Fluid Dynamics & Materials Processing
DOI:10.32604/fdmp.2020.09591
Article

Influence of Diesel Engine Intake Throttle and Late Post Injection Process on the Rise of Temperature in the Diesel Oxidation Catalyst

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Received: 04 January 2020; Accepted: 10 March 2020

Abstract: In order to effectively implement DPF (Diesel Particulate Filters) regeneration control, thermal management of exhaust products before and inside Diesel Oxidation Catalyst (DOC) is necessary. In the present study, the Influence of the intake throttle valve and late post injection process on temperature rise inside DOC is analyzed through engine bench tests. The steady experiment results show that adjustment of the intake throttle valve can effectively increase exhaust temperature before DOC; in particular, with intake throttle valve opening at 20%, temperature before DOC can be increased by about 170°C with respect to the full opening. An increase in the late post injection quantity can produce a significant rise of the temperature inside DOC, however its impact on the exhaust temperature before DOC is relatively limited. As the late post injection quantity increases, Hydrocarbon (HC) emissions also grow; in the present work it is shown that with a proper injection quantity, a considerable temperature increase inside the DOC can be obtained with relatively low HC emission. More specifically, with the intake throttle valve at 30% and DOC reaching ignition temperature as the late post injection quantity is increased, the exhaust temperature after DOC can be made larger than 550°C, adequate for DPF active regeneration.

Keywords: Exhaust thermal management; diesel engine; DOC; intake throttle; late post injection

Nomenclature

CA	crank angle
CO	carbon monoxide
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
HC	hydrocarbon
NO_x	nitrogen oxides
PM	particulate matter
WGT	wastegate turbocharger

1 Introduction

With strict internal combustion engine emission regulation promulgated in recent years, inner engine emission control is increasingly inadequate for clarification of the two major diesel engine pollutants, NOx and soot, application of aftertreatment devices is necessary. Inhalable particulate within diesel engine emission especially, which can be a serious threat to human health, is 30~80 times larger than petrol engine emission with similar power output. Soot generation process within diesel engine, and thermal diffusion of hydrocarbon mixtures is rather complicated [1,2]. Diesel Particulate Filter (DPF) has been generally acknowledged as the main clarification method for diesel engine particulate emission. Filter regeneration is a key technology of DPF, which includes active regeneration and passive regeneration. During active regeneration, high temperature exhaust will rapidly oxidize PM collected within DPF. As high exhaust temperature is essential to initiate the rapid oxidization process, exhaust thermal management for actuate temperature control is critical for DPF active regeneration [3–7].

However, at medium or small loads, which are relatively common during actual diesel engine operation, the exhaust temperature can be too low (150~350°C) for DPF active regeneration to initiate, the engine control strategy needs adjustment to rise the exhaust temperature before DPF. Exhaust thermal management strategy based on coupling intake throttle adjust and late post injection, can rise exhaust temperature for DPF active regeneration initiation. Adjust intake throttle valve opening can effectively increase exhaust temperature before diesel particulate filter (DOC) to ignition temperature, while late post injection can further increase temperature inside DOC, reaching DPF active generation temperature through a two-phase exhaust temperature increase [8–13].

This study used certain vehicle diesel engine, chose lower speed and lower load working point, to analyze the influence of intake throttle valve on exhaust temperature before DOC, late post injection on temperature inside DOC and HC emission, injection quantity on DOC temperature rise behavior and engine specific fuel consumption. Experimental result showed that coupling intake throttle adjustment and late post injection can increase exhaust temperature after DOC significantly, to reach DPF active generation temperature.

2 Experimental Apparatus and Methodology

2.1 Experimental Apparatus

The engine used in the experiment is a certain 4-cylinder high-pressure common rail diesel engine, with principle technical parameter showed in Tab. 1.

