International Journal of Automotive Technology, Vol. 21, No. 5, pp. 1185−1194 (2020)
DOI 10.1007/s12239−020−0112−x

pISSN 1229−9138/ eISSN 1976−3832

EXPERIMENTAL RESEARCH ON EXHAUST THERMAL MANAGEMENT CONTROL STRATEGY FOR DIESEL PARTICULAR FILTER ACTIVE REGENERATION

Jian Wang[1)*], Bin Wang[1)] and Zheng Cao[2)]

[1)]School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212000, China
[2)]Power-train Application Department, United Automotive Electronic System Co., Ltd., 555 Rongqiao Rd., Pudong New District, Shanghai 200000, China

(Received 17 September 2019; Revised 13 December 2019; Accepted 16 December 2019)

ABSTRACT−The regeneration was the main barrier restricting the development of diesel particulate filter (DPF), and the exhaust thermal management control strategy are the premise of efficient DPF active regeneration. This paper took a light vehicle equipped with high-pressure common rail diesel engine as the object, studied the influences of exhaust thermal management including intake throttling, fuel injection strategies and late post injection (LPI) coupling diesel oxidation catalyst (DOC) on exhaust temperature by experiment. The results indicated that the reduction of intake throttle valve opening at low speed and light load working conditions, where the exhaust temperatures were low, could dramatically increase the exhaust temperature. With a reasonable match of fuel injection parameters, the exhaust temperature could be increased. LPI coupling DOC could have a further increment on exhaust temperature, but it would have obvious negative effects on fuel economy and hydrocarbon emissions at the same time. In this paper, a comprehensive exhaust thermal management control strategy was proposed. The test bench indicated clearly that the demand of DPF regeneration temperature can be met in most working conditions through the reasonable integrated control strategies of exhaust thermal management.

KEY WORDS : Diesel, DPF (Diesel Particulate Filter), Exhaust Thermal Management, Control Strategy

1. INTRODUCTION

Diesel engine has been widely used in light-duty vehicles for its higher thermal efficiency, greater performance on power and fuel economy, as well as less carbon monoxide (CO) and total hydrocarbon (THC) emissions compared with gasoline engine. However, as the problems of global environment pollution becoming more serious and the total amount of exhaust emissions produced by diesel engines increasing in recent years, more attentions have been paid to emission reduction of diesel engines, especially for the reduction of particulate matter (PM) emissions. Studies showed that PM can induce parasympathetic dysfunction in healthy individuals, which will lead to the occurrence of cardiovascular diseases (Tobaldini *et al*., 2018). As a result, regulations on diesel engine emissions have been upgraded to limit PM emissions. Latest European emissions legislations (i.e. Euro VI) are set on the basis of both mass and number counts to ensure the control of the ultrafine particles which are thought to be the more critical indicators of health impact (Mamakos *et al*., 2014). The US standards come into force with even more stringent measures to reduce PM. For light-duty vehicle, the California Air Resources Board (CARB) finalized the low emissions vehicle (LEV III) emissions standards, calling for a 90 % cut in PM, down to 0.625 mg/km, by 2025. (Joubert and Seguelong, 2004). Therefore, it is critical to reduce diesel engine emissions to satisfy the stricter emission regulations.

In order to meet the strict emission standards, the development of light-duty vehicles has been focused on optimization of engine structure, clean combustion and after-treatment systems. Modern techniques such as low temperature combustion (LTC) and homogeneous charge compression ignition (HCCI) need further research to be applied in commerce (Northrop *et al*., 2007). The difficulties in minimizing particulate emissions for internal purification technologies such as electronically controlled high pressure common rail system, supercharged inter-cooling and multi valves lie on reasonable cooperation with each other (Ishikawa *et al*., 2004; Johnson, 2009). As a result, after-treatment technology has become the main measure to control PM emissions (Xu *et al*., 2010). The utilization of diesel particulate filters (DPF) tended to be necessary to achieve the goal of reducing PM emissions, (Alimin *et al*., 2009; Neely *et al*., 2005). In addition, DPF has been recognized as the most mature commercial PM after-treatment technology for it can reduce PM by up to 99

**Corresponding author*: e-mail: wangjian@mail.ujs.edu.cn

percent. However, DPF regeneration has always been a barrier restricting its further development (Tan *et al.*, 2005; Suresh *et al.*, 2009). With the increase of vehicle mileage, continuous accumulation of particles inside DPF leads to the rise of exhaust backpressure and the decline of power and fuel efficiency. Therefore, it is important for DPF to burn and eliminate the trapped particles timely, which is called DPF regeneration. DPF regeneration can be done in either a passive or an active way and each way corresponds to different regeneration technologies (Chang *et al.*, 2003). It requires a large amount of NO_2 for passive regeneration to facilitate the chemical reaction between carbon and NO_2 in a relatively low exhaust temperature (Sugino *et al.*, 2017). Unfortunately, suitable passive regeneration conditions do not occur with enough frequency, and for this reason, active regeneration containing post-injection, secondary fuel injection, fuel additives and other measures has become the mainstream due to its completeness and safety during the regeneration (Bermudez *et al.*, 2012).

