Guo et al.
Journal of Engineering and Applied Science *(2023) 70:93*
https://doi.org/10.1186/s44147-023-00264-y

Journal of Engineering and Applied Science

RESEARCH **Open Access**

Thermal management strategy for active regeneration of diesel particulate filter

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Abstract

The method of diesel oxidation catalyst (DOC) assistance is an effective way to achieve active regeneration of diesel particulate filter (DPF). Therefore, an appropriate DOC inlet temperature is the essential boundary condition for this regeneration process. In this paper, the thermal management measures and a novel strategy based on the requirements of DPF active regeneration have been proposed and studied through experiments. Results show that intake throttling can increase DOC inlet temperature by 45% at high speed and 13% at low speed. However, its effect becomes significant only after the throttle closure exceeds 65%. Near post-injection is a more effective method than intake throttling to increase the DOC inlet temperature, and is suitable for situations where the DOC inlet temperature differs greatly from the target value. Under the premise of economic consideration, the optimal value of near post-injection time is always 20°CA after top dead center (TDC). The near post-injection quantity has a greater effect on DOC inlet temperature than the near post-injection time. However, too large near post-injection quantity can also lead to a sharp deterioration in fuel economy. Meanwhile, a novel thermal management strategy based on engine working zone division is proposed according to the ability of different thermal management measures and the distribution law of original DOC inlet temperature. With this strategy, the DOC inlet temperature in whole engine operating range increases significantly. In steady state, more than 80% of the operating points can reach the target value of 450 ℃. In world harmonized transient cycle (WHTC), the average DOC inlet temperature is also increased by 28.8%.

Keywords: Diesel particulate filter, Exhaust thermal management, Intake throttling, Near post-injection

Introduction

Hydrocarbon, nitrogen oxides (NO_X), and particulate matter (PM), as the major air pollutants, are abundant in diesel engine exhaust. With the increasing severity of air pollution and stricter emission regulations, it is more and more important to use proper after-treatment technology to reduce the adverse impact on environment.

DPF, which uses porous cordierite material to adsorb PM, is recognized as the most effective way to solve the PM problem in diesel engine. However, large deposition of soot particles and heavy hydrocarbon groups will lead to the increase of flow resistance in

DPF and the deterioration of diesel engine performance. Therefore, periodic removal of deposited PM is indispensable for DPF regeneration [1–4].

The most simple and reliable method is to promote the complete oxidation of deposited PM by increasing the DPF temperature. However, the diesel engine has a wide working range and its exhaust temperature in medium and low load points is too low to meet the requirement of DPF regeneration. In this condition, additional heat is required to maintain the regeneration temperature of DPF. Generally, the catalytic combustion of unburned hydrocarbons on platinum-palladium catalysts in DOC can release a large amount of heat. Therefore, the method of DOC-assisted DPF active regeneration, that is, providing more unburned hydrocarbons to DOC through the adjustment of fuel injection strategy and supplemented by engine intake management, can effectively increase the DPF inlet temperature [5–7]. However, too high temperature may still cause irreversible damage of cordierite material and the adjustment of fuel injection strategy may also lead to the increase of fuel consumption. Thus, the exhaust thermal management strategy based on the requirements of DPF active regeneration should be studied carefully according to the working conditions of the diesel engine, so as to achieve accurate control of DPF regeneration temperature while ensuring well power, economy and emission performances of the engine.

Thomas Korfer and Hartwig Busch et al. [8] conducted numerous exhaust thermal management tests on a 2.0-L diesel engine for an operating condition of 1500 r/min and an average effective pressure of 2 bar. According to the results, they proposed an active exhaust-temperature management strategy based on various thermal management measures. Sungjun Yoon et al. [9] investigated the relationship between the post-injection strategy and the DPF regeneration temperature, and concluded that the optimal post-injection time was between 40°CA ATDC and 110°CA ATDC. Hyunjun Lee et al. [10, 11] proposed a cylinder pressure-based multiple injection MFI control method for DPF regeneration. The main injection quantity was decided by precise feedback control of average indicated pressure, excess air coefficient and upstream temperature of the DPF. The post-injection time was decided by the crankshaft angle, which corresponded to the moment that the instantaneous heat release rate reached 60% of its maximum value. Wang Jian et al. [12] used a light vehicle diesel engine to study the effects of different injection patterns on exhaust temperature, fuel consumption and emissions under small and medium load, experimentally. It was shown that delaying the main injection time had no significant influence on the increase of DOC inlet temperature, while increasing the near post-injection quantity seemed to be a more effective measure. Currently, there are various studies on the exhaust thermal management for DPF active regeneration, but most of them are based on a single engine working point, so it is necessary to conduct a detailed study under full engine working range to form a systematic whole-field thermal management strategy.

In this paper, a heavy-duty diesel engine was selected as the experimental machine. The influence of intake throttling, near post-injection time and near post-injection quantity on exhaust temperature has been researched under extensive engine working points. According to the abilities of different thermal management measures, a novel thermal management strategy was proposed to increase the DOC inlet temperature under whole engine working range. This could provide upstream DOC temperature conditions for DPF active regeneration and has great significance in the formulation of DPF control strategy.

Experimental setup

Experimental equipment

The experimental prototype is a heavy-duty diesel engine, and its specific parameters are shown in Table 1. The after-treatment system includes DOC, DPF, Selective Catalytic Reduction (SCR), and Ammonia Slip Catalyst (ASC), with a U-shaped layout. The physical system is shown in Fig. 1 and the schematic diagram of the experimental bench is shown in Fig. 2. Constant temperature and humidity (25 °C and 45% RH) air is provided by the intake air conditioner. It goes by an ABB Sensyflow-P meter to measure the mass flow rate and then enters the engine supercharger. The intercooling system controls the temperature of pressurized air to be constant, after which the air enters the engine intake manifold. The electronic throttle valve is also located on intake manifold to control the inlet airflow rate. The fuel temperature and mass flow rate are controlled and measured by AVL 753 and AVL 735, respectively. The coolant temperature is maintained at 90 °C by the coolant constant temperature system. The DOC inlet is equipped with a K-type thermocouple and two exhaust sampling tubes to monitor the DOC inlet temperature and engine emissions, respectively. The measures The NO_x concentration is measured by AVL AMA i60 emission analyzer and the Soot concentration is measured by AVL 483 micro soot sensor. The engine speed and torque are controlled by a JD450 electric dynamometer, which is manufactured by Nantong Changshu Testing Company. The adjustment of the injection parameters in ECU is done through the INCA software. The uncertainties of the main parameters are shown in Table 2. As we can see, the parameters can be divided into directly measured parameters and computed parameters. For directly measured parameters, the uncertainty is determined by the accuracy of the instruments. For computed parameters, the uncertainty can be calculated based on the techniques of error propagation:

$$e_R = \left[\left(\frac{\partial f}{\partial x_1} e_1 \right)^2 + \left(\frac{\partial f}{\partial x_2} e_2 \right)^2 + \cdots + \left(\frac{\partial f}{\partial x_n} e_n \right)^2 \right]^{\frac{1}{2}} \tag{1}$$

Table 1 Basic parameters of the prototype

Parameters	Values
Type of diesel engine	Four stroke, supercharged, intercooling, high pressure common rail
Type of intake throttling valve	Electrically controlled circular valve
Number of cylinders	Six
The cylinder diameter (mm)	120
Stroke (mm)	125
Displacement (L)	8.5
Compression ratio	17.5
Maximum power (kW)	290
Maximum torque (N·m)	1730