Table 1: Engine principle technical parameter

Item	Parameter
Cylinders	4
Valves per cylinder	4
Bore/mm	98
Stroke/mm	105
Displacement/L	3.2
Pressure Ratio	17
Standard Power/kW	81
Standard Speed/($r \cdot min^{-1}$)	2400

This experiment used HORIBA Dynas3 electrodynamometer for engine test, and HORIBA 1600 analyzer for emission analyze. Exhaust aftertreatment system include mainly DOC and DPF, with principle parameters showed in Tab. 2.

Structure of the engine test bench is given in Fig. 1.

Table 2: DOC and DPF principle parameter

Item	DOC	DPF
Substrate Material	Cordierite	SiC
Substrate Size/mm·mm	121.5·φ153.5	145.3·φ167.6
Pore Number/cpsi	400	300
Catalyst Density/(g·cm^{-3})	0.34	0.79
Noble Metal	Pt/Pd	Pt/Pd
Shape	Cylinder	Cylinder

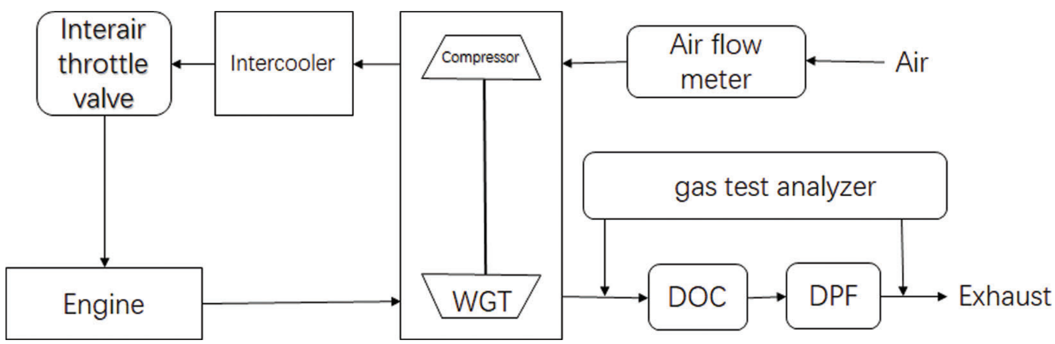


Figure 1: Engine test bench structure

2.2 Experimental Methodology

Influence of intake throttle on exhaust temperature before DOC is studied through experiment, with engine speed at 1400 r/min, load ratio at 40%. Intake airflow is altered through adjust intake throttle valve opening, to study DOC temperature rise behavior during different intake airflow. Influence of late post injection on exhaust temperature before DOC and engine emission is also studied through experiment, with engine speed at 1400 r/min, load ratio at 30% and 40%. Injection quantity is altered in both working point to study the influence. Based on these two preliminary experiments, choose engine speed at 1400 r/min, load ratio at 40%, intake throttle valve opening at 70% for coupling influence of intake throttle and late post injection on DOC temperature rise behavior, and specific fuel consumption at different late post injection quantity.

To study temperature change inside DOC, seven k-type thermocouples have been deployed inside DOC during experiment, as showed in Fig. 2. Define test points as T1 to T7 along exhaust flow. Also, extra thermocouples have been deployed before and after DOC. Besides, during late post injection control, injection timing remains at 140°CA after top dead center, other injection parameters remain constant.

3 Results and Discussion

3.1 Influence of Intake Throttle on Exhaust Temperature before DOC

Intake throttle valve is an important device for exhaust temperature control. Through adjusting intake throttle valve, intake airflow will change accordingly as effective intake section changes, thus changes