The exhaust temperature of diesel engine can reach the regeneration requirement only at full loads, generally 550-600°C, where PM can be effectively burned during DPF regeneration. However, the exhaust temperature is lower at medium and light loads, generally 100 ~ 550 °C. Exhaust thermal management is the premise for DPF regeneration (Bai *et al.*, 2017). The regeneration efficiency depends largely on exhaust temperature, and the regeneration capacity of DPF can be improved by suitable exhaust thermal management measures (Leahu *et al.*, 2018). Therefore, take emissions and fuel consumption into consideration, exhaust thermal management measures must be reasonably cooperated for it is difficult to increase the exhaust temperature by a single exhaust thermal management measure (Yu and Chen, 2017). In addition, the space is restrictive for light-duty diesel vehicles to install complex after-treatment equipment and the costs are high. Moreover, light-duty diesel vehicles operate mainly in medium-low speed and medium-light load conditions where exhaust temperatures are relatively low. It is of significant importance to adopt a reasonable comprehensive exhaust thermal management system which will both make full use of the energy of exhaust gas to increase exhaust temperature and benefit to the efficient operation of DPF regeneration (Zheng *et al.*, 2017).

This paper took a high pressure common rail diesel engine for light-duty vehicle to study the two-stage temperature increment strategies of exhaust thermal management system including intake throttling, fuel injection strategies and late post injection (LPI) coupling diesel oxidation catalyst (DOC). Stage one temperature increment is to increase the exhaust temperature (inlet temperature of DOC) by intake throttling and fuel injection strategies, stage two is to increase the inlet temperature of DPF by LPI coupling DOC. Taking fuel economy and exhaust emissions into consideration, this study aimed at studying the influences of different parameters on exhaust temperature, and exploring a reasonable integrated control strategies of exhaust thermal management which can meet the temperature requirement for DPF regeneration under most working conditions of diesel engine for light-duty vehicle.

2. TESTING EQUIPMENT AND PROCEDURES

2.1. Testing Equipment

Table 1 lists the specifications of the test diesel engine. The after-treatment system includes DOC and DPF and the specifications are displayed in Table 2. The schematic diagram of the engine test bench showed in Figure 1 and Figure 2.

In this study, AC dynamometer was HORIBA Dynas3. Piezoelectric pressure sensor KISLER-6127B was applied to measure in-cylinder pressures. Combustion parameters were calculated by AVL-622 combustion analyzer. NO_X,

Table 1. Specifications of Test Diesel Engine.

Project	Specifications
Engine type	4-cylinder, in-line, turbocharged inter-cooling
Bore × Stroke (mm × mm)	95 × 87.4
Displacement (L)	2.5
Compression ratio	17
Rated power (kW)	90
Rated speed (rpm)	3600

Table 2. Specifications of the After-Treatment Device.

Project	DOC	DPF
Carrier material	cordierite	SiC
Carrier size (mm) × mm (mm)	118.4D × 152.4L	143.8D × 177.8L
Hole density (cpsi)	400	300
Carrier density (g/cm^3)	0.31	0.76
Precious metal species	Pt, Pd	Pt, Pd
External shape	cylinder	cylinder

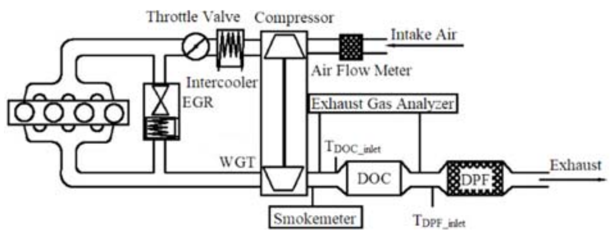

Figure 1. Schematic diagram of test bench.

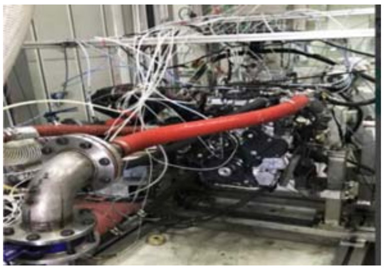

Figure 2. Test bench site map.

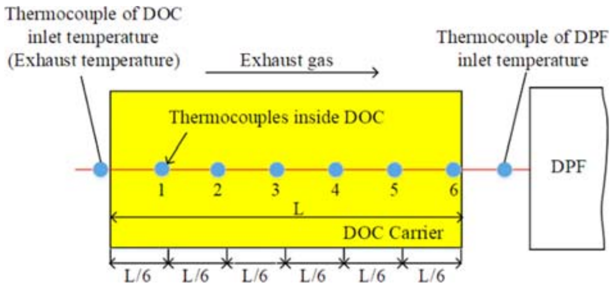

Figure 3. Thermocouple layout.

HC and CO were measured by exhaust gas analyzer (HORIBA MEXA-7100FX). AVL-415S Smoke meter was employed. An air flow meter (BOSCH-EH-56921) was applied to measure air flow. The thermocouples (0.5 mm type K) were utilized to scale exhaust temperature and temperatures inside DOC.

2.2. Experimental Procedures

Exhaust thermal states are different according to different working conditions of diesel engine, which means different exhaust temperature increment for reaching DPF active regeneration temperature is needed. Therefore, control strategies of exhaust thermal management be utilized to increase exhaust temperature at different working conditions are not identical. Three typical steady-state conditions of diesel engine at light, medium and heavy loads (1250 rpm, 25 % load; 2000 rpm, 40 % load; 3000 rpm, 70 % load, respectively recorded as condition A, B, C) were selected to conduct the research. The initial fuel injection parameters and exhaust temperature are exhibited in Table 3.

