of filter.
(3) In actual operation, the non-uniformity of soot load will lead to the reduction in the filtration speed and convective heat removal, resulting in uncontrolled regeneration.

In addition to three common reasons for uncontrolled regeneration, a new reason was proposed in Lee and Rutland's model (Lee and Rutland 2012). When the additional fuel needed to be injected into DOC for DPF regeneration, some HC substances in the fuel slightly oxidized. Although this leakage was conducive to the regeneration of DPF, too much HC material might lead to uncontrollable regeneration. As shown in Fig. 21, curves A, B, and C represented the peak temperature at which the exhaust flow quickly reaches the idle condition in the post critical zone, the pre critical zone and the critical zone respectively. HC leakage could greatly increase the peak temperature and caused damage to the filter.

In the study of Zhan et al. (Zhan et al. 2006), the temperatures of type I and II uncontrolled regeneration were measured. As shown in Fig. 22 type A curve, when type I uncontrolled regeneration occurs, the peak temperature reaches more than 1120°C. The peak temperature of type II regeneration was above 1100°C, as shown in the type B curve. From the rising trend of the curve in the figure, it could be seen that the sudden rise of regeneration temperature would have a large thermal impact on DPF, which could be observed even when the inlet regeneration temperature was normal.

In order to control uncontrollable regeneration, DPF is optimized in two aspects: preventing uncontrolled regeneration and controlling uncontrolled regeneration rate. Accurate soot load estimation can avoid excessive back pressure and excessive PM deposition that may lead to uncontrolled regeneration (Wang et al. 2021a). The control of regeneration rate mainly depends on the reasonable temperature rise strategy of DPF (Dawei et al. 2017). Some structural optimizations are introduced, such as reducing filter length, reducing porosity and increasing solid thermal capacitance to reduce the temperature peak of uncontrollable regeneration (under normal or idle driving conditions) (Yu et al. 2013). When uncontrolled regeneration occurs, it will have a great thermal shock to the material. Calis Acikbas et al. (2017) adjusted the thermal shock resistance number of theoretically dense SiC for DPF. They concluded that the elongated and aligned microstructure could be adjusted to increase the thermal conductivity of DPF materials and improved the resistance to thermal shock. This had a positive effect on the improvement of the durability of DPF during uncontrolled regeneration.

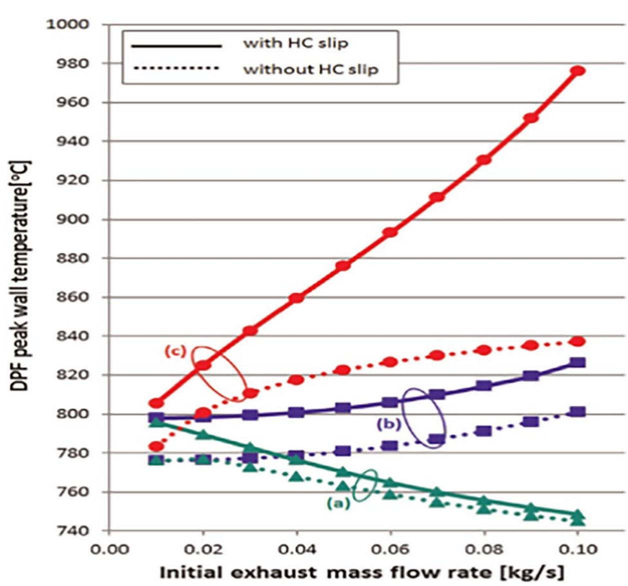

Fig. 21 Effects of HC leakage and the mass flow rate on the DPF peak wall temperature when the mass flow rate is reduced to 0.01 kg/s (Lee and Rutland 2012)

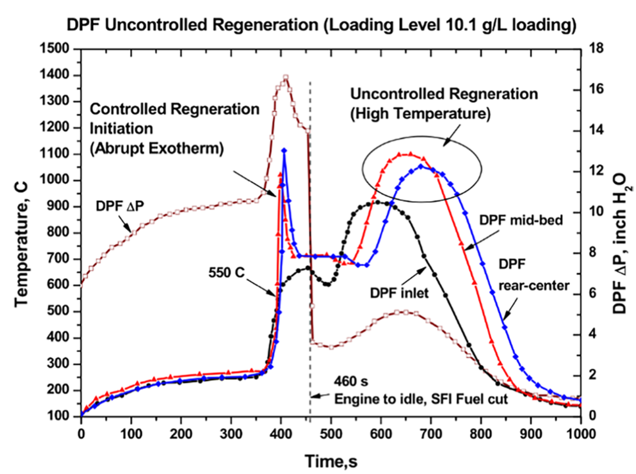

Fig. 22 Temperature trend of DPF uncontrolled regeneration (PM load 10.1 g/L) (Zhan et al. 2006)

Regeneration management of diesel particulate filter

Regeneration timing for DPF is still being optimized for better fuel economy and longer service life. In modern diesel vehicles, ECU usually applies for active regeneration to the driver (Singalandapuram Mahadevan et al. 2018). In this process, the ECU estimates the soot load according to the internal model and compares the results with the set threshold to determine whether to send an active regeneration request to the driver. The key index to judge the regeneration start is the soot load. Frequent regeneration at low soot load not only increases pollution, but also impairs fuel economy. When the soot is overloaded, the regeneration tends to cause excessive temperature gradient in the DPF (Chen et al. 2011b). Inhomogeneous temperature rise can cause the filter to crack or melt (Chen and Sun 2013). Therefore, for advanced regeneration strategies, accurate soot prediction is essential.