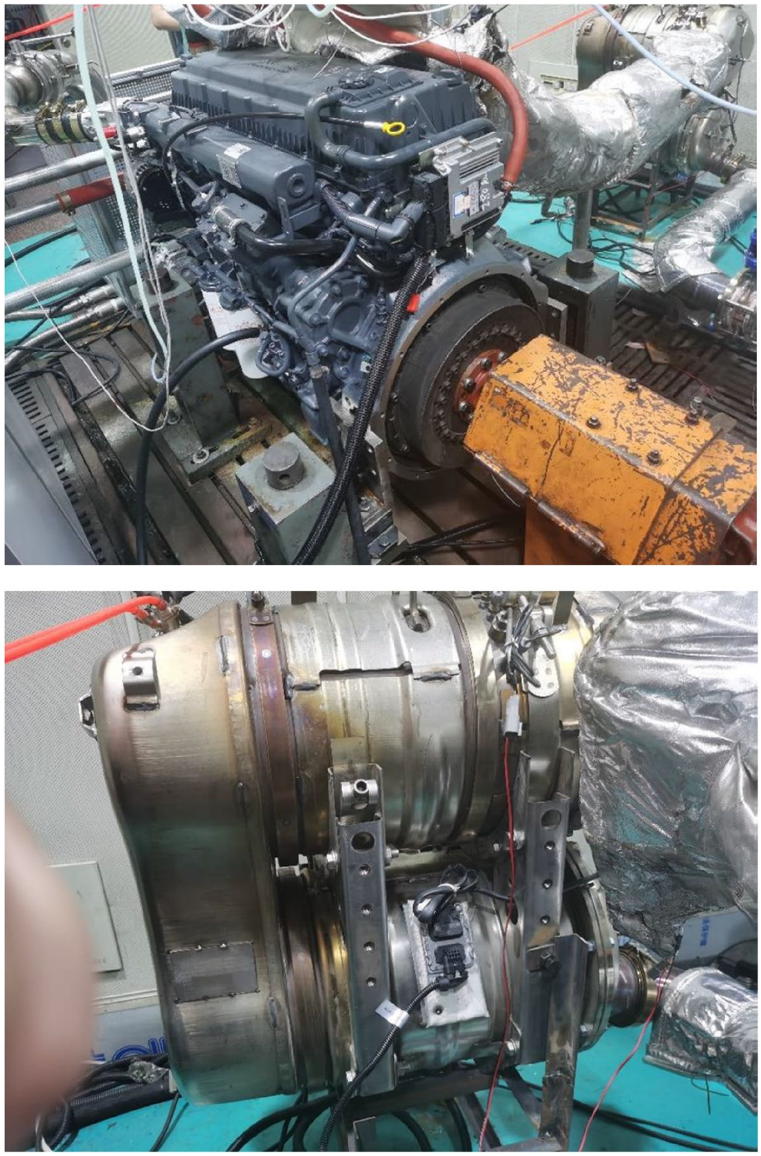

Fig. 1 Physical picture of experimental engine and after-treatment system

where e_R is the uncertainty of computed parameter, *f* is the given function between computed parameter and measured parameters, e_1, e_2, …,e_n are the uncertainty of related measured parameters.

Experimental scheme

Six working conditions of the diesel engine are selected in the experiments, which are denoted as A, B, C, D, E, and F respectively. The specific parameters of each condition are shown in Table 3. The engine speed and torque are kept constant in all experiments. If the torque is affected by thermal management measures, it will be compensated just by adjusting the main fuel injection quantity while the main fuel injection time always keeps unchanged. The position of intake throttling valve

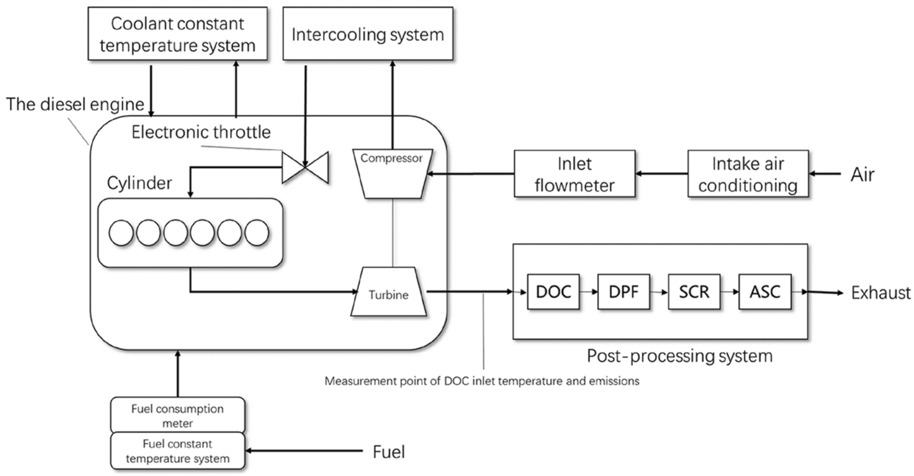

Fig. 2 Schematic diagram of test bench

Table 2 Uncertainty of major parameters

Measured parameters	Measurement uncertainty
Speed	0.02%
Torque	0.2%
Effective power	0.2%
Air flow rate	1.0%
Fuel flow rate	0.4%
NO_x	1.0%

Table 3 Basic parameters of experimental points

Condition	Speed(r/min)	Torque (N·m)	Main injection time (°CA after TDC)	Original DOC inlet temperature (℃)
A	900	300	0.13	279
B	1200	400	-1.99	285
C	1300	700	-2.49	352
D	1500	100	-2.85	177
E	1600	1000	-6.41	372
F	1800	400	-7.48	246

is represented by its closure percentage. That is, when the closure of the intake throttling valve is 0%, it means that the throttling valve is fully open, and when the closure of the intake throttling valve is 100%, it means that the throttling valve is fully closed. The fuel injection time is represented by the crank angle (°CA) after TDC. During the experiments, the charge air temperature is kept constant by the intercooling system. The charge air pressure is determined by the state of the supercharger and is not controlled separately.

Influence of intake throttling on engine performance

Influence of intake throttling valve closure on inlet flow rate

Figure 3 shows the influence of intake throttling valve closure on inlet flow under different working conditions. It can be seen from the figure that the inlet flow decreases in all working conditions with the increase of the closure. Besides, the flow rate decreases faster at larger closures. When the closure percentage varies from 0 to 50%, the change of inlet flow rate is not obvious under all working conditions. However, when the closure percentage varies from 50 to 80%, especially when it exceeds 70%, the inlet flow rate is significantly reduced. Detailed data show that when the closure is 50%, the inlet flows of A, E, and F vary from 268 kg/h to 266 kg/h, 1076 kg/h to 1044 kg/h and 909 kg/h to 887 kg/h, decreasing by 1%, 3%, and 2%. As a contrast, when the closure is 80%, the intake flows of A, E, and F vary to 241 kg/h, 803 kg/h, and 659 kg/h, decreasing by 7%, 25%, and 27% respectively. This is because the effective cross-sectional area of the intake throttling valve decreases sharply at large closure percentage, so the flow resistance increases and the decrease of the inlet flow becomes more obvious. Meanwhile, the influence of intake throttling valve closure on working condition E and F is more obvious than that on A. When the closure percentage increases from 0 to 80%, the inlet flow of condition A varies from 268 kg/h to 241 kg/h, decreasing by 7%. As a contrast, the inlet flows of E and F vary from 1076 kg/h to 803 kg/h and 909 kg/h to 659 kg/h, decreasing by 25% and 27%. This is because the engine has a larger air demand in E and F working conditions, so the decrease of the effective cross-sectional area of the intake throttling valve has greater influence on inlet flow rate [13].