A throttle valve was installed downstream of compressor, which can change the opening degree to control air intake flow. Fuel injection parameters was calibrated by INCA calibration software. Six thermocouples were evenly installed along the axis of DOC carrier to study the temperature-rising rules inside DOC. Temperature measuring positions are exhibited in Figure 3. More detailed experimental procedures were displayed at each control strategies behind.

3. RESULTS AND DISCUSSION

3.1. Influence of Intake Throttling

The intake throttle valve opening 0 is fully closed and 100% is fully open. The speed and torque were kept constant during the test. Different valve openings (20 %, 40 %, 60 % and 80 %) were set to study the influences of intake throttling.

Intake throttling led to a sharp increase of intake resistance, as a result, air intake flow under condition A, B, and C all decreased significantly with the decrement of intake throttle valve opening, as showed in Figure 4. When the valve opening was reduced to 20 %, the air intake flow for three working conditions were as low as 60, 167, and 275 kg/h respectively, with reductions of 60 %, 45 %, and 40 % compared to 100 % opening. For excess air coefficient, it reduced from 2.30 to 1.54 at condition A, from 2.59 to 1.75 at condition B and from 2.68 to 2.03 at condition C. It is obviously that the in-cylinder working process had been affected by these changes in air intake

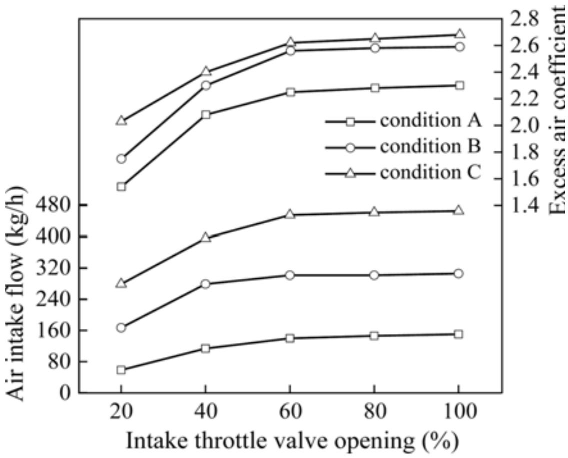

Figure 4. Effect of intake throttling on air intake flow.

Table 3. Initial Fuel Injection Parameters and Exhaust Temperature.

Condition	Speed (rpm)	Torque (N·m)/ Load (%)	Main injection timing (°CA ATDC)	Pilot injection quantity (mg/cycle)	Pilot injection timing (°CA ATDC)	Common Rail fuel pressure (MPa)	Exhaust temperature (°C)
A	1250	65/25	0	1.5	− 6.5	75	255
B	2000	120/40	2	1.5	− 12	120	315
C	3000	187/70	3	1.5	− 18	160	364

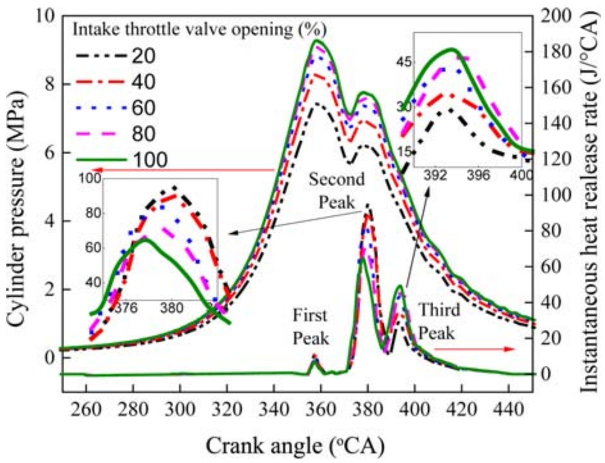

Figure 5. Effect of intake throttling on in-cylinder pressure and instantaneous heat release rate under condition B.

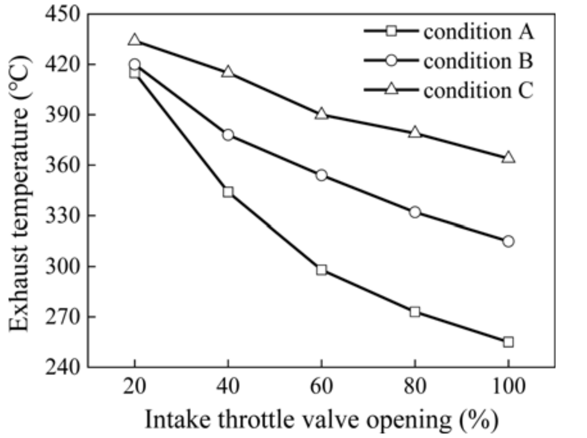

Figure 7. Influence of intake throttling on exhaust temperature.

flow and excess air coefficient, as showed in Figure 5. For brevity, taking condition B as an example. When the opening decreased from 60 % to 20 %, the peak in-cylinder combustion pressure decreased sharply, it reduced 0.84 MPa and the corresponding crank angle shifted back by 1 °CA. Second peak value of instantaneous heat release rate increased and the start of combustion (SOC) delayed simultaneously. The decrement of air intake flow thickened the mixture, which deteriorated the combustion, finally decreased the peak combustion pressure. Postponement of SOC extended the ignition delay, which resulted in an increment in the amount of combustible mixture in the premixed combustion period. As a result, second peak value of instantaneous heat release rate increased.

Intake throttling would increase brake specific fuel consumption (BSFC) as well, as showed in Figure 6. When the throttle valve opening decreased to 20 %, BSFC increased by 90 and 35 g/(kW·h) respectively under condition A and C. Under condition A, in-cylinder temperature was low at the end of compression stroke. Meanwhile, sharper decline of air intake flow and richer air-fuel mixture would further deteriorate the combustion. In order to keep output power constant, cycle fuel injection quantity increased. Therefore, BSFC increased more at working conditions of lighter load and smaller valve opening.