Secondly, in order to prevent the temperature from getting out of control during regeneration. The heating strategy of active regeneration is also an important part of regeneration control. The second section of this chapter reviews the decisions and methods of temperature control.

Soot load prediction

DPF soot deposition is a complex and constantly changing process. In addition to the real operating conditions, the sensor output is very difficult to exhibit an intuitive linear relationship with the actual soot load due to the changing operating conditions. The deposition of ash and the coating with passive regeneration slightly fluctuates the output conditions, which will directly affect the researchers' judgments of soot burden during transient operation (Zhang et al. 2018). In addition, due to different engine operating conditions, the same soot load level may have different soot distribution. This may cause regeneration hot spots and uneven heat transfer (Zöllner et al. 2019). Therefore, it becomes important to develop a stable soot estimation model.

The mainstream method is to predict soot load through pressure drop model (Zöllner et al. 2019). In terms of capture mechanism, the capture process of DPF is mainly divided into two stages: deep bed filtration and cake filtration (Wang et al. 2021a). The former starts with a clean filter, and the particles gradually form an uneven soot layer on the wall. A dense soot layer has been formed on the filter wall of the latter. The pressure difference between the inlet and outlet of DPF is called pressure drop due to the blockage of exhaust flow caused by particles blocking the pores. Compared with the deep bed filtration stage, the pressure drop and load in the cake filtration stage show a more obvious linear relationship. Therefore, the researchers are keen to use pressure drop to develop DPF soot load model.

Laboratory bench test is the main way to verify DPF pressure drop model. In the experiment, the soot load and pressure drop data per unit time can be measured by the electronic weighing device and the pressure sensors at both ends of the DPF. The DPF inlet temperature and soot mass are functions of engine load and speed, soot load under various operating conditions. Thus, it can be employed to verify the model more accurately. Recently, Wang et al. (Wang et al. 2021a) developed a new soot prediction model by a particle capture mechanism. The new model was divided into two parts: Firstly, the mechanism of packed bed collection was introduced to describe the growth process of soot layer on the wall of clean DPF. The distribution of soot was represented by defining a shape factor. Secondly, by separating the pressure drop and the composition of deposition stages, they used Darcy's law to establish the equivalent permeability model of each stage. As show in Fig. 23, the maximum error between the prediction of the new model and the test bench is less than 5%, and the average error is 2.72%.

Although the model using pressure drop to predict soot load has been optimized for many years, it does not completely eliminate the influence of uncertainties. Therefore, some additional input conditions or operational parameters are introduced and employed to improve the accuracy of estimation. The ash load correction introduced by Zhang et al. (Zhang et al. 2018) had great potential for fuel saving. The typical soot load model based on pressure drop will misestimate the real load under actual

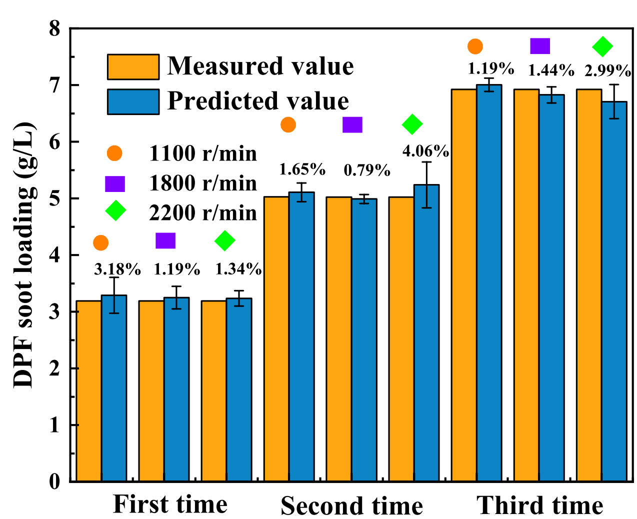

Fig. 23 Model predictions contrast with experimental results (Wang et al. 2021a)

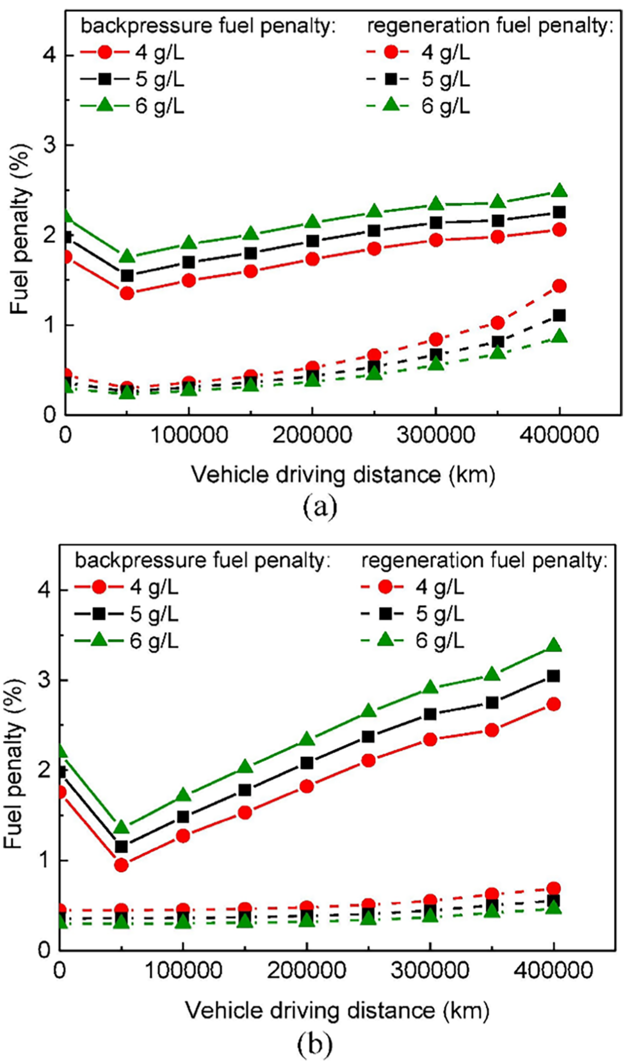

Fig. 24 The influence of DPF maximum soot load on back pressure and regenerative fuel loss before regeneration (**a**) no ash correction; (**b**) ash correction (Zhang et al. 2018)