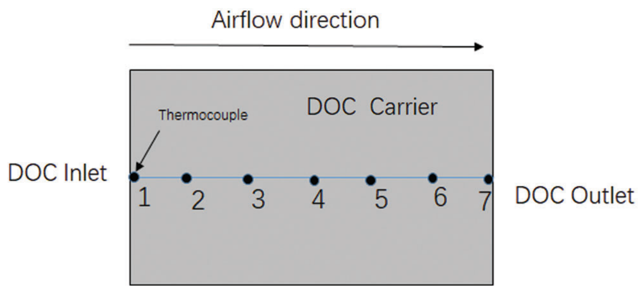


Figure 2: DOC internal thermocouple arrangement

exhaust flow. As intake throttle valve opening decreases, excess air coefficient will decrease, which deteriorates engine thermal efficiency and increases NOx and CO emission, yet HC emission will improve [14–16]. Fig. 3 showed the Influence of intake throttle valve opening on intake airflow and exhaust temperature before DOC. As showed in Fig. 3, decrease intake throttle valve opening will reduce effective intake section in turn decrease intake airflow. With opening at 70%, the influence on intake airflow is relatively small, while as engine working in low load with higher volumetric efficiency, the effect on temperature before DOC is insignificant. As opening decreases to below 40%, the increase of intake resistance will decrease engine intake airflow considerably, with opening at 20%, intake airflow decreases to 45% of the original airflow. As heat generated from fuel combustion will not change as significantly, decrease intake airflow will increase exhaust temperature, thus intake air flow decrease is the main reason for this exhaust temperature increase. With intake throttle valve opening at 20%, exhaust temperature before DOC increased from 292°C to 443°C, increased by 52%, which showed intake throttle valve adjustment can increase exhaust temperature before DOC significantly.

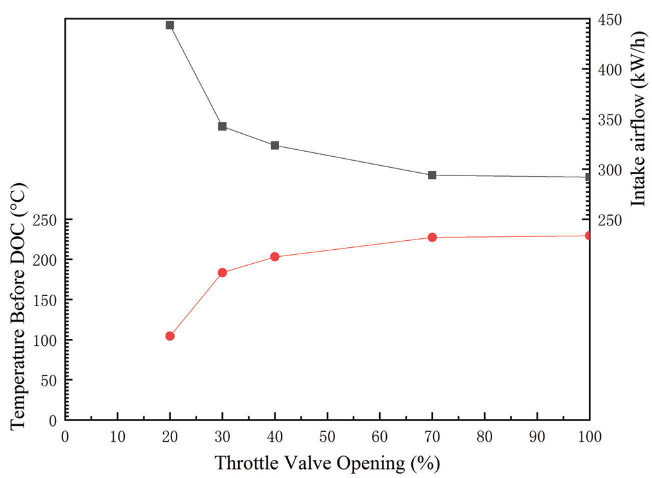


Figure 3: Influence of intake throttle valve opening on intake airflow and exhaust temperature before DOC

To control exhaust temperature through adjusting intake throttle valve, the opening needs to remain in a rational range. Otherwise, with valve opening irrationally small, intake resistance will be overly high, causing insufficient intake airflow and deteriorate engine combustion, increase fuel consumption rate significantly, worsen engine performance stability, and may even cause engine close down [17–19]. Considering exhaust temperature requirement and experiment results, throttle valve opening is suggested to remain in 20%~40%.

3.2 Late Post Injection Quantity

During late post injection quantity analyze, injection timing remains at 140°CA after top dead center, with engine speed at 1400 r/min, choose working points with load ratio at 30% and 40% for comparison.

3.2.1 Influence of Late Post Injection Quantity on Temperature Rise Behavior of DOC

Influence of late post injection quantity on exhaust temperature before and after DOC is showed in Fig. 4. As late post injection quantity increases, exhaust temperature before DOC increases slightly, while temperature after DOC increases rapidly. Maximum temperature increase before DOC occur at 40% load rate with injection quantity of 4 mg/cycle, at 308.0°C, increased by 6.1% compared to no late post injection. Insignificant temperature increase is resulted from limited fuel oxidization, as late post injection started at the latter part of combustion stroke, with exhaust valve opened due to the advance angle, temperature and pressure inside cylinder is relatively low. However, the majority of late post injection will dissociate into unburned HC, and flow into DOC with exhaust flow, and oxidize inside DOC, generates large amount of heat, thus temperature after DOC increases rapidly.