As displayed in Figure 7, exhaust temperatures increased when intake throttle valve opening decreased. When the opening decreased from 100 % to 20 %, exhaust temperature of condition A increased by 160 °C, reached 415 °C, while that of condition C increased by 70 °C, reached 434 °C. The reduction of air intake flow prolonged the ignition delay and increased the proportion of premixed combustion, therefore, the SOC delayed, and more fuel released heat at premixed combustion period. These changes in combustion process led to the increment of exhaust temperature. Except the effect of the combustion process, the decrease of heat capacity of the intake air mass was essential reason for the exhaust temperature increase, especially for light loads.

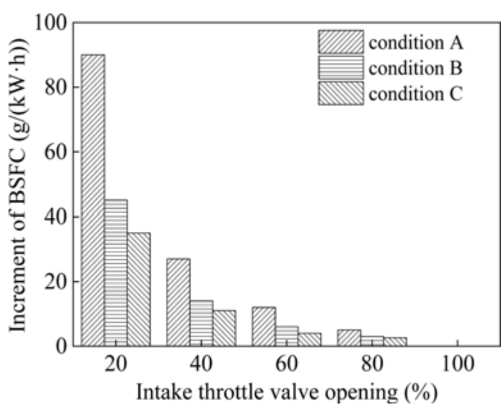

Figure 6. Effect of intake throttling on BSFC.

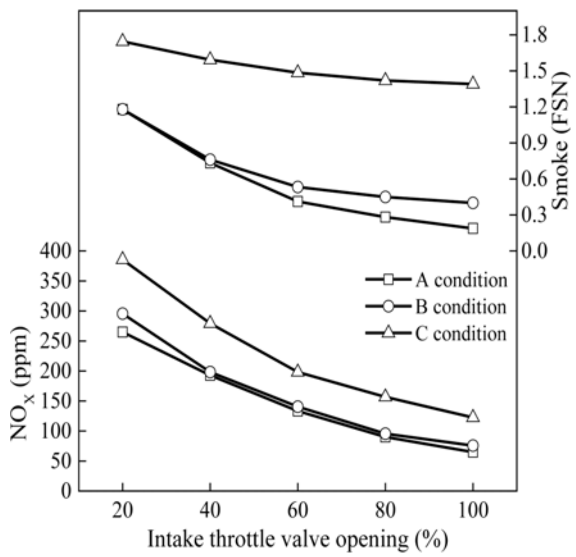

Figure 8. Influence of intake throttling on emissions.

Table 4. Test scheme of fuel injection strategies.

Condition	Main injection advance angle (°CA ATDC)				Close post injection (mg/cycle)				Main-close post injection interval angle (°CA)			
A	− 3	− 1	1	3	0	2	4	6	18	33	48	55
B	− 3	− 1	1	3	0	2	4	6	18	33	48	55
C	− 3	− 1	1	3	0	2	4	6	18	33	48	55

When the intake throttle valve opening decreased from 100 % to 20 %, emissions of smoke and NO_X increased obviously, as showed in Figure 8. For smoke, the increments at condition A, B and C were 0.77, 0.65 and 0.26 FSN respectively. For NO_X, the increments at condition A, B and C were 200.1, 219.8 and 263.1 ppm respectively. The decrement of valve opening caused a sharp reduce of air intake flow, which further led to the generation of smoke. Meanwhile, despite the reduction of oxygen content, the increment of in-cylinder temperature increased the amount of NO_X emission.

We can conclude that intake throttling had obvious positive effect for increasing the exhaust temperature, but had obvious negative effect on fuel economy and emissions at the same time, especially when the valve opening was too small. Therefore, the intake throttle valve opening needs to be controlled within a reasonable range according to working conditions. In this study, the opening should be set within 35 % ~ 45% at condition A, while 50 % ~ 60 % at condition B and 70 % ~ 80 % at condition C.

3.2. Influence of Fuel Injection Strategies

In this section, Parameters such as the total fuel injection quantity, pilot-injection quantity, pilot-injection timing and supercharging pressure were kept constant during the test. Only the quantities of main injection (MI), close post injection (CPI) and late post injection (LPI) were adjusted. Table 4 showed the detailed test scheme of fuel injection strategies.

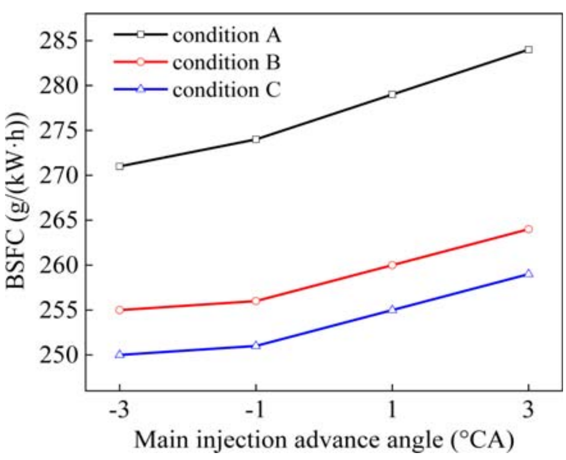

Figure 9. Effect of main injection advance angle on BSFC.