working conditions. Figure 24(a) and (b) shows the effect of the maximum soot load before DPF regeneration without and with ash correction on DPF back pressure and regenerative fuel loss, respectively. Under the DPF regeneration control strategy condition, the fuel penalty caused by regeneration tends to be stable. More fuel penalties were attributed to pressure drop. This is of great significance for formulating fuel-saving regeneration strategy and ash removal interval. Qu et al. (Dawei et al. 2017) coupled the monitoring of temperature and fuel consumption on the basis of the traditional pressure drop model method. The multi-level soot prediction method had significantly improved in approaching the actual soot deposition. In the future, the method of judging soot deposition by multi output auxiliary pressure drop model will gradually become the mainstream.

Although significant progress has been made, there is almost no reliable and repeatable connection between pressure drop and soot load under some special conditions (such as damaged DPF) (Minagawa et al. 2014). Therefore, the researchers are keen to find new methods that can replace the pressure drop model. Feulner et al. (Feulner et al. 2017) realized direct and in-situ soot load detection based on microwave on the experimental bench. Electrically, the conductive filter housing formed a resonator. Soot deposition changed the electrical material properties of the resonator, which could be measured in the field distribution and characteristic spectrum. The amount of soot deposition could be roughly deduced by comparing the frequency change with the previous model. However, most of the new methods have only completed laboratory validation, and there is still a lot of work to be done before they are truly put into the market.

Regeneration strategy

While developing accurate soot estimation models, the researcher and manufacturers have to face another challenge of regeneration: a moderate temperature increase strategy. In the process of DPF active regeneration, overheating exceeding the melting point and excessive local temperature gradient may lead to very high thermal and mechanical stresses (Chen and Wang 2014). This is clearly what the owners and transportation companies are unwilling to foresee.

Gentle temperature control depends on the built-in program of DPF software. However, regeneration is a time closely coupled with the engine and aftertreatment system. In addition to the DPF adjustment by the built-in program, it also needs to control the global exhaust temperature. Some engine parameter settings and DOC outlet temperature control have been proved to assist DPF regeneration (Wang et al. 2020c) (Huang et al. 2021b) (Basaran and Ozsoysal 2017) . This section focuses on the regulation of DPF itself and global system control for regeneration

Active regeneration heating strategy

A perfect active regeneration control includes precise control of reaction rate and regeneration time. However, the regeneration is a complex chemical reaction, and it is difficult to quantify the specific degree of reaction in regeneration. Therefore, in order to control the reaction rate, the temperature often is employed to control the regeneration rate (Bencherif et al. 2015). It is due to the fact that the temperature is a sensitive factor of regeneration. More specifically, the DPF regeneration controller becomes a closed-loop system by setting up some feedback devices. In addition, the optimal regeneration temperature can be adjusted continuously in a range to meet the temperature demand in the regeneration stage. The regeneration will be finished when the system detects that the soot oxidation is complete, which is conducive to saving fuel and improving vehicle driving. At the same time, the regeneration strategy is different according to different working conditions. The specific changes will be made according to the environmental characteristics.

The target temperature of DPF control is considered as a function of soot estimation (Bencherif et al. 2015). The underlying logic of control is the combustion rate to characterize active regeneration as an output. Each inlet temperature corresponded to a combustion rate range. The greater the mass of soot, the smaller the range. The combustion rate is obtained by DPF structural parameters, fuel flow, oxygen concentration, temperature at the inlet of oxidation catalyst and interference. Compared the combustion speed value with the reference provided by the manufacturer, and finally fed back and adjusted the inlet temperature.

For some commercial vehicles, cordierite base material makes it more sensitive to the high temperature. Therefore, when Eck and Nakano (Eck and Nakano 2017) made the regeneration strategy, it set a wider and lower safety margin. In the face of actuators with poor control temperature, the regeneration frequency could be increased by shortening the regeneration time to avoid the possibility of excessive temperature. On the contrary, the regeneration time could be appropriately extended and the regeneration frequency could be reduced. Both strategies improve regeneration efficiency.

Based on pressure drop, fuel consumption and model method, the determination of traditional regeneration time has the resistance to find the optimal solution of temperature rise control and uncontrolled regeneration. The new regeneration control strategy proposed by Qu et al. (Dawei et al. 2017) had improved the accuracy of regeneration timing by using multi-level judgment method based on the coupling of three traditional methods. At the same time, the dual monitoring of temperature output and pressure drop avoided the emergence of regeneration hot spots and uncontrollable regeneration to the greatest extent.

A dangerous process is that the engine condition suddenly drops to idle speed at the initial stage of active regeneration. The reduction of exhaust volume and the increase of oxygen concentration may lead to the occurrence of uncontrollable regeneration. To avoid this phenomenon, the idling strategy developed by Bai et al. (Bai et al. 2018) could control the peak temperature and maximum temperature gradient of cordierite ceramic filter. The heat generated by particles is taken away by controlling the intake throttle valve, EGR valve and exhaust mass flow. The test results showed that when the DPF soot load was 4 g/L, the engine working condition fell to idle speed during regeneration. When the idle speed increased to 1100 r/min, the peak temperature was decreased from 820 to 632°C, and the maximum temperature gradient was decreased from 30 to 10°C/cm.