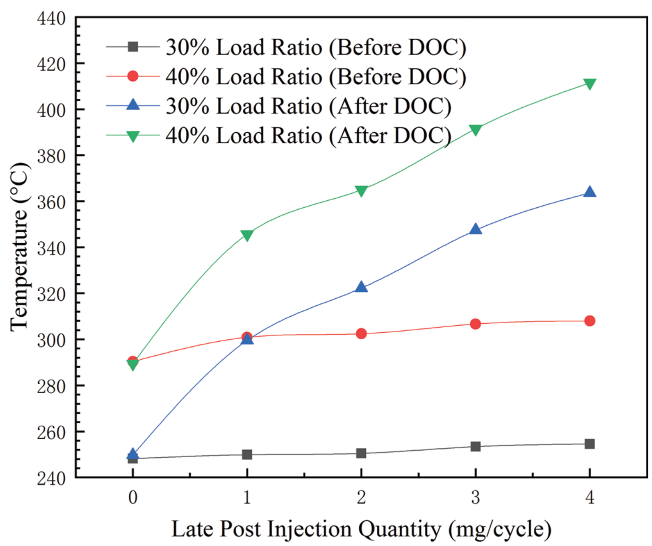
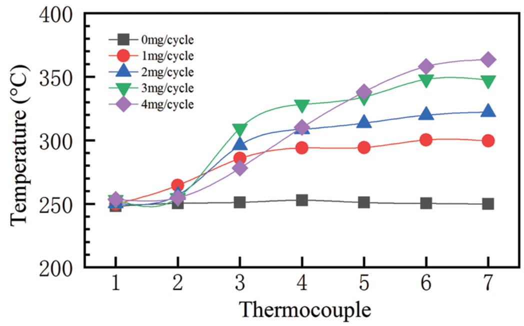
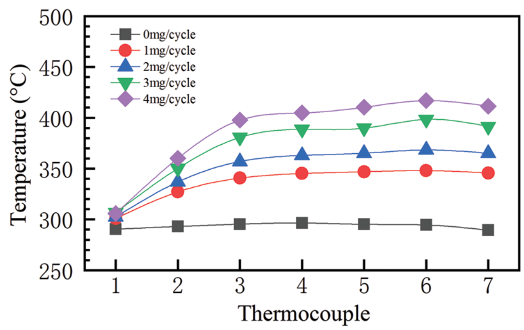


Figure 4: Influence of late post injection quantity on exhaust temperature before and after DOC

Temperature within DOC at different late post injection quantity is showed in Fig. 5. With load ratio at 30% and 40%, the temperature rise behaviors inside DOC are not exactly similar. As showed in Fig. 5a, without late post injection, temperature of exhaust within DOC will increase slowly, reaching the peak of 252.8°C near the fourth thermocouple, temperature increased 4.6°C compared to temperature before DOC; then temperature will decrease slowly, with temperature after DOC slightly smaller than before DOC. As late post injection quantity increase, the temperature rise period will protract, the peak point of DOC temperature increase rate will move forward to latter part of DOC. With injection quantity at 1 mg/cycle, the peak temperature increase rate point is between thermocouple 2 and 3; at 4 mg/cycle, the peak increase rate point is between thermocouple 3 and 4. DOC temperature rise period protract, and peak DOC temperature increase rate point move forward, is resulted from increased HC oxidization within DOC. With load ratio at 30%, exhaust temperature before DOC, 248.2°C, is relatively low. With injection quantity at 1 mg/cycle, the majority of unburned HC will oxidize at former part of DOC, thus exhaust temperature increase rate of latter part of DOC will decrease compared to former part. At 4 mg/cycle, large amount of unburned HC remained in exhaust, at similar oxidation process within DOC, temperature rise period will protract, yet exhaust temperature increase will still be slow. Therefore, to



(a)



(b)

Figure 5: Temperature of different test point within DOC (a) 30% Load ratio, (b) 40% Load ratio

increase temperature within DOC through late post injection, other method which increases exhaust temperature before DOC shall be applied, or choose a working point with higher temperature before DOC.