3.2.1. Influence of Main Injection Advance Angle

Figure 9 showed the effect of main injection advance angle on BSFC. As main injection timing delayed from − 3 to 3 °CA ATDC, BSFC gradually increased, it increased 13 g/(kW·h) at condition A, increased 9 g/(kW·h) at condition B, and increased 9 g/(kW·h) at condition C. The fuel could not be burned rapidly near the TDC due to the postponement of main injection timing, resulted in an extension of after combustion period and a decrement of effective thermal efficiency. Therefore, the fuel consumption increased.

Postponing main injection led to the increment of DOC and DPF inlet temperatures, as showed in figure 10. When main injection advance angle delayed from − 3 to 3 °CA ATDC, DOC inlet temperature increased to 295 °C, 342 °C and 381 °C under condition A, B and C, with growths rate of 15.7 %, 8.6 % and 4.4 %, respectively. For DPF inlet temperature, it increased to 275 °C, 327 °C and 372 °C under condition A, B and C, respectively. Postponement of main injection timing caused in-cylinder pressure and peak combustion temperature decrease, which further led to the delay of combustion and the prolongation of after combustion period. Therefore, exhaust temperature

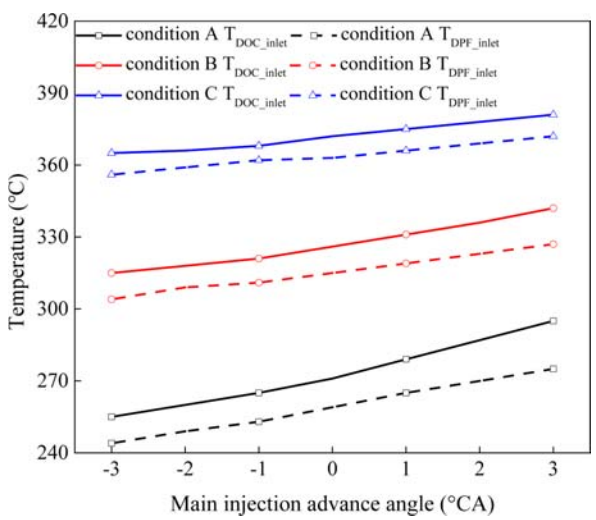

Figure 10. Effect of main injection advance angle on DOC and DPF inlet temperatures.

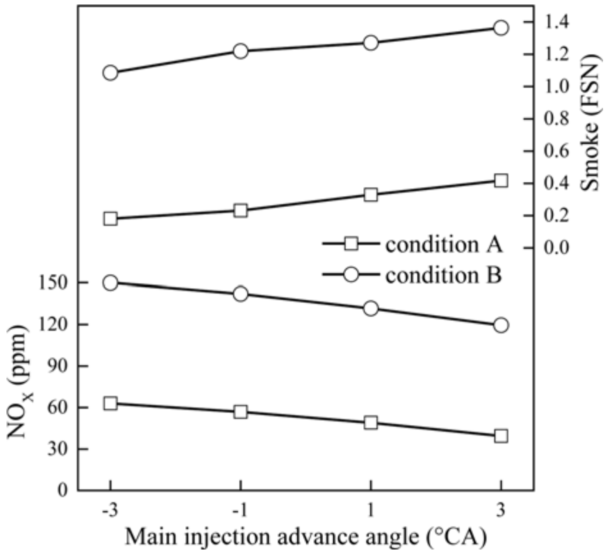

Figure 11. Effect of main injection advance angle on emission.

increased. In addition, there was a certain distance between DOC and DPF (as showed in Figure 1), where existed a large heat loss, as a result, DPF inlet temperature was slightly lower than DOC inlet temperature. Therefore, postponing main injection advance angle could be adopt to increase exhaust temperature when the requirement of exhaust temperature-rising is less urgent.

Figure 11 shows the influence of main injection advance angle on exhaust emissions, condition A and B was selected for brevity. As main injection timing delayed, exhaust emissions of NO_X and smoke displayed a trade-off relationship. For condition A, when main injection advance angle delayed from – 3 to 3 °CA ATDC, NO_X reduced to 40 ppm while smoke increased to 0.425FSN. Decrement of in-cylinder pressure and peak combustion temperature reduced NO_X emission. When main injection timing delayed, the non-uniformity of the mixture increased, and the diffusion combustion period prolonged. These changes led to the deterioration of the particle oxidation process. As a result, the concentration of smoke increased. The same results can be seen in other papers (Zhou, 2013 and Bermúdez *et al.*, 2019).

3.2.2. Influence of close-post injection

BSFC would increase with the delay of CPI and the increase of fuel quantity, as showed in Figure 12. The adoption of CPI had no obvious effect on the increase of BSFC when there was less fuel injection quantity or the main and close-post injection interval angle was small. However, when the fuel quantity further increased (6 mg/cycle) and interval angle was larger (55 °CA), BSFC increased by 43 g/(kW·h) significantly. The combustion duration was prolonged when the interval angle increased, which led to an increase in BSFC. At a certain CPI timing,

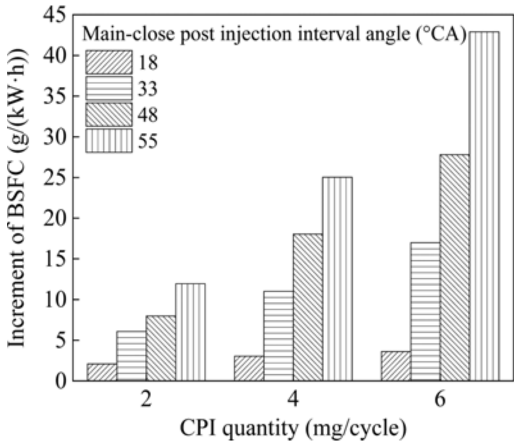

Figure 12. Effect of fuel injection parameters on fuel economy under condition A.

since the total fuel injection quantity was constant at each cycle, the increment of the fuel injection quantity caused a reduction of MI quantity. MI quantity reduction decreased the in-cylinder explosion pressure and further led to the increase of BSFC.