The operating conditions are very important for the regeneration strategy. Based on some special working conditions, regeneration strategies are also different. In the regeneration strategy of high-altitude areas, Piqueras et al. (Piqueras et al. 2022) had considered the decrease of inlet temperature with the increase of altitude and the increase of exhaust mass flow and had developed a new injection strategy during regeneration process. In addition to the increase of fuel volume, PI was divided into two events: The first PI was delayed relative to the normal mode. The second PI was placed at the end of the expansion stroke to prevent its combustion from entering the cylinder. Thus, it promotes the oxidation of HC in DOC and improve the inlet temperature of DPF. In addition, in order to improve the soot oxidation capacity at high altitude, they recalibrated the variable geometry turbine (VGT) position and maintain low EGR rate. Due to the improved regeneration strategy, the pollutant emissions of vehicles at high altitude were at the same level as that at sea level.

Diesel oxidation catalyst export control

As described in the "In-exhaust fuel injection + diesel oxidation catalyst" and "Continuously regenerating trap" sections, the DOC plays an important role in DPF thermal regeneration. In the process of DPF thermal regeneration, in order to maintain high-efficiency regeneration, the DOC outlet temperature is required to be stabilized at an appropriate temperature and maintained for a period of time (Liu et al. 2021a). The complex dynamic system composed of DOC and DPF faces many uncertainties in the changeable environment (such as catalyst aging, inaccurate fuel injection) (Huang et al. 2021b). Therefore, it is particularly important to develop an accurate control strategy for DOC outlet temperature.

In the past few years, several control algorithms and compensation schemes based on the principle of active disturbance rejection control (ADRC) (Huang et al. 2021b), the internal model control (IMC) (Huang et al. 2021a), gain scheduling techniques (Zhang and Wang 2018), control theory based on model prediction (Sarkar et al. 2022) have been proposed and developed. In the control strategy based on IMC method proposed by Huang et al. (Huang et al. 2021a), the exhaust flow and temperature were considered in the feedforward and feedback control strategies to deal with lag and interference. The strategy could maintain an error range of ± 15°C with the temperature target value under urban operation and radical suburban driving conditions, ensuring the safety of the filter and the high efficiency of regeneration. In their subsequent optimization, a control strategy based on the combination of IMC design and extended state predictive observer (ESPO) in ARDC structure was proposed (Huang et al. 2021b). In the experimental verification of old and new DOC under engine bench and on-board real driving conditions, the interference compensation of the new strategy could reduce the recovery time by about 15%. Obviously, the computing power and memory of the ECU currently used in vehicles cannot meet the requirements of highly complex solvers. For this reason, Sarkar et al. (Sarkar et al. 2022) used neural network method to simulate the behavior of DOC. The evaluation showed that the trained model could find the optimal solution of DOC output with the least computational resources. The optimal solution of DPF regeneration could be obtained by evaluation methods. In addition to temperature control, NO_x played a key role in passive regeneration. A luenburger observer with gain scheduling was used to estimate the NO_x concentration at the DOC outlet (Zhang and Wang 2018). This could help adjust the operating parameters of the engine and aftertreatment system in time for the efficiency of passive regeneration.

Engine-assisted diesel particulate filter regeneration control

After the DPF software issues the active regeneration command, the engine management system adjusts the engine operating parameters to increase the exhaust temperature as much as possible on the premise of avoiding uncontrolled regeneration. According to the operating conditions, ECU will select one or more of the following items to increase the exhaust temperature.

The following control events will be initiated during active regeneration (Wang et al. 2020b) (Basaran and Ozsoysal 2017) (Chen et al. 2021):

(1) By using variable valve timing (VVT) technology. The combustion efficiency will be improved by controlling the intake and exhaust valves. Under the low load conditions, VVT can increase the exhaust temperature and improve the economy.
(2) Reduce or disable EGR. The use of EGR is conducive to the formation of soot in the engine cylinder. Secondly, the exhaust temperature is also reduced due to the use of EGR.
(3) Change the injection strategy. Postpone the main injection (MI) advance angle, set the post injection (PI), and couple late post injection (LPI) and DOC, which are suitable for the regeneration under different working conditions.

In order to obtain the ideal exhaust heat state, the engine can sacrifice appropriate emissions and fuel efficiency. The specific engine modification parameters shall be determined according to the driving conditions. The strategy of Wang et al. (Wang et al. 2020b) adjusted the engine control according to the load. Under the low and medium loads, the regeneration temperature could be achieved by opening the intake throttle with a small opening and increasing the fuel injection volume. Under heavy load, the valve opening should be increased to 70–80%, the post injection (CPI) could be cancelled and LPI could be reduced appropriately. Under the full load conditions, intake throttling and LPI were not required, and the main injection timing should be appropriately advanced.

For passive regeneration, some research on the influence of in-cylinder behavior provide the direction for design strategies. The NO_2/NO_x ratio will be increased by the EGR and it can improve the oxidation reaction of soot in the presence of catalyst (Chen et al. 2021). Therefore, it is necessary to evaluate the use of EGR in passive regeneration, especially when oxygenated fuel is used.