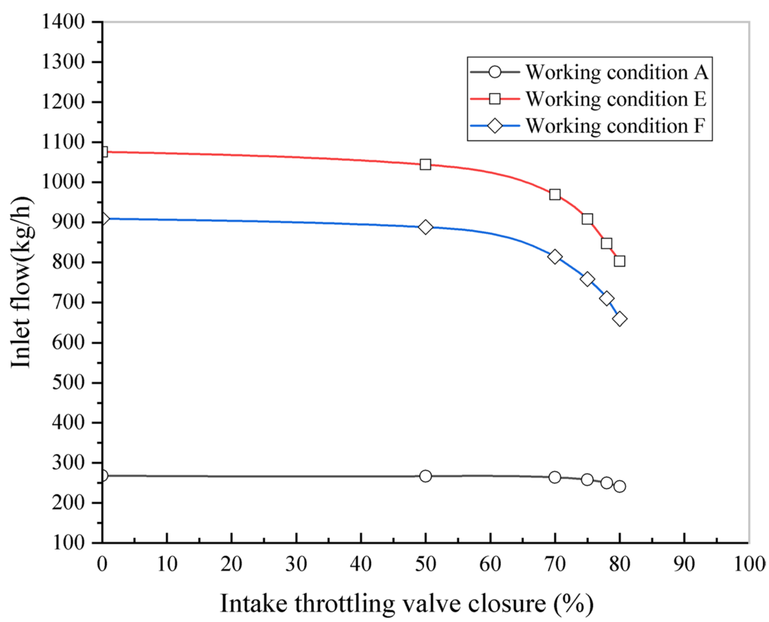

Fig. 3 Influence of intake throttling valve closure on inlet flow rate

Influence of intake throttling valve closure on DOC inlet temperature

Figure 4 shows the influence of intake throttling valve closure on DOC inlet temperature under different working conditions. The figure shows that the DOC inlet temperature rises with the increase of the closure. In addition, the temperature increases quicker at larger closures. When the closure varies from 0 to 50%, the temperature variation for each working condition is not significant. However, when the closure varies from 50 to 80%, significant temperature changes are observed. Especially, the temperature increases dramatically when the closure is larger than 70%. The nonlinear relationship between the valve closure and the increase of DOC inlet temperature is consistent with the results of Jinliang Zhu's research [14], which is caused by the circular shape of the valve. Detailed data show that when the closure is 50%, the DOC inlet temperature of A, E, and F vary from 279 ℃ to 281 ℃, 372 ℃ to 382 ℃ and 246 ℃ to 257 ℃, increasing by 1%, 3%, and 4.5%. In comparison, when the closure is 80%, the temperature of A, E and F vary to 316 ℃, 541℃ and 356℃, increasing by 13%, 44%, and 45% respectively. The effect of valve closure on DOC inlet temperature is opposite in trend to the effect on inlet flow, but to the same extent. This is because the inlet flow is decreased by intake throttling. It will reduce the heat capacity of gas mixture in cylinder and delay combustion phase, ultimately lead to higher exhaust temperature.

Meanwhile, the effect of valve closure on DOC inlet temperature varies for different operating conditions. E is the working condition with the most significant temperature change. From Fig. 4 and the detailed data above, it can be seen that the effect of closure on DOC inlet temperature in A working condition is much smaller than that in E and F. This is because the change of inlet flow caused by intake throttling at small loads is not significant.

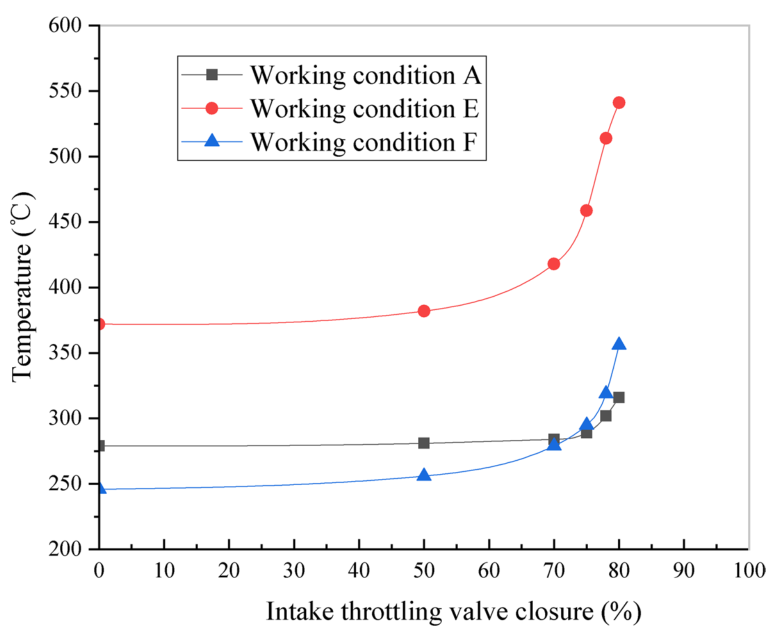

Fig. 4 Influence of intake throttling valve closure on DOC inlet temperature

Influence of intake throttling valve closure on NOx and Soot emissions

Figure 5 shows the influence of intake throttling valve closure on NO_x and Soot emissions under different working conditions. The figure shows that the NO_x emissions rise with the increase of the closure for all working conditions. In addition, the NO_x emissions increase quicker at larger closures, and F is the working condition with fastest increasing rate. Detailed data show that when the closure is 80%, the NO_x emissions of A, E, and F vary from 451($\times 10^{-6}$) to 483($\times 10^{-6}$), 241($\times 10^{-6}$) to 532($\times 10^{-6}$) and 572($\times 10^{-6}$) to 340($\times 10^{-6}$), increasing by 17.9%, 18.4%, and 41.0% respectively. The NO_x emissions are related to the oxygen content in cylinder, the combustion temperature

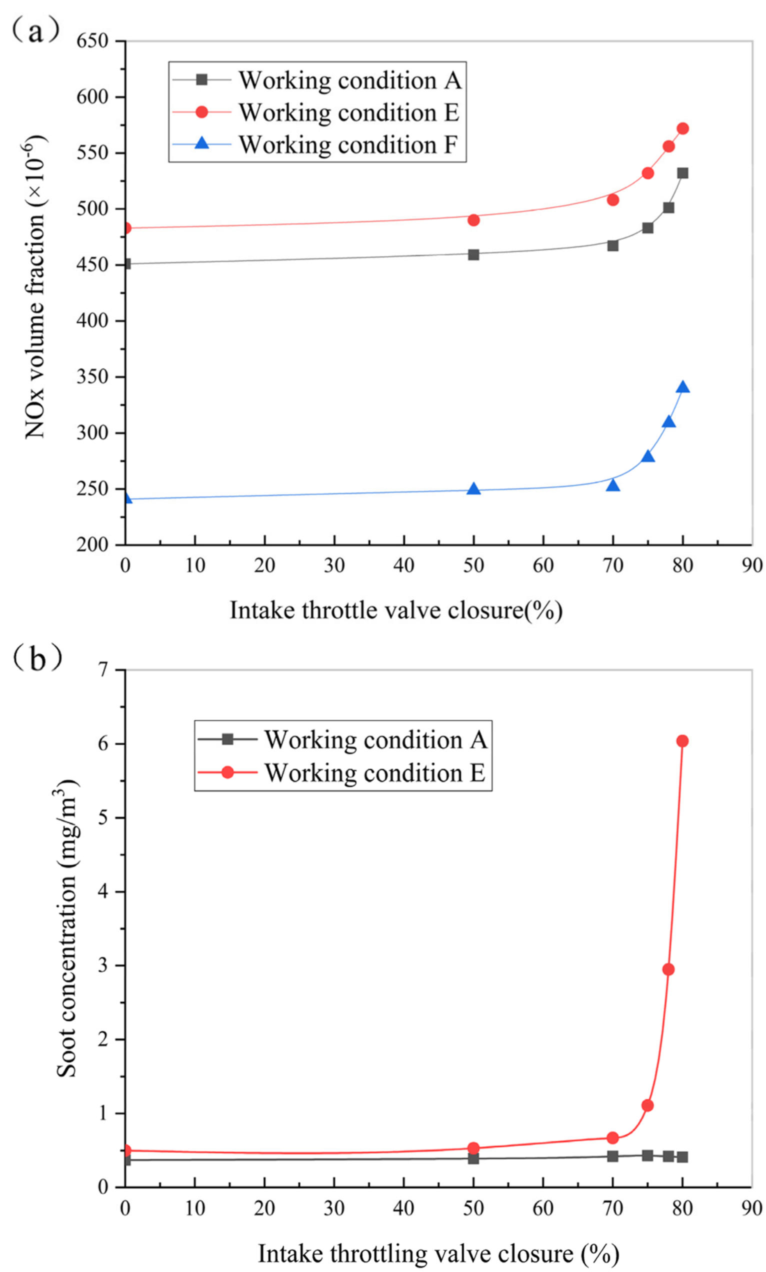

Fig. 5 Influence of intake throttling valve closure on **a** NO_x and **b** Soot emissions

and the duration of high temperature. Therefore, the increase in closure causes a large increase of the average combustion temperature, which creates a conducive high-temperature environment to NO_x generation. On the other hand, the intake throttling causes an unfavorable environment for NO_x generation with decreasing oxygen content. However, the overall oxygen content in cylinder is still at a relatively high level due to the basic operating criteria of excessive air for diesel engine. Thus, the effect of combustion temperature is dominant and the combined result of these two factors is still an increase in NO_x emissions [15]. The Soot emissions show different patterns under different working conditions. Under working condition A, the effect of intake throttling on Soot emissions is very inconspicuous. This is because the engine speed and torque are really small under this condition, so the in-cylinder temperature is low, which means the condition is not in the main region of Soot generation. Under working condition E, the Soot emissions rise with the increase of throttling valve closure, and the phenomenon is more obvious at larger closure. This is consistent with the variation of the inlet flow in Fig. 3. At large closure, the reduction of inlet flow rate becomes obvious. In this case, the excess air coefficient decreases significantly and the in-cylinder temperature rises sharply, so the Soot emissions rise faster.