Figure 13 showed the effect of CPI quantity and timing on DOC inlet temperature under condition A. At the same main-close post injection interval angle, DOC inlet temperature increased when CPI quantity increased. At the same CPI quantity, DOC inlet temperature increased when the interval angle increased from 18 °CA to 48 °CA. When the CPI quantity was 6 mg/cycle, the temperature at 55 °CA interval angle decreased to 299 °C, slightly lower than the temperature at 48°CA interval angle. The post injection fuel could not be fully oxidized and burned in time. Unburned HC entered the exhaust pipe and ultimately reduced DOC inlet temperature. So, post injection is a proper control strategy to increase exhaust temperature when the main-close post injection interval angle can be controlled in an appropriate range.

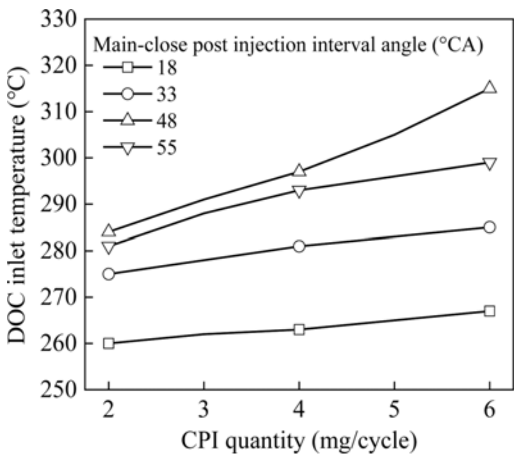

Figure 13. Effect of fuel injection on DOC inlet temperature under condition A.

3.3. Influence of LPI coupling DOC

The main function of LPI coupling DOC was to increase the exhaust temperature for DPF regeneration. In this paper, LPI injection timing was after the exhaust valve opening timing, so the injected fuel was in the form of unburned HC and exhausted instead of be burned in the cylinder. The unburned HC was oxidized and burned inside DOC which could increase DOC outlet temperature (DPF inlet temperature) significantly. This part mainly focused on studying the influences of LPI quantity on DOC internal temperature rising characteristics, HC escaping and fuel efficiency. Finally, the control strategy of LPI coupling DOC which can be employed for DPF active regeneration will be determined. Six 0.5 mm thermocouples were set to measure the temperature inside DOC to study the temperature-rising process of DOC. The measurement of temperature displayed in Figure 3. Six temperature measuring points along the exhaust gas direction were defined as T_{DOC_1}, T_{DOC_2}, T_{DOC_3}, T_{DOC_4}, T_{DOC_5}, and T_{DOC_6} respectively. Table 5 showed the test scheme of LPI coupling DOC.

Figure 14 shows the influences of LPI quantity on temperature-rising of different positions inside DOC at condition A, when LPI quantity was 2.5 mg/cycle. Unburned HC was oxidized by DOC and the released heat was transferred to the DOC. DOC finally reached a stable temperature along the direction of exhaust flow. The results showed that there were obvious temperature difference in different position, but maximum temperature appeared at measuring position 4 and 5 corresponding temperatures were T_{DOC_4} and T_{DOC_5}. So, enough attention should be paid to the test results, because there may be a risk of internal burning damage of DOC when the LPI quality was increased in order to achieve the goal of heating up for DPF regeneration. So, for it was essential for the DPF regeneration, the T_{DOC_6} temperature rising rate was studied. Figure 15 shows the T_{DOC_6} temperature rising rate at different LPI quantities under condition A. It can be seen that the peak temperature-rising rate gradually increased and the time required to reach the peak decreased when LPI quantity increased. Temperature rising rate peaked at 13.1°C/s when LPI quantity was 1.5 mg/cycle, and the heating time was 14s. When LPI quantity was 3 mg·cycle^{-1}, temperature rising rate peaked at 34.5 °C/s and the heating time was shortened to 11 s. So increasing LPI quality could get a higher T_{DOC_6} temperature in a shorter time.

Table 5. Test scheme of LPI coupling DOC.

Condition	LPI fuel quantity (mg/cycle)			
A	1.5	2	2.5	3
B	1.5	2	2.5	3
C	1.5	2	2.5	3

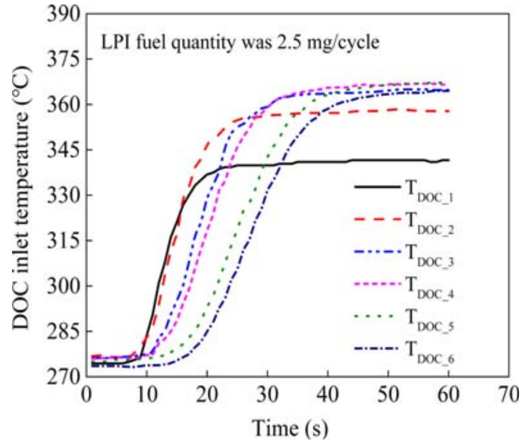

Figure 14. Influences of LPI fuel on temperature-rising under condition A.