At present, much work is focused on soot estimation and regeneration strategy control. Excellent pressure drop models have been able to reduce the estimation error to less than 5% (Wang et al. 2021a). In fact, the uncertainty of real working conditions (such as low pressure drop in high altitude areas (Piqueras et al. 2022)) may lead to ECU misjudgment. In addition, the DPF regeneration is no longer a problem of a single device, but a timing cycle problem that affects the whole vehicle. The global regeneration control model is the key part to solve the problem. The high data volumes brought by accurate estimation and regeneration control makes the conflict between DPF control and ECU computing power allocation increasingly obvious. For example, Sarkar et al. (Sarkar et al. 2022) used neural network to train the low occupancy computational intelligence model, which may be one of the mainstream directions in the future. Another noteworthy thing is that due to the success of alternative fuels in emission reduction and soot reactivity, there is no mature soot estimation model and regeneration control for alternative fuels on the market for the time being. The error caused by applying the traditional model will cause unnecessary fuel consumption and filter damage. The next step hinfor DPF regeneration control include detailed differences in different working conditions, intelligent, low computational power achievable control schemes, and special control schemes for alternative fuels.

Interaction between regeneration and other aftertreatment equipment

China has always maintained a strict attitude towards the supply and management of diesel vehicles. As shown in Table 4, compared with the current regulations, China's latest regulations in 2023 tightened the NO_x limit by 40%, HC limit by 50%, and CO limit by 28%. DPF alone cannot complete the comprehensive treatment of exhaust. Therefore, the manufacturers are solving this problem by introducing more aftertreatment devices and an aftertreatment

Table 4 China's emission standards in different periods

	Date	CO (g/km)	THC (g/km)	NMHC (g/km)	NO_x (g/km)	PM (g/km)	PN (p/km)
China V	2018.01	1.0	0.10	0.068	0.060	0.0045	-
China VI-a	2020.07	0.7	0.10	0.068	0.060	0.0045	$6x10^{11}$
China VI-b	2023.07	0.5	0.05	0.035	0.035	0.0030	$6x10^{11}$

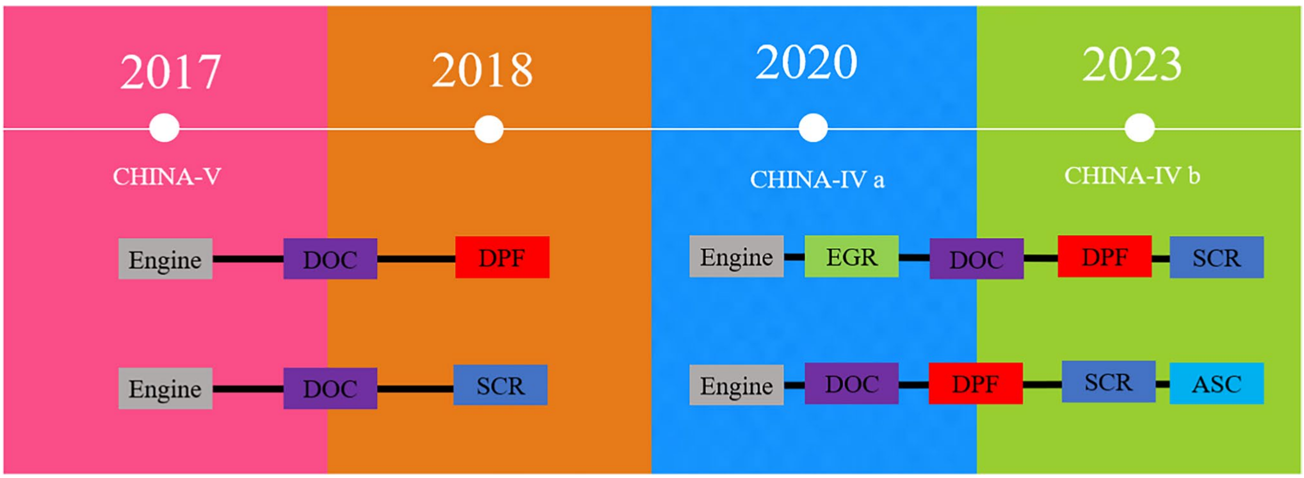

Fig. 25 Various emission reduction technologies and standards in China

system is formed. As shown in Fig. 25, some representative devices are used with DPF, such as DOC, selective catalytic reduction (SCR), EGR, LNT etc., to form an aftertreatment system with DPF (Liu et al. 2021a) (Zhang et al. 2022c) (Kang et al. 2018). Generally, engines equipped with DOC and DPF can reduce THC emissions by more than 70%, CO emissions by more than 97%, and PM emissions by more than 98% (Zhang et al. 2022a) (Zhang et al. 2022f). On this basis, adding SCR can reduce NO_x emission by more than 90%, which is beneficial to reducing acid rain (Cai et al. 2021a) (Cai et al. 2021c). In addition, DPF regeneration, as an accidental event, lacks a centralized description of its interaction with the aftertreatment system in the previous review. Recently, integrated equipment is regarded as the best solution to solve the space constraints of vehicles, and people attach importance to it. This chapter puts forward some original opinions from the perspective of regeneration and integration, hoping to help formulate advanced regeneration strategies and optimize aftertreatment systems.

For the composition of aftertreatment system, the mainstream scheme is DOC+SCR+DPF (Leskovjan et al. 2018) (Lao et al. 2020) (Ko et al. 2019). Each device is designed to control unique pollutants, and the residual pollutants in parallel will have a positive or negative impact on the control behavior. Therefore, the layout of aftertreatment equipment has a significant impact on the control efficiency of aftertreatment system.