Influence of near post-injection parameters on engine performance

The near post-injection quantity and the near post-injection time are parameters that have a critical impact on the engine combustion process. The adjustment of the near post-injection time is based on the crank angle after TDC, and the unit is °CA. The adjustment of the near post-injection quantity is based on the cycle injection quantity and the unit is mg/cyc. Three working conditions B, C, and D are selected to show the effect of near post-injection parameters on engine performance.

Influence of near post-injection parameters on DOC inlet temperature

Figure 6 shows the effect of near post-injection time and quantity on DOC inlet temperature at working condition B. The figure shows that the DOC inlet temperature increases with the increase of the near post-injection quantity. Meanwhile, the DOC inlet temperature first increases and then decreases with the increase of the near post-injection angle. The temperature increases most significantly when the near post-injection quantity is 8 mg/cyc. At this condition, the highest temperature point in this experiment appears at the near post-injection angle of 20° CA after TDC and the highest value is 369 °C, 84 °C higher than the temperature without post-injection. On the whole, the highest temperature for each working condition is always found at the near post-injection angle of 20° CA after TDC. Detailed data show that when the engine near post-injection quantity is 2 mg/cyc, 4 mg/cyc, 6 mg/cyc, and 8 mg/cyc, the maximum DOC inlet temperature is 302 ℃, 325 ℃, 352 ℃ and 369 ℃, which are 17 ℃, 40 ℃, 67 ℃, and 84 ℃ higher than the value without post-injection and increase by 5.9%, 14.1%, 23.5%, and 29.4%, respectively.

With the increase of the near post-injection quantity, the post-burning in cylinder increases and the engine thermal efficiency decreases. Thus, more fuel energy is released into the exhaust without doing work, which causes the DOC inlet temperature to rise. Meanwhile, with the delay of near post-injection time, the DOC inlet temperature increases first and then decreases, reaching the highest value at

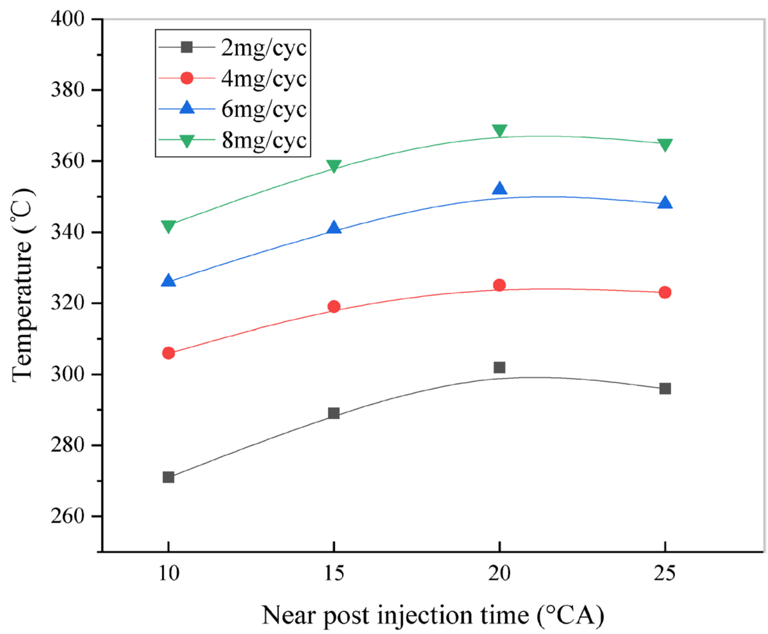

Fig. 6 Influence of near post-injection parameters on DOC inlet temperature

20° CA. When the near post-injection angle is small, the near post-injection fuel can still participate in combustion, but increases the post-burning, which brings a higher exhaust temperature. However, when the near post-injection time delays too much, the mixing quality of fuel and air becomes so poor that most of the fuel is exhausted in the form of unburned HC. Therefore, there is an optimal near post-injection time, so that the post-injection fuel can be fully combusted in the cylinder and most of the heat generated by combustion is used to raise the exhaust temperature.

Influence of near post-injection parameters on effective fuel consumption rate

Figure 7 shows the effect of near post-injection quantity on the effective fuel consumption rate in B, C, and D working conditions. In this experiment, the near post-injection time keeps constant at 20° CA after TDC. The figure shows that the effective fuel consumption rate increases with the near post-injection quantity. Detailed data show that the effective consumption rates of B, C, and D change from 213.7 g/(kW·h) to 235.2 g/(kW·h), 194.4 g/(kW·h) to 213.9 g/(kW·h) and 347.2 g/(kW·h) to 373.3 g/(kW·h) when the near post-injection quantity is increased from 2 mg/cyc to 6 mg/cyc, respectively. The increase in near post-injection quantity enhances post-burning, so the proportion of fuel energy converted to work decreases and the indicated thermal efficiency gets lower [16, 17]. Thus, the effective fuel consumption rate is bound to increase. Besides, the variation is most obvious for the D working condition, because it is in the poor economic working area with high speed and low torque. At this working point, the fuel injection is more frequent and the mixing quality is worse, so the deterioration effect of near post-injection is more prominent.

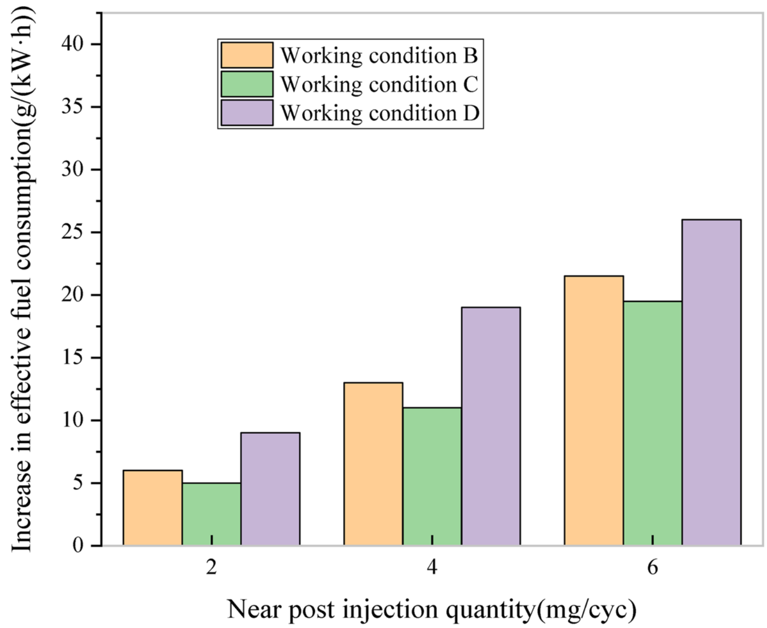

Fig. 7 Influence of near post-injection quantity on effective fuel consumption rate

Influence of near post-injection parameters on NOx and Soot emissions

Figure 8 shows the effect of near post-injection quantity on NO_x and Soot emissions under different working conditions. In this experiment, the near post-injection time is also constant at 20° CA after TDC. The figure shows that the NO_x emissions decrease with increasing near post-injection quantity. Detailed data show that the NO_x emissions in B, C, and D working conditions decrease from $445(\times 10^{-6})$ to $384(\times 10^{-6})$, $493(\times 10^{-6})$ to $421(\times 10^{-6})$, and $258(\times 10^{-6})$ to $202(\times 10^{-6})$ respectively when the near post-injection quantity is increased from 0 to 8 mg/cyc, with a reduction of 13.7%, 14.6%, and 21.7%. In order to maintain the constant speed and torque, the main injection quantity should be reduced when the near post-injection quantity is increased, so the maximum combustion temperature which appears near TDC gets lower and the NO_x emissions decrease [18, 19]. The Soot emissions rise with the increase of near post-injection quantity for all working conditions. This is because the near post-injection fuel is directly injected into flame, so this part of fuel begins combustion before it is effectively mixed with air, which causes Soot generation. However, the increase in working condition D is much less obvious than that in B and C. This is because the working condition D is in the high speed and low load region with a very large excess air coefficient, which mitigates the lean oxygen combustion problem of near post-injection fuel.