As showed in Fig. 5b, with load ratio at 40%, temperature change without late post injection is similar to with load ratio at 30%, temperature of exhaust within DOC increases slowly along exhaust flow at former part, while temperature after DOC is slightly lower than before DOC. With injection quantity at 4 mg/cycle, temperature gradient inside DOC is the highest, peak temperature point near the sixth thermocouple is 416.8°C, increased 110.9°C compared to temperature before DOC, increased by 36.2%. Without late post injection, unburned HC and CO within exhaust is small, and generates only limited heat through oxidization within DOC, as oxidization mostly finished in former part, temperature peak will be in former part. As late post injection quantity increases, more unburned fuel will oxidize inside DOC and protract oxidization process and temperature rise period, temperature peak will transfer to latter part of DOC. As most unburned fuel oxidized, less heat will regenerate in latter part of DOC than heat radiation loss, causing temperature decrease at latter part of DOC. As peak temperature is inside DOC, causing considerable temperature gradient, late post injection for DPF regeneration shall take DOC peak temperature into consideration, lest high temperature and thermal stress damage DOC structure.

3.2.2 Influence of Late Post Injection Quantity on HC

Influence of late post injection quantity on HC emission and conversion efficiency is showed in Fig. 6. Without late post injection, HC emission before and after DOC are relatively low in both working point. With load ratio at 40%, as late post injection quantity increases, HC emission before DOC increases significantly, while emission after DOC shows and rapid increase first, then tends to stable output, with conversion efficiency of HC increases gradually. With load ratio at 30%, HC emission before DOC increases significantly as late post injection quantity increases, while conversion efficiency of HC increases to peak

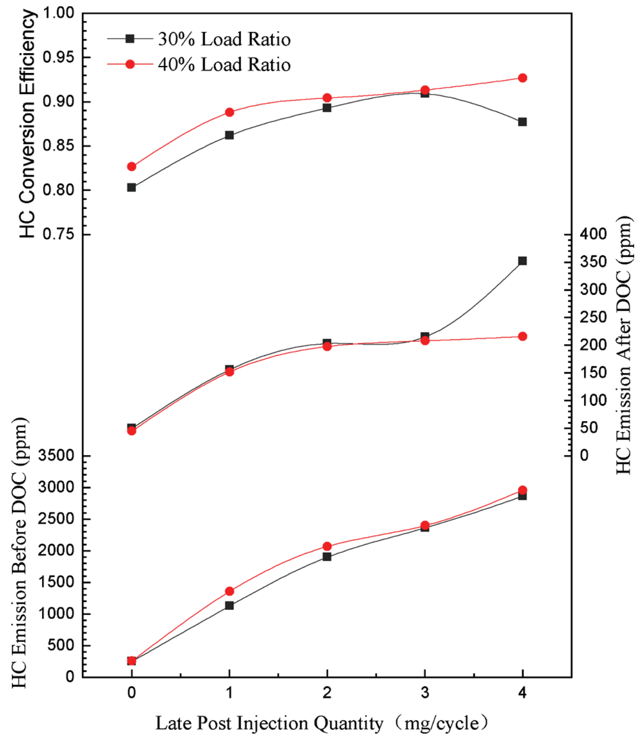


Figure 6: Influence of late post injection quantity on HC emission and conversion efficiency

point at late post injection quantity of 3 mg/cycle, then tends to decrease. At 3 mg/cycle, even HC conversion efficiency increased by 13.2% compared to no late post injection, with HC before DOC increased by 931%, HC after DOC is still 4.3 times higher than no late post injection, HC emission deteriorated severely. At 4 mg/cycle, HC conversion efficiency decreases, yet HC before DOC further increases, thus HC emission after DOC increased significantly. The conversion efficiency increase is resulted from catalyst activity increase during temperature increase, as more unburned HC oxidize inside DOC, exhaust temperature inside DOC will increase accordingly, increases the activity of catalyst inside DOC, increases HC conversion efficiency [20–22]. However, with excess late post injection, large quantity of HC cannot oxidize in time, decreases HC conversion efficiency comparatively, and deteriorates HC emission. Therefore, increase exhaust temperature before DPF through late post injection, shall take DOC oxidization capacity into consideration, lest excess late post injection deteriorates HC emission.