In the layout of common DOC-DPF-SCR aftertreatment system, DOC is usually closest to the engine. It is due to the fact that the exothermic reaction inside DOC helps to activate the catalyst in the downstream equipment. In addition, DOC can oxidize NO to NO_2, which is beneficial to DPF passive regeneration (as described in "Continuously regenerating trap") and SCR remove NO_x performance (Leskovjan et al. 2018). The interaction between DPF and SCR is competitive. In the layout of common DOC-SCR-DPF aftertreatment system, if DPF is placed in front of SCR, the soot entering SCR will be greatly reduced. However, the warm-up time of SCR during cold start is prolonged due to the presence of DPF. In addition, the passive regeneration of DPF reduces the proportion of NO_2 in the exhaust and weakens the performance of SCR. During the active regeneration of DPF, the heat generated rapidly has a negative impact on SCR (Lao et al. 2020). The SCR arranged upstream of the DPF is shown in the layout of common DOC-SCR-DPF aftertreatment system. Although the better SCR performance is obtained, the cost is more frequent active regeneration of downstream DPF (Lao et al. 2020). In the experiment of Gao et al. (Gao et al. 2021), SCR was considered to be placed closest to the engine, in the layout of common SCR-DOC-DPF aftertreatment system. Due to the overall thermal improvement of the aftertreatment system, the NO_x emission coefficient is better than the first two layouts, but at the cost of higher PM emission and fuel consumption.

Under actual working conditions, layout (b) is suitable for light vehicles, and layout (a) is more suitable for heavy vehicles (Brookshear et al. 2012). From the perspective of DPF regeneration, selecting layout (a) can reduce the active regeneration frequency and reduce fuel consumption. The specific matching needs to refer to the purpose and driving conditions of the vehicle.

In addition to the flexible choice of layout in different vehicle conditions, the collocation of aftertreatment devices can also be flexibly combined in specific driving scenes. As a widely used diesel engine control strategy, EGR has a good control effect on NO_x emission (Hu et al. 2021). However, due to the reduction of peak temperature, the cost of EGR controlling NO_x is the increase of HC and PM emissions. Therefore, a potential aftertreatment system with DPF and DOC is formed when the SCR is replaced by EGR (García et al. 2020). García et al found that that it was feasible to use EGR instead of SCR to control NO_x. Because the fuel consumption was increased by 2.4%, García et al. suggested that the new system was suitable for long-distance applications. In non-road machinery, the effect of replacing SCR with EGR on emission reduction was also considerable (Hu et al. 2021) (Boccardo et al. 2019). In addition, the DPF's regeneration had a positive impact on EGR scaling. After 40 hours of continuous operation by Galindo et al. (Galindo et al. 2021), the amount of deposited soot observed from the visual EGR channel was in the satisfactory range. However, it was worth noting that the high temperature and high-pressure exhaust during active regeneration reduced the EGR mass flow. The NO_x emission was reduced by 60% (Lapuerta et al. 2012). Therefore, in addition to developing more accurate EGR control, the long-distance and high load conditions are another important factor in using EGR to replace SCR.

In addition to SCR, the LNT is another representative technology to control NO_x emission (Cai et al. 2023). LNT does not require the additional reductant setting and low installation cost, which makes it more popular with diesel engine designers (Kang et al. 2018). In addition, according to a survey of NO_x control participated by DPF, the LNT showed a more stable working efficiency than SCR (Lee et al. 2021c). The existing practice was to place LNT in front of DPF while cooperating with EGR. Myung et al. (Myung et al. 2017) measured that the NO_x emission system control rate under each emission certification cycle (NEDC, WLTC, HWFET and FTP-75) was between 36.3% and 71.7%. The experimental results showed that the control effect was far beyond the regulation of Euro VI except NEDC. In DPF regeneration event, the shutdown of EGR and the high temperature generated by active regeneration led to the low efficiency time of NO_x emission control. The conversion efficiency was decreased by 55.2% compared with normal operation. Thus, the conversion capacity at high temperature should be optimized when the SCR was replaced by LNT. In addition, the improvements of HC and CO by LNT/DPF was still reflected in the regeneration. This phenomenon was more obvious in LNT/DPF+SCR/DPF hybrid system. Kang et al. (Kang et al. 2018) explained that THC was used as reducing agent in SCR/DPF catalyst of mixing system. Except the good effect of THC control, the mixed system is also better than the single LNT/DPF in the control effects of CO and NO_x. The former is due to the additional oxidation capacity provided by SCR/DPF. The latter is because NO_2 is a stronger oxidant than O_2 in SCR/DPF, which combines with ammonia to produce ammonium nitrate (NH_4NO_3). Therefore, for the future application of LNT, it may not appear in the aftertreatment system as an independent NO_x emission control device. At present, the coupling of LNT and SCR/DPF can improve the defects that require high working environment. The development of new high temperature tolerant catalysts also helps to reduce the cost of the coupling system and enhance the NO_x emission control capability during DPF regeneration (Kim et al. 2019).

Although the combination of individual aftertreatment devices has been proved to have good control effect, recently people have shown a great interest in aftertreatment devices and combine them as a whole. In addition to controlling the packaging volume and cost of aftertreatment devices, the improvement of heat conduction is also the main goal of integrated equipment (Karamitros and Koltsakis 2017). Figure 26 shows the effect of different transition lengths on the DPF regeneration performance (Meng et al. 2020).

The result showed that DPF regeneration performance and regeneration efficiency decreased significantly with the increase of inlet transition length. It is necessary to optimize the transition length between aftertreatment devices and make them closer to the exhaust source. Based on the above situation, some manufacturers and laboratories have launched integrated equipment (Kang et al. 2018) (Karamitros and Koltsakis 2017).