Combined influence of intake throttling and near post-injection on DOC inlet temperature

Both intake throttling and near post-injection are effective in increasing the DOC inlet temperature. When the difference between the current DOC inlet temperature and the target value is small, a single thermal management measure can successfully raise the temperature to target value. However, when the difference is too large in small load area, the target temperature cannot be achieved just by a single thermal management measure. This is also consistent with the findings of Thomas Korfer and Hartwig Busch [8].

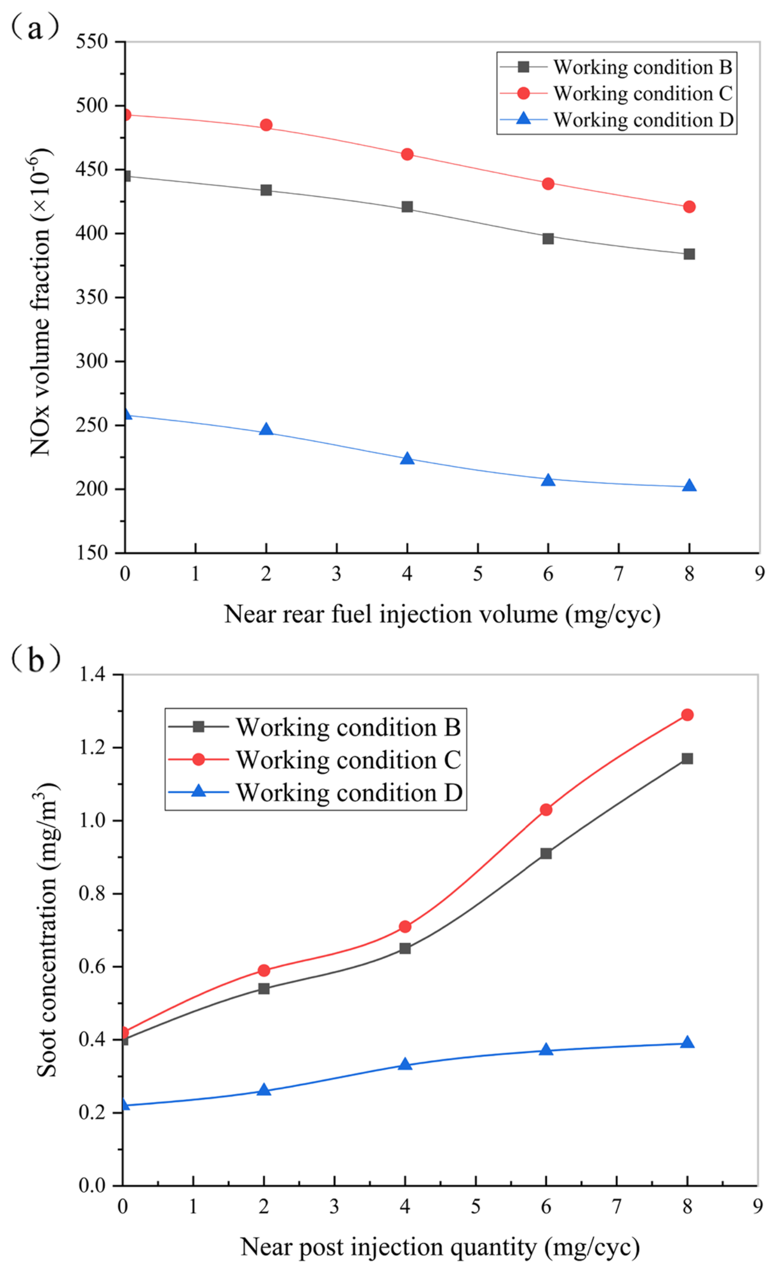

Fig. 8 Influence of near post-injection quantity on **a** NO_X and **b** Soot emissions

Thus, the experimental study in this section is the combined effect of intake throttling and near post-injection on DOC inlet temperature.

The study selects three working conditions A, D and F with lower original DOC inlet temperature, at the constant intake throttling closure of 80% and the constant near post injection time of 20° CA after TDC. Figure 9 shows the effect of the near post-injection quantity on the DOC inlet temperature under different working conditions. The figure shows that the DOC inlet temperature increases with the increase of the near post-injection quantity for all working conditions. With the same near post-injection quantity, the DOC inlet temperature always has a higher value in F

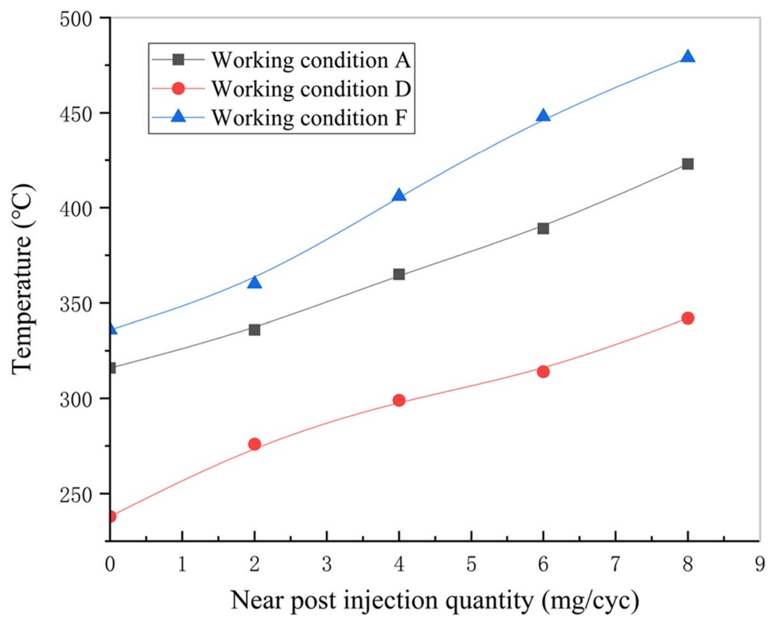

Fig. 9 Influence of near post-injection quantity on DOC inlet temperature

condition than in A and D condition. Meanwhile, the temperature rise in F condition is more prominent than that in A condition. When the intake throttling closure is 80% and the near post-injection quantity is 2 mg/cyc, the DOC inlet temperature increases from 279 °C to 336 °C, 177 °C to 276 °C and 246 °C to 356 °C for A, D, and F working conditions, increasing by 20%, 56%, and 44%, respectively. With the increase of near post-injection quantity to 8 mg/cyc, the DOC inlet temperatures also increase to 403 °C, 342 °C, and 479 °C for A, D, and F working conditions. Compared to the condition without thermal management, the temperature increments are 124 °C, 165 °C, and 233 °C with a percentage of about 44%, 93%, and 94% respectively.

Thermal management control strategy

Analysis of thermal management control strategy for whole engine working range

A suitable DOC inlet temperature is an important condition for DPF regeneration. The current general conclusion is that the deposited particles can achieve spontaneous combustion to complete the DPF regeneration process without any external assistance, when the DPF inlet temperature reaches 600 °C [20–22]. At the same time, the oxidation of THC emissions within the DOC will also lead to a temperature rise. Therefore, the DOC inlet temperature should be lower than 600 °C with a certain margin. However, if the DOC inlet temperature is too low, it is difficult to raise the DPF inlet temperature to a suitable range only by the exothermic oxidation of THC emissions within DOC. Thus, additional measures such as fuel injection at DOC inlet are essential in this case, but this is no longer in line with the technical route of this paper. Combined with the original engine data, the target range of DOC inlet temperature is set at 450 ~ 500 °C in this paper.