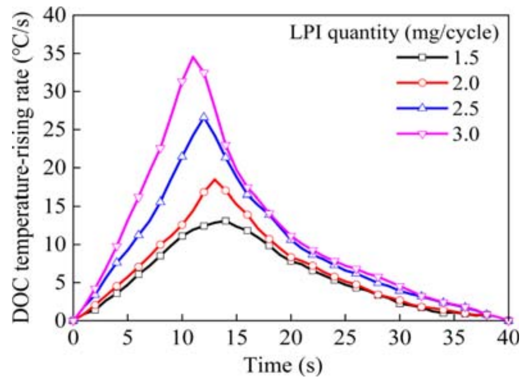

Figure 15. DOC heating rate under condition A.

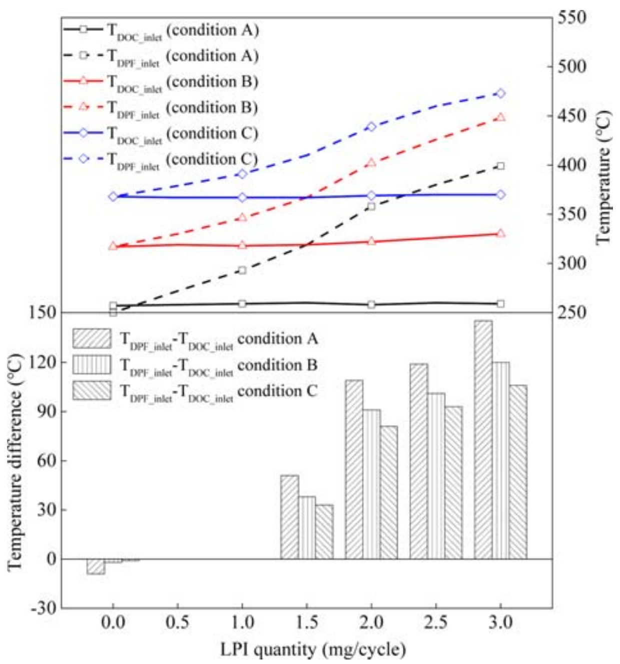

Figure 16. Effect of LPI quantity on DPF and DOC inlet temperature.

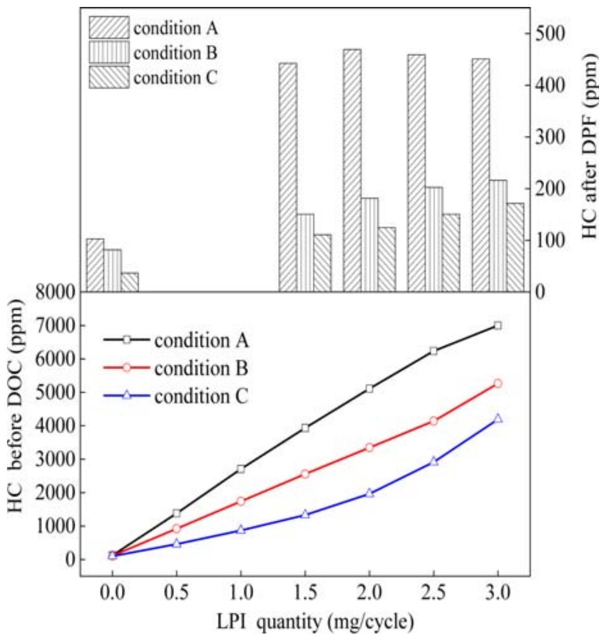

Figure 17. Effect of LPI quantity on HC concentration.

Larger LPI quantity would not only take a quicker response to DOC temperature-rising but also increase the exhaust temperature, as showed in Figure 16. In condition A, DPF inlet temperature was slightly lower than DOC inlet temperature when LPI quantity was 0mg. When LPI quantity increased to 3 mg/cycle, DPF inlet temperature was 145 °C higher than DOC inlet temperature. Compared with DOC inlet temperature, the increment of LPI quantity could rise DPF inlet temperature more significantly. Therefore, LPI coupling DOC has a significant heating effect to serve as an important control strategy to increase DPF inlet temperature.

Even though LPI coupling DOC could increase exhaust temperature significantly, but it would led to the deterioration of HC emissions and higher fuel consumption. Figure 17 showed the influence of LPI quantity on HC concentration. Generated HC from LPI (before DOC) increased with the increment of LPI quantity. Because of lower in-cylinder temperature and exhaust temperature, more HC generated at the light load. HC emissions (after DOC) under condition B and C increased with the increment of LPI quantity. The increment of LPI quantity speeded up the exothermic oxidation of unburned HC, therefore, HC emissions under condition A increased first and then displayed a slight reduction. Low DOC inlet temperature (less than 280 °C) under condition A reduced the conversion efficiency of HC, as a result, HC emissions was higher under condition A compared with condition B and C.

BSFC increased with the increment of LPI quantity at all working conditions, as showed in Figure 18. LPI injection timing was a little later than the exhaust valve opening timing, in-cylinder pressure and temperature were relatively lower, only a very small part of the fuel was oxidized. The heat generated was mostly taken away by exhaust gas instead of being utilized to do work. As a result, LPI quantity was mostly reflected in increment of BSFC. Take condition B as an example, when LPI quantity was 3 mg/cycle, BSFC increased 20 g/(kW·h).