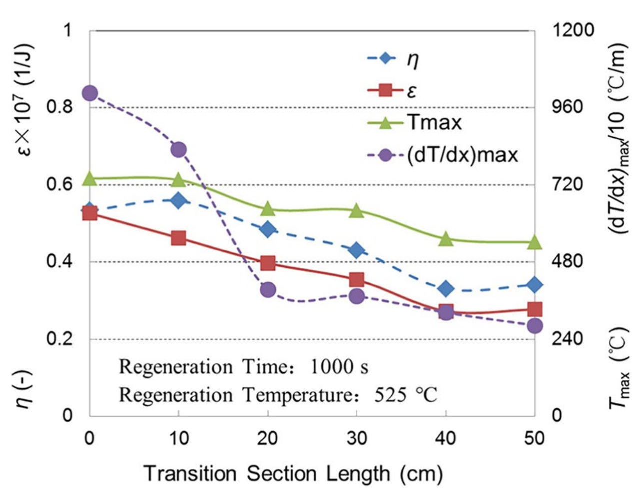

Fig. 26 Effect of different transition lengths on the DPF regeneration performance (Meng et al. 2020)

As described in Chapter 3, the synergy between DPF regeneration and DOC makes it extremely attractive in closely coupled work. Due to the exothermic reaction of DOC, the lower distance between DPF and DOC is conducive to reducing heat dissipation and enhancing the regeneration performance of DPF (Meng et al. 2020). In addition, in the experiment of Millo et al. (Millo et al. 2017), the tightly coupled DOC+DPF could recover the efficiency decline caused by sulfur poisoning highlighted on DOC. This may be able to resist the sulfur content instability of low sulfur diesel caused by accidental factors. In terms of non-road machinery, the integrated equipment composed of DOC+CDPF could remove 73.7% HC, 81.5% CO, 88% PM, and 96% PN (Zhang et al. 2019d). The integrated equipment has the lower emission than CDPF, but its reduction in particle size has more development potential.

The integration of DPF and SCR into a single device (so-called SCRF or SDPF) has been commercially used. However, the competitive consumption of NO_2 and cross reaction between soot chemistry and SCR make the performance of SDPF lower than that of a single device. The new coating technology is a feasible optimization scheme. Compared with the traditional uniform coating technology, the new coating technology can selectively concentrate the washing coating in the axial (zoning) or wall (delamination) direction. Karamitros and Koltsakis (Karamitros and Koltsakis 2017) had developed a CFD model and investigated the effects of different catalyst loads on catalytic performance of NRTC in a 4.6L heavy-duty engine, as shown in Fig. 27. After 50 cycle calculations of the model, the results of pressure drop, soot load, NO_x conversion rate and NH_3 concentration are shown in Fig. 28. "Zone 1:2" configuration shows the lower

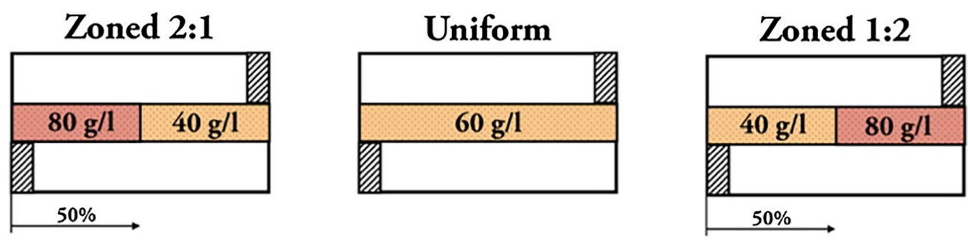

Fig. 27 SDPF coating configurations considered in the model-based analysis (Karamitros and Koltsakis 2017)