The DOC inlet temperature of this experimental prototype varies widely, and the ability of different thermal management measures also varies under different working conditions. The intake throttling can increase the DOC inlet temperature by up to 45% at high speed with large intake flow, and by 13% at low speed. The increase of near post-injection quantity is great beneficial to raise DOC inlet temperature, but too much post-injection quantity will also lead to poor fuel economy and instable engine working. Therefore, the overall strategy to increase DOC inlet temperature to the target value within the whole engine working range is as follows. When the difference between the DOC inlet temperature and the target value is small, only the intake throttling is used. When the difference is large, the intake throttling and near post-injection are used together. When the difference is too large (i.e., the combination of these two measures can still not meet the requirements), the DOC inlet temperature should be increased as much as possible under the premise of ensuring the stability of engine working. Based on the DOC inlet temperature distribution, the ability of intake throttling and near post-injection, the whole engine working range is divided into five regions as shown in Fig. 10.

In region 1, the DOC inlet temperature is always above 500 ℃. The working conditions in this area are near the engine external characteristic, which has a high power and exhaust temperature. The DOC inlet temperature exceeds the set target value and this is an uncontrollable area due to the limitations of engine hardware, so no additional thermal management measures are applied.

In region 2, the DOC inlet temperature is between 450 °C and 500 °C. It is just within the target temperature range and no additional thermal management measures are required.

In region 3, the DOC inlet temperature under most working conditions is between 350 °C and 450 °C. The difference between the current DOC inlet temperature and the target value is small, and the engine just works under medium load conditions. Thus, the

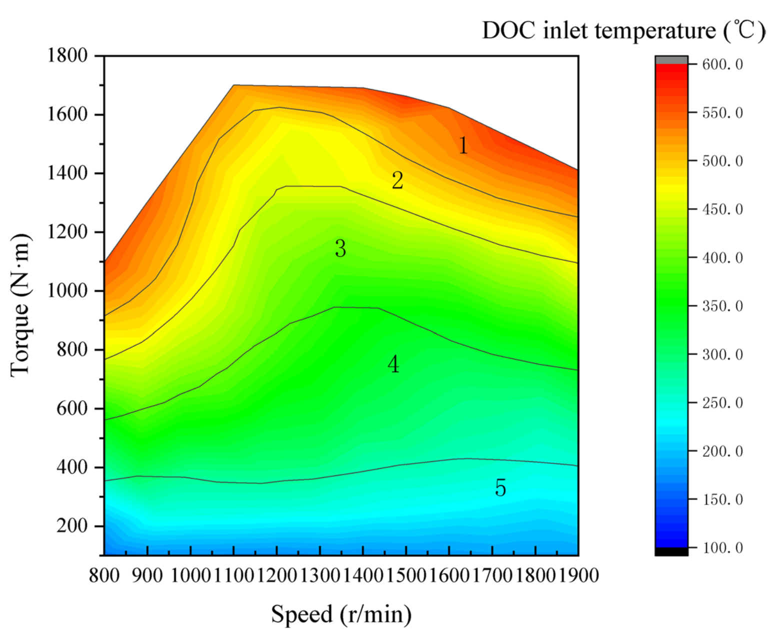

Fig. 10 Schematic diagram of engine working zone division

target temperature can be reached only by intake throttling. Meanwhile, the temperature in low speed region is higher than 350 °C, while it is lower than 350 °C in high-speed region. Thus, there is stricter requirement for exhaust temperature rise in high-speed region. Fortunately, this is consistent with the characteristics of intake throttling with stronger heating ability in high-speed region.

In region 4, the DOC inlet temperature is between 250 ℃ and 350 ℃. The temperature is higher than 250 °C in low speed region and lower than 250 °C in high-speed region. Also, it differs significantly from the target value. The intake throttling can effectively increase the DOC inlet temperature, but the current temperature in this region is relatively low and the target value cannot be reached by intake throttling alone. Therefore, a combination of intake throttling and near post-injection is required. The control strategy in this region is to use both intake throttling and near post-injection.

In region 5, the DOC inlet temperature is mostly below 250 °C. It can be concluded from the original DOC inlet temperature distribution law that the temperature changes more obviously with torque. In this region, the engine torques are all below 400N·m, while the speed covers a wide range. Thus, the DOC inlet temperature is low because of the small engine torques. However, the temperature difference is so large that the target value cannot be reached even if both intake throttling and near post-injection are used. On the other hand, the use of excessive intake throttling closure and near post-injection quantity will have negative effects such as severe engine vibration, risk of flameout and increased fuel consumption. Therefore, the primary calibration objective in this region is to keep the engine working steadily. At the same time, select appropriate intake throttling valve closure and near post-injection quantity to increase the DOC inlet temperature as much as possible.

DOC inlet temperature verification after calibration

Figure 11 shows the distribution of DOC inlet temperature under whole engine working range after calibration. It shows a significant increase in DOC inlet temperature. As a whole, the DOC inlet temperature in most working conditions is between 450 °C and 500 °C, which satisfies the set target value. In region 1, the DOC inlet temperature is between 550 °C and 600 °C. This is an uncontrollable region according to the analysis in Sect. 6.1. Thus, no thermal management measures are applied in this region and the temperature has no change compared with that before calibration. In region 2, the DOC inlet temperature is already between 450 °C and 500 °C which satisfies the target value, so no additional thermal management measure is needed as well. In region 3, the DOC inlet temperature is in the range of 450 °C to 500 °C. In this region, the DOC inlet temperature can be increased to the target value only with intake throttling. In region 4, the DOC inlet temperature is around 450 °C. The target value is reached with the combination of intake throttling and near post-injection, because only intake throttling cannot compensate for such a large temperature difference. In region 5, the DOC inlet temperature is between 350 °C and 450 °C. In the low load working conditions, the target temperature cannot be reached even with both intake throttling and near post-injection because the original DOC inlet temperature is too low. This is especially obvious for the working conditions with both low speed and small torque. However, small torque conditions are really rare use for heavy-duty diesel engines. Thus, it has little effect on the

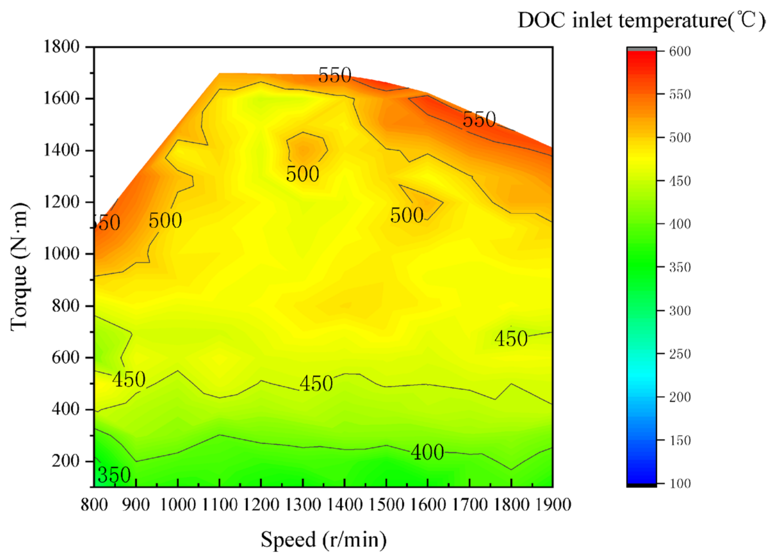

Fig. 11 DOC inlet temperature distribution after calibration

process of DPF traveling regeneration although the DOC inlet temperature in region 5 fails to reach the target value. From the steady-state results of the calibration, the DOC inlet temperature required for DPF traveling regeneration process can be achieved by the proposed thermal management control strategy.

