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Research Paper

# Influence of active control strategies on exhaust thermal management for diesel particular filter active regeneration

Bai Shuzhan, Chen Guobin, Sun Qiang, Wang Guihua *, Li Guo-xiang *

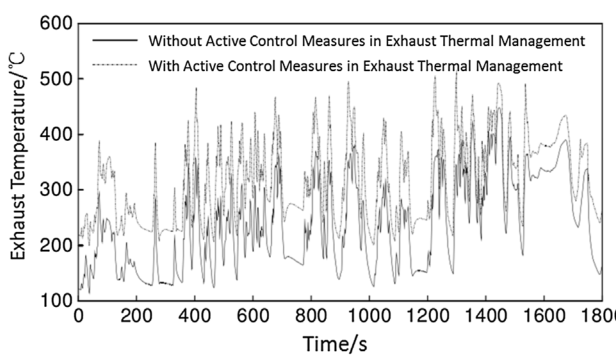
*School of Energy and Power Engineering, Shandong University, Jinan 250061, China*

## HIGHLIGHTS

- Using the intake throttle to controlling intake air can increase exhaust temperature obviously.
- The effects of injection pressure and injection advance angle on exhaust temperature is studied.
- The effects of post injection angle and injection quantity on exhaust temperature is studied.
- The effects of active control strategies on oxygen concentration in exhaust is studied.
- Active control strategies can increased exhaust temperature effectively in WHTC transient cycle.

## GRAPHICAL ABSTRACT

This figure shows the exhaust temperature comparison in WHTC transient cycle between using the active control measures in exhaust thermal management and without active control measures. We can conclude, in the 1800 s transient cycle period, exhaust temperature increased completely and effectively, especially in idling condition and low temperature conditions. Exhaust temperature at all time were over 200 °C, with 96% over 220 °C, 78% over 250 °C, the average exhaust temperature of whole cycle increased from 238 °C to 318 °C, increase by 34%, secure the exhaust temperature before DOC capable of match current injection start condition.

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## ABSTRACT

The control strategies of exhaust thermal management are the premise of achieving the regeneration for Diesel Particulate Filter (DPF). In steady conditions with medium and low load, the effects of active control strategies on exhaust thermal management were studied at the test bench, which include intake throttle valve opening, injection advance angle, injection pressure and post injection.

Compared with full opening of intake throttle valve, the 15–20% opening of intake throttle valve could increase the exhaust temperature by about 140 °C, decrease the NOx emission but deteriorated the Particulate matter (PM) emission and fuel consumption. The change of injection advance angle and injection pressure have little effect on the exhaust temperature, but have a great effect on the emissions of NOx, PM and the fuel consumption. Optimized matching of the injection advance angle and quantity of post injections improves the exhaust temperature by about 70 °C. The World Harmonized Transient

*Abbreviations:* DPF, Diesel Particulate Filter; PM, particulate matter; WHTC, The World Harmonized Transient Cycle; PN, Particulate Number; DOC, Diesel Oxidation Catalyst; HCI, Hydrocarbon Injection; SCR, Selective Catalytic Reduction; CDPF, Catalytic Diesel Particulate Filter; TDC, Top Dead Center; VGT, variable geometry turbocharger; EGR, exhaust gas recirculation.

* Corresponding authors.
*E-mail addresses:* wgh@sdu.edu.cn (G. Wang), liguox@sdu.edu.cn (G.-x. Li).

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Cycle (WHTC) was used to evaluate the effect of improving exhaust temperature. WHTC experimental results indicated clearly that the exhaust temperature was effectively increased within the whole 1800 s, especially in the idle and low load conditions.



## 1. Introduction

Diesel engine emission contains inhalable Particulate Matter (PM) which can be a serious threat to human health. Euro VI Standard's regulation of PM emission not only further rigorously limited the mass of PM emission, but also restricted the Particulate Number (PN) [1,2]. Heavy-Duty diesel engines have to apply Diesel Particulate Filter (DPF) accordingly to match Euro VI Standard [3,4]. Diesel Particulate Filter (DPF) uses a wall-flow structure to collect PM in engine exhaust on the filter walls for PM elimination, yet subsequent PM generation can plug DPF, causing exhaust backpressure increase, fuel economy worsen and other problems, therefore PM plugged DPF needs periodic regeneration to restore its filter capacity [5,6]. Regeneration of diesel particulate filters can be accomplished continuously in a passive system or periodically in an active system [7]. The passive system works with the aid of $NO_2$, which is formed by the oxidation of engine-out NO over the Diesel Oxidation Catalyst (DOC) [8,9]. Continuous soot oxidation starts at approximately 250 °C. Penghao Jiao studied the coupling reaction of NOx with soot particulates and CO of the complex reaction in DPF regeneration process [10]. H Zhang found reactions in upstream DOC + DPF also have influences to the downstream Selective Catalytic Reduction (SCR) [11]. The passive regeneration system is often used for long-haul trucks, where the exhaust temperature is sufficiently high over a large enough proportion of the operating time to ensure significant continuous regeneration. For active regeneration system of DPF, the exhaust temperature needs to be raised up to 600 °C to enable the oxygen driven soot oxidation. Common heating methods are internal (post injection) or external fuel injection to raise the amount of unburnt fuel in the exhaust. Hydrocarbon Injection (HCI) system and DOC shall usually be placed before DPF for this propose. Fuel is injected into the exhaust pipe and oxidized in DOC, which increase the exhaust temperature to more than 600 °C, then quickly oxidizing the PM collected in DPF, thus regenerates the DPF [12,13]. Dieter studied the influence of active regeneration of a DPF on the particle emission with HCI and DOC [14]. Ali Hocine studied the influence of diesel post injection and exhaust gas expansion on the thermal cycle, the consumption is linked to the exhaust gas flow temperature and the post injection is useful to the exhaust temperature rise [15]. Singh measured the PM and gaseous emissions during active regeneration to optimize their models, the results showed that higher CDPF-inlet temperature and particulate matter mass loading are more effective for regeneration of the CDPF [16]. Since the DOC cannot oxidize the hydrocarbon fuel at low temperature, HCI strategy usually set the injection start condition as exhaust temperature before DOC is above 250 °C, however, there are many cases of medium and small loads in WHTC transient cycle test of Euro VI Standard, which will lead to the exhaust temperature can be too low to start the injection before DOC [17]. Therefore, a suitable control strategies to raise exhaust temperature before DOC is significantly important.

Although there have been a lot of studies done in this area and some researchers found a significant increase in the total number of particles emitted during active regeneration [18–21]. Knowledge of the active control strategies for exhaust temperature at low load is still lacking. Consequently, the aim of our study was to analyze the effects of active control strategies of exhaust thermal management on