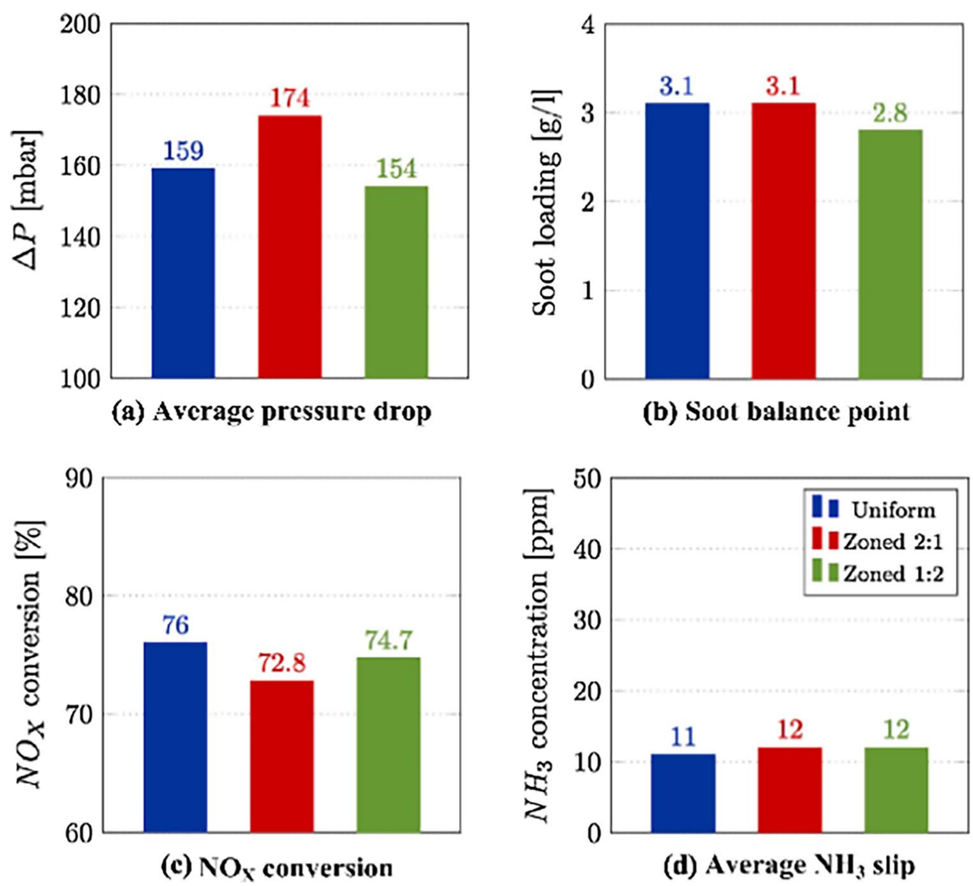

Fig. 28 Performance comparison between the uniform and the zone-coated SDPF in an NRTC driving cycle (Karamitros and Koltsakis 2017)

pressure drop and lower soot emission. In the application field of heavy system, the "zone 1:2" configuration is conducive to reducing the fuel consumption. In addition, the competitive relationship between SCR and soot reaction can be alleviated by the improvement of catalyst. The same conclusion appeared in Smit et al.'s (Smit et al. 2019) integrated transformation of DPF and SCR for Volvo Olympian and Alexander Dennis Trident buses. The new SCRT system reduces 69% NO_x and 69% NO_2 emissions. Martinovic et al. (Martinovic et al. 2020) mixed the potassium carbonate into single component (Cu-ZSM-5 or Fe-ZSM-5) and found that the new catalyst had the better catalytic activity than single component catalyst. At the same time, the thermal stability of K was improved by the low loading and high calcination temperature, so that the new catalyst could still ensure a good catalytic activity after active regeneration.

At this stage, the aftertreatment system composed of DOC+DPF+SCR has been recognized by the industry. However, with the tightening of regulations, the overall optimization of the aftertreatment system includes but is not limited to fuel performance improvement, control program optimization, and equipment coupling. In order to meet the possible new pollutant control (such as NH_3, N_2O), the manufacturers should remain highly sensitive to regulations at all times and make judgments in advance for the reconstruction of aftertreatment systems or the addition of new aftertreatment equipment. In the past few years, the popularity of integrated equipment is rising. The performance of physically mixed multi-component catalyst is very eye-catching (Martinovic et al. 2020). Unfortunately, the experiments of new catalysts are mostly based on laboratory environment, and there is a lack of practical application. It is worth noting that there are few integrated equipment research reports on the impact on the deposition of nonflammable ashes (Zhao et al. 2015a). For closely coupled equipment, how to clean non-combustible soot and its impact on regeneration should be further investigated (Zhao and Guan 2022). We believe that the aftertreatment system should be designed by a modular and integrated way. Different equipment collocation and layout are good for the reduction in fuel consumption under different working conditions.

Conclusions

In this review, we attempt to review various work done for DPF regeneration in the last decade (Hu et al. 2023). Pressure drop is one of the main indexes to measure the working performance of DPF. When too many accumulated particles block the channel, the pressure drop generated will increase the engine fuel consumption, and even damage the engine in serious cases. Therefore, regeneration technology is introduced to keep DPF clean.

(1) The research of various fuel compositions, operating environment and engine parameters shows that the soot with low-load, low-speed, oxygen enriched fuel and post injection operating parameters have the stronger reactivity. The contents of sulfur and phosphorus in the fuel should be controlled to prevent catalyst deactivation. In addition, the effects of small amounts of ash and biodiesel impurities on the oxidation reactivity of soot remain to be discussed.
(2) Regenerative technology provides a variety of options for vehicles. Among them, the field synergy optimization in microwave regeneration can help other regeneration behaviors to think about the binary relationship between flow field and heat transfer. How to coordinate active regeneration and passive regeneration brings great challenges to vehicle regeneration control.
(3) Regeneration control is mainly controlled by analyzing the pressure drop sensor signals at both ends of the filter and introducing them into the pressure drop model. Recently, the complicated calculation program can be simplified by using neural network training model in advance. Therefore, in the subsequent work, it will be an interesting direction to use the algorithm training model to process more inputs to judge the soot deposition and filter health.
(4) The mainstream view is that the best post-processing system consists of DOC, DPF and SCR. In fact, other devices or operations (such as LNT and EGR) can be used to change the mainstream configuration according to the specific working conditions. In addition, the improvement of sulfur poisoning and cold start due to aftertreatment device layout is discussed in the review. Unfortunately, there are few literature reports on road comprehensive aftertreatment equipment.

Optimization is the key to meeting regulations in the future. The investigations on the alternative fuels, vehicle intelligence and aftertreatment device modularization should be carried out further. In addition, the further development of regeneration technology can benefit from the developments of fluid dynamics, the detailed characterization of soot and the simplified control strategy of the vehicle.

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Data availability Not applicable.

Declarations

Ethical approval This paper is an original contribution and not submitted elsewhere for publication and also, authors confirm that, if accepted for publication in "Environmental Science and Pollution Research," it will not be published elsewhere.

Consent to participate We affirm that all authors have participated in the research work and are fully aware of ethical responsibilities.

Consent for publication We affirm that all authors have agreed for submission of the paper to ESPR and are fully aware of ethical responsibilities.

Competing interests The authors declare no competing interests.

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