Figure 12 shows the increment of the DOC inlet temperature in steady-state condition. The figure shows that there is almost no change of DOC inlet temperature under high load working conditions, because the original DOC inlet temperature is high enough and there is no need to use any additional thermal management measures. With the decrease of engine torque, the temperature increment before and after calibration

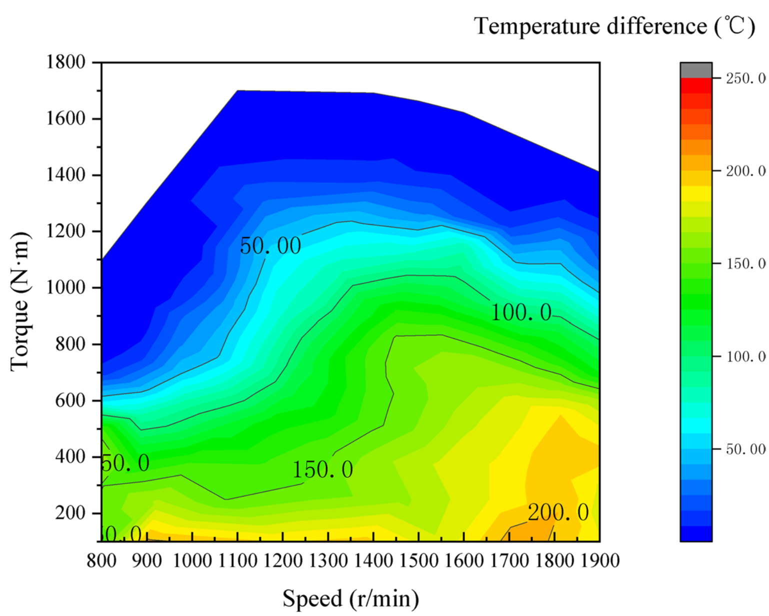

Fig. 12 Increment of DOC inlet temperature in steady-state condition

becomes larger because the original DOC inlet temperature drops sharply and more thermal management measures are applied in this process. The maximum increment is 200 °C and it appears in the region with small torque and high speed. On the one hand, the original DOC inlet temperature is low under small torque condition. On the other hand, the effect of intake throttling is more obvious under high-speed condition. Besides, large near post-injection quantity is also applied, so the maximum temperature increase appears in this region.

Figure 13 shows the increment of the DOC inlet temperature before and after the calibration in WHTC cycle. On the whole, the DOC inlet temperature has significant increase after calibration, especially for the idle and low load conditions. The original DOC inlet temperature of the prototype is low and has a scattered distribution, with 80% of the working points between 150 °C and 350 °C during WHTC test. After calibration, the temperature gets higher and more concentrated, with 90% of the working points between 250 ℃ and 450 ℃.

Parameters analysis of thermal management measures after calibration

Based on the transient and steady-state results after the calibration above, it can be seen that the zonal thermal management control strategy can effectively increase the DOC inlet temperature to meet the requirements of DPF traveling regeneration. Only giving the control strategy has limited guidance for the subsequent work, while detailed parameter values can provide useful references for similar work that can reduce the total experiments, save costs and further improve efficiency.

Figure 14 shows the intake throttling valve closure after calibration. The closure is mainly between 75 and 85%, just with several special points close to 85% under the working conditions of low speed and small torque. This is consistent with the pattern derived above. When the intake throttling closure is small, it has little effect on intake air

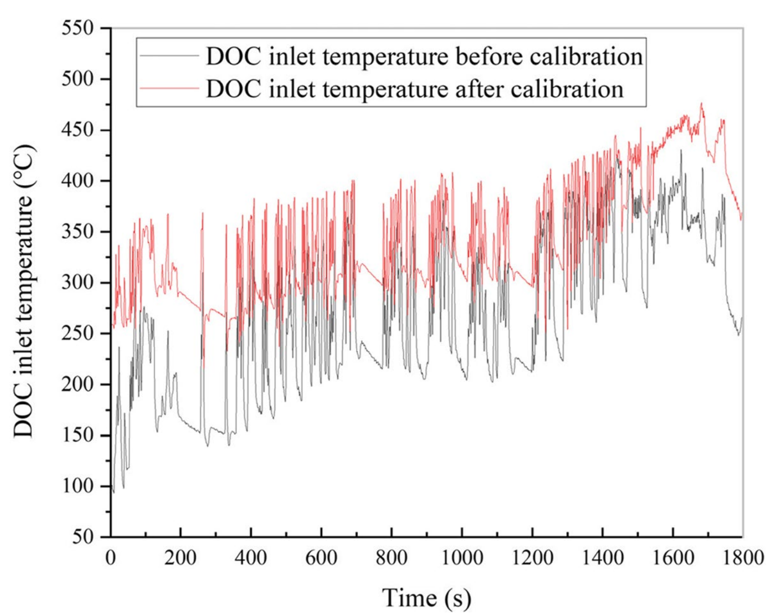

Fig. 13 Increment of DOC inlet temperature in WHTC cycle

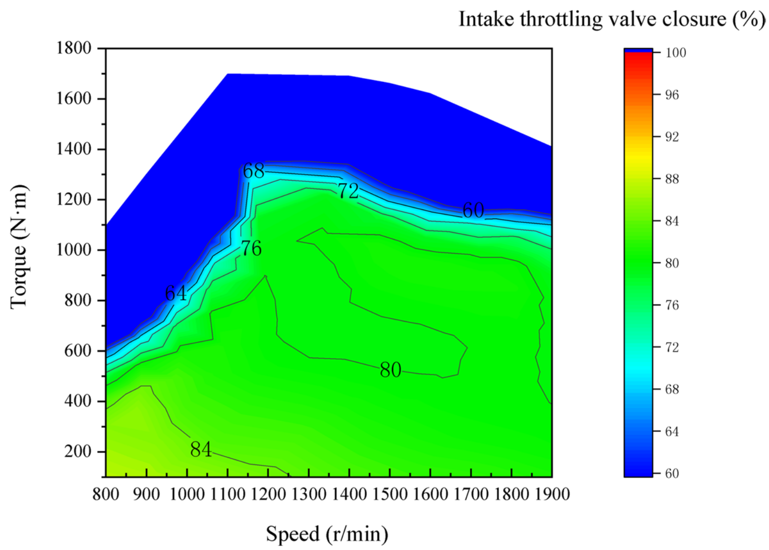

Fig. 14 Distribution of intake throttling valve closure after calibration

flow and the DOC inlet temperature. Therefore, the closure should be above 65% to produce a substantial effect. Meanwhile, the higher the needed temperature rise, the greater the closure is. The maximum closure appears under the working condition with both low speed and small torque. At this condition, the engine only needs a very small intake flow, so the large intake throttling closure will not make this flow significantly lower than the normal value.

Figure 15 shows the near post-injection quantity after calibration. As we can see, the conditions those require near post-injection to increase DOC inlet temperature are concentrated in the low and medium torque region. With the enlarged difference between the original DOC inlet temperature and the target value, the near post-injection quantity increases

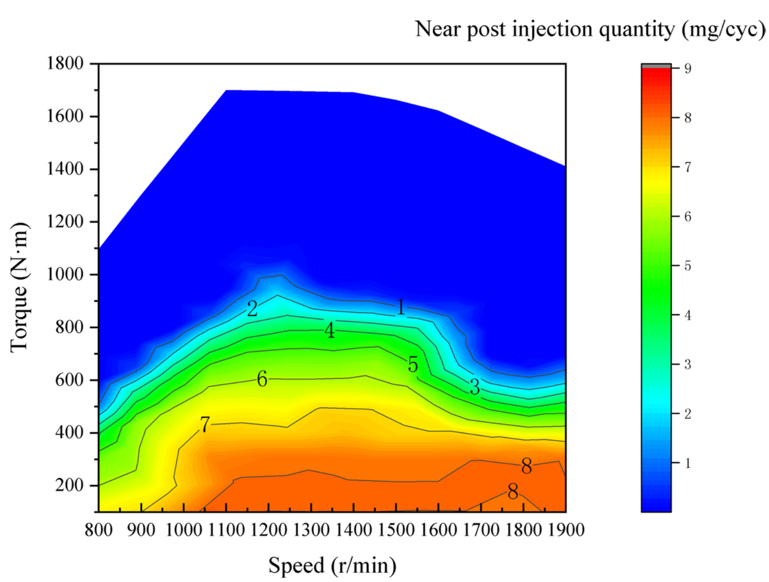

Fig. 15 Distribution of near post-injection quantity after calibration

gradually. The maximum quantity is reached in high speed and small torque region. However, the same large quantity is not adopted in low speed and small torque region despite of the unimproved huge temperature difference. This is because the normal fuel demand in this region is really small. If a large near post-injection quantity is used at this condition, it will cause excessive deterioration on engine combustion and the stable operation cannot be maintained. Therefore, it is more important to maintain the normal engine combustion rather than increase the DOC inlet temperature in low speed and small torque region.