3.2.3 Influence of Late Post Injection Quantity on Specific Fuel Consumption

Influence of late post injection quantity on specific fuel consumption is showed in Fig. 7. At each working point, as late post injection quantity increases, specific fuel consumption increases accordingly. With load ratio at 40% and injection quantity at 4 mg/cycle, maximum specific fuel consumption is 269.4 g/(kW·h), increased by 14.3% compared with no late post injection. Fuel consumption increase is resulted from limited fuel oxidization, as late post injection started at the latter part of combustion stroke, the majority of fuel cannot oxidize in cylinder, while the heat generated through partial fuel combustion cannot converse to engine output, only increased exhaust temperature, thus increased fuel consumption [23,24]. Influence of late post injection quantity on power output is showed in Fig. 8. Late post injection quantity has barely any influence on engine output, which proved the heat generated through partial fuel oxidization did not converse to power output.

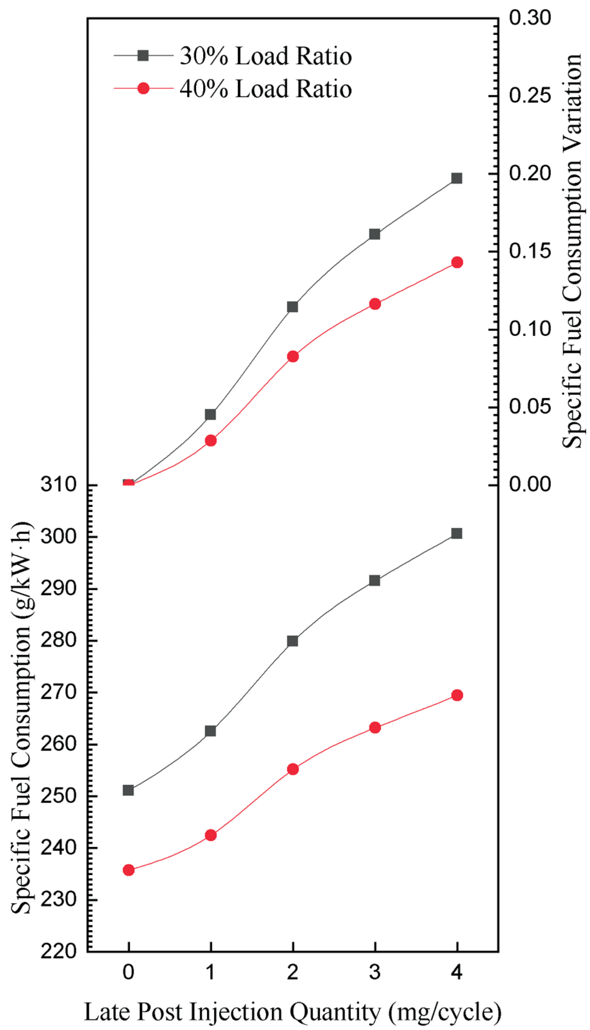


Figure 7: Influence of late post injection quantity on specific fuel consumption

3.3 Couple Effect of Intake Throttle and Late Post Injection on Temperature Rise Behavior of DOC

Intake throttle adjustment can effectively increase diesel engine exhaust temperature; late post injection has only limited effect on exhaust temperature before DOC, yet can significant increase temperature inside DOC. At lower load, adjust intake throttle to increase temperature before DOC, and apply late post injection, to study the couple effect of intake throttle and late post injection on temperature rise behavior of DOC. Set engine speed at 1400 r/min, 40% load ratio and 70% intake throttle valve opening for experiment.