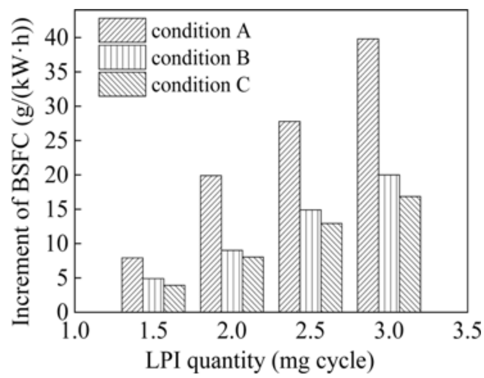

Figure 18. Influence of LPI quantity on fuel economy.

3.4. Exhaust thermal management control strategy

The results showed that exhaust temperature under low speed and light load conditions could be increased significantly through the adjustment of intake throttling and fuel injection strategies. However, there is still a gap

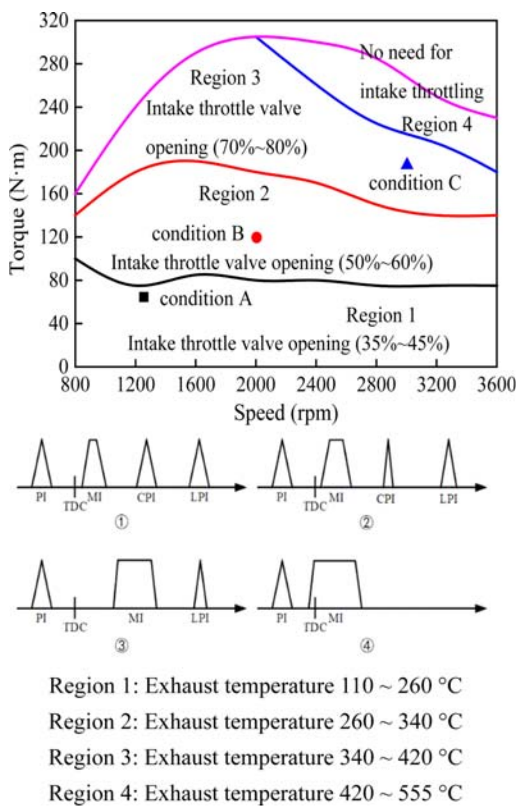

Figure 19. Exhaust thermal management control strategies under all working conditions.

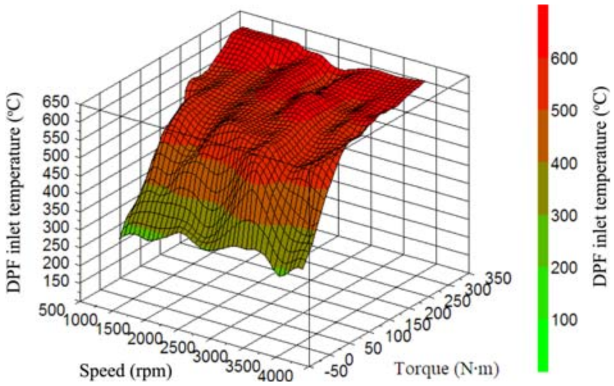

Figure 20. DPF inlet temperature in all working condition.

compared with the target value of DPF active regeneration temperature. Therefore, LPI coupling DOC should be applied to further increase exhaust temperature in the area of medium and light load. Figure 19 showed the exhaust thermal management strategy for different running regions divided by different exhaust temperature. Condition A, B and C have been marked in the figure. In region 1, it is suggested to postpone main injection timing appropriately and employ smaller intake throttle opening (35 % ~ 45 %) along with larger CPI and LPI quantity. In region 2, when speed and load increase, the valve opening should be increased to 50 % ~ 60 %, CPI and LPI quantity should be reduced properly. In region 3, the valve opening should be increased (70 % ~ 80 %) and main injection timing should be appropriately postponed while CPI and LPI quantity should be reduced reasonably. In region 4, there is no need to adopt intake throttling and LPI, the main injection timing could be advanced for output power requirement.

4. BENCH TEST VERIFICATION OF EXHAUST THERMAL MANAGEMENT

The exhaust thermal management active control strategy was verified by bench test. Figure 20 shows the results. DPF inlet temperatures in medium and light load conditions have been obviously increased by the exhaust thermal management, and DPF inlet temperature was mainly concentrated at the range of 450 to 650 °C. In summary, after adopting the exhaust thermal management control strategy, exhaust temperature-rising requirement for DPF regeneration can be met in most region of all working condition of the prototype.

5. CONCLUSION

(1) Exhaust thermal state changes with the working condition, so different control strategies are needed to meet the temperature-rising demand. These strategies, including intake throttling, fuel injection strategies and LPI coupling DOC, could increase exhaust temperature by properly sacrificing emissions and fuel efficiency. When the load is smaller, the intake throttle valve opening is smaller, and the CPI and LPI quantity is larger. At light and medium loads, small valve opening (35 % ~ 60 %) and a combination of "PI + MI + CPI + LPI" should be adopted. At heavy load, the valve opening should be increased to 70 % ~ 80 %, CPI can be cancelled and LPI quantity can be decreased appropriately. There is no need for intake throttling and LPI under full loads condition, and main injection timing can be advanced appropriately.

(2) Bench test results indicated that when the exhaust thermal management control strategy was applied, the demand of DPF regeneration temperature can be met in most working conditions.

ACKNOWLEDGEMENT–the authors would like to thank the Wabertec Co., Ltd. for its support of this work.

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