Conclusions

A heavy-duty diesel engine was selected as the experimental machine in this study. The influence of intake throttling, near post-injection time and near post-injection quantity on DOC inlet temperature has been researched under extensive engine working points. Meanwhile, a novel thermal management strategy suitable for whole engine working map has been proposed to meet the requirements of DOC assisted DPF regeneration.

(1) The influence of intake throttling on DOC inlet temperature is little at small intake throttling valve closure. It just becomes obvious when the closure is larger than 65%. This measure is more suitable for the case with large inlet flow and can achieve a maximum temperature rise of 45%.
(2) Near post-injection is a more effective measure than intake throttling when the difference between actual DOC inlet temperature and its target value becomes larger. The optimal near post-injection time is 20°CA after TDC with the biggest temperature rise. Larger near post-injection quantity has stronger effect on DOC inlet temperature, but causes much worse fuel economy.
(3) The combination of intake throttling and near post-injection has great better heating ability than either of them. It is used in the region where the difference between the original DOC inlet temperature and the target value is huge.
(4) Based on the heating ability of different thermal management measures and the distribution law of original DOC inlet temperature, the engine working zone is divided into five regions and different thermal management measures are matched. After calibration, the DOC inlet temperature is significantly improved for whole engine map. In steady-state condition, more than 80% of the working points can reach the target temperature. In WHTC transient cycle, the average DOC inlet temperature is increased by 28.8%, which can meet the requirement of DPF traveling regeneration. Meanwhile, detailed analysis of the parameters' values after calibration is also given. The intake throttling valve closure is set between 60 and 85%. The closer the condition is to low speed and small torque, the larger the valve closure is. Meanwhile, the post-injection quantity is kept between 0 and 8.3 mg/cyc. The closer the condition is to high speed and small torque, the larger the injection quantity is.

Abbreviations

DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
TDC	Top dead center
WHTC	World harmonized transient cycle

NO_X	Nitrogen oxides
SCR	Selective catalytic reduction
ASC	Ammonia slip catalyst

Acknowledgements
We would like to thank support from our team members, and the reviews whose constructive and detailed critique contributed to the quality of this paper.

Authors' contributions
The idea and conceptualization of the study were made by author SG. The experimental and numerical analysis were carried out by SG, YZ, XZ, and HM. The preparation of the manuscript was carried out by YZ, XZ, HM, and HL, and expert suggestions were provided by SG. The final version of the manuscript was approved after all author's detailed editing and evaluation.

Funding
This study was financially supported by the the Science Fund of State Key Laboratory of Engine Reliability (No. SKLER-202013).

Availability of data and materials
The datasets generated and analyzed during the current study are available in the manuscript.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 22 March 2023 Accepted: 24 July 2023
Published online: 11 August 2023

References

1. Tan PQ, Duan LS, Li EF, Hu ZY, Lou DM (2020) Experimental study on the temperature characteristics of a diesel particulate filter during a drop to idle active regeneration process. Appl Therm Eng 178:115628
2. Wang J, Cao Z, Zhang D, Liu S (2018) Intake throttling control strategy based on DPF active regeneration temperature for diesel. Trans Chin Soc Agric Eng 34(2):32-39
3. Yoon S, Quiros DC, Dwyer HA, Collins JF, Burnitzki M, Chernich D, Herner JD (2015) Characteristics of particle number and mass emissions during heavy-duty diesel truck parked active DPF regeneration in an ambient air dilution tunnel. Atmos Environ122:58-64
4. Hamedi MR, Doustdar O, Tsolakis A, Hartland J (2021) Energy-efficient heating strategies of diesel oxidation catalyst for low emissions vehicles. Energy 230:120819
5. Wang J, Wang B, Cao Z (2020) Experimental Research On Exhaust Thermal Management Control Strategy for Diesel Particular Filter Active Regeneration. Int J Automot 21:1185-1194
6. Wu D, Deng B, Li M, Fu J, Hou K (2020) Improvements on performance and emissions of a heavy duty diesel engine by throttling degree optimization: A steady-state and transient experimental study. Chem Eng Process Process Intensif 157:108132
7. Andrisani N, Tominška L, Scassa M, Nencioni M (2019) Thermal Management System for the Exhaust Aftertreatment of Passenger Car Diesel Engines. MTZ worldwide 80(1):48–53
8. Korfer T (2012) Proceedings of the 2012 Internal Combustion Engine Fall Technical Conference. The American Society of Mechanical Engineers, New York, America, Torino, Piemonte, Italy
9. Yoon S, Kim H, Kim D, Park S (2016) Effect of the fuel injection strategy on diesel particulate filter regeneration in a single-cylinder diesel engine. J Eng Gas Turbines Power 38(10):102810
10. Lee H, Han M, Sunwoo M (2016) Cylinder pressure information-based post injection timing control for aftertreatment system regeneration in a diesel Engine-Part I: derivation of control parameter. J Eng Gas Turbines Power 138(8):081507
11. Lee H, Shin J, Han M, Sunwoo M (2016) Cylinder pressure information-based post injection timing control for aftertreatment system regeneration in a diesel Engine-Part II: active diesel particulate filter regeneration. J Eng Gas Turbines Power 138(8):081508
12. Jian W, Zheng C, Duojun Z (2018) Experimental study of injection strategy control based on diesel engine exhaust heat management [J]. Automotive Engine 2:79–86
13. Sun K, Da Li HL, Bai S (2020) Influence of Diesel Engine Intake Throttle and Late Post Injection Process on the Rise of Temperature in the Diesel Oxidation Catalyst. Fluid Dyn Mater Process 16(3):574-584
14. Zhu J (2022) Study on SCR control strategy for heavy-duty diesel engine to meet National VI emission standard. Shandong University, Jinan
15. Zhu J, Wang X, Wang G, Zhong X, Li Z, Wang Z, Sun K, Bai S (2022) Experimental Analysis of the Influence of Exhaust Thermal Management on Engine NOx Emission. Fluid Dyn Mater Process 18(3):701–11
16. Farhan SM, Pan W, Yan W, Jing Y, Lili L (2022) Effect of post-injection strategies on regulated and unregulated harmful emissions from a heavy-duty diesel engine. Int J Engine Res 23(2):169–79
17. Hamedi MR, Doustdar O, Tsolakis A, Hartland J (2021) Energy-efficient heating strategies of diesel oxidation catalyst for low emissions vehicles. Energy 230:120819

18. Lu Y, Liu Y (2020) Effects of multiple injections on combustion and emissions in a heavy-duty diesel engine at high load and low speed. Adv Mech Eng 12(12):1687814020984628
19. Fan C, Song C, Lv G, Wei J, Zhang X, Qiao Y, Liu Y (2019) Impact of post-injection strategy on the physicochemical properties and reactivity of diesel in-cylinder soot. Proc Combust Inst 37(4):4821–9
20. Boger T, Rose D, Tilgner IC et al (2019) Regeneration strategies for an enhanced thermal management of oxide diesel particulate filters. SAE Int J Fuels Lubr 1(1):162–172
21. Ke Z (2017) Research on diesel engine particulate trap and its regeneration system. Southwest Jiaotong University, Chengdu
22. Jing T, Yilin C, Zhongchang L et al (2013) Control of carrier temperature during the regeneration of diesel engine particulate traps at reduced idle speed [J]. J Int Combustion Engines 31(2):154–158

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