Influence of late post injection quantity on temperature inside DOC is showed in Fig. 9. Temperature of exhaust inside DOC will first increase gradually towards peak point near the sixth thermocouple, and then slightly decrease. As late post injection quantity increase, temperature inside DOC increases gradually along exhaust flow, temperature gradients also increase. With late post injection quantity at 3 mg/cycle, temperature peak point inside DOC appeared near the sixth thermocouple at 639.3°C, increased 279.4°C compared to before DOC, increased by 77.6%. Because most of late post injection fuel cannot combust due to lower cylinder pressure and temperature, unburned HC before DOC will increase and oxidize inside DOC, causing DOC temperature increase; more injection quantity will generate more unburned HC, resulted more significant temperature increase after DOC.

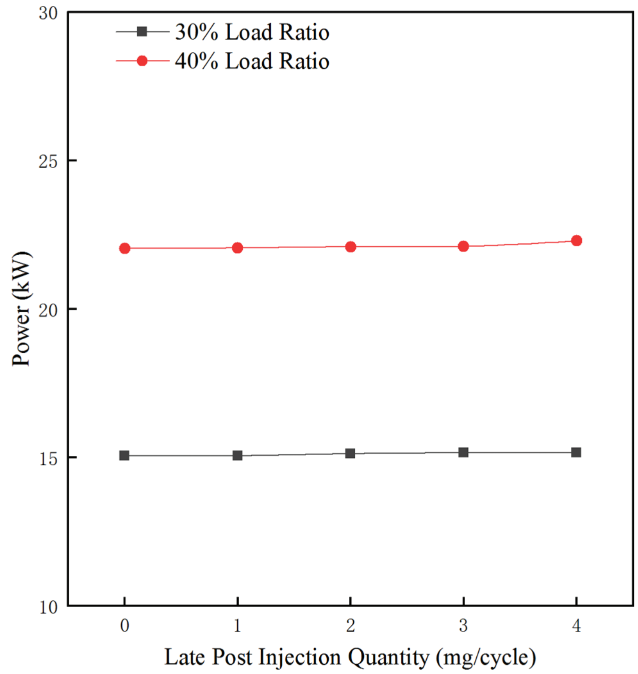


Figure 8: Influence of late post injection quantity on power output

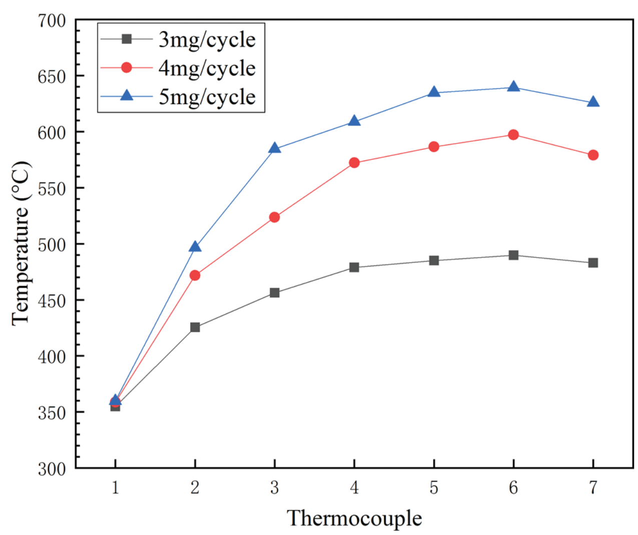


Figure 9: Influence of late post injection quantity on temperature inside DOC

Influence of late post injection quantity on temperature rise behavior after DOC is showed in Fig. 10. As late post injection quantity increase, temperature after DOC increases accordingly, with more significant increase at higher injection quantity, while DOC temperature increase rate and its peak increase, and time span to peak point decreases. With late post injection quantity at 3 mg/cycle, temperature increase rate change is relatively gradual and reaches peak point of 4.4°C at 27 s, temperature after DOC is 483.0°C. At 5 mg/cycle, temperature increase rate increases significantly and reaches peak point earlier at 20 s, the peak temperature increase rate of 8.6°C/s increased by 95.4% compared to at 3 mg/cycle, with time span shortened by 7 s, temperature after DOC is 625.8°C. As late post injection quantity increases, more

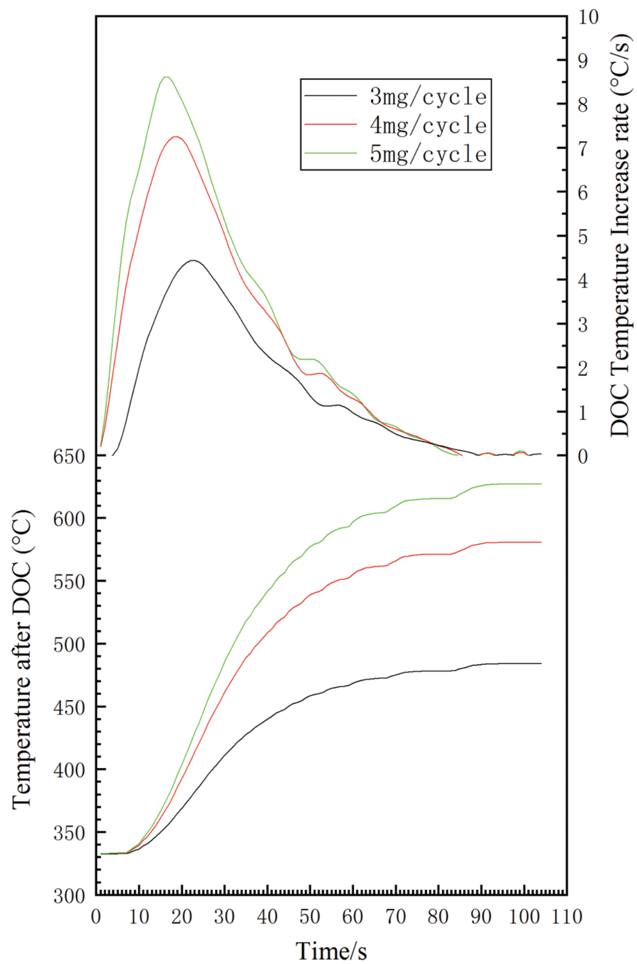


Figure 10: Influence of late post injection quantity on temperature rise behavior after DOC

unburned HC will oxidize inside DOC, increase temperature after DOC, and as exhaust temperature inside DOC increases, the activity of catalyst inside DOC will increase accordingly, increases HC conversion efficiency. Coupling intake throttle and late post injection can significantly increase DOC output temperature, adequate for DPF active regeneration.

4 Conclusions

1. Decrease intake throttle valve opening will decrease intake airflow significantly, thus increase exhaust temperature before DOC to ignition temperature during lower load. Yet irrational small valve opening will worsen engine performance stability, and may even cause engine close down.
2. Increase late post injection quantity has limited influence on temperature before DOC, yet can significantly increase temperature after DOC; temperature gradient inside DOC is relatively high, with peak temperature at latter part; HC conversion efficiency increases, yet HC emission after DOC also increases.
3. Coupling intake throttle adjustment and late post injection, can increase temperature before and inside DOC significantly, while late post injection quantity increase can rise DOC temperature increase rate significantly, and decrease the time span to reach peak temperature increase rate.

Acknowledgement: Personally, I would like to thank the support from my beloved wife Xue Song, and my lovely daughters. I would like to thank support from our team members, and the reviews whose constructive and detailed critique contributed to the quality of this paper.

Funding Statement: This work was supported by the Ministry of Science and Technology of the People's Republic of China [grant numbers 2017YFC0211304], the Natural Science Foundation of Shandong Province [grant number ZR2019MEE041], and the Open Fund of the National Engineering Laboratory for Mobile Source Emission Control Technology [grant number NELMS2017A14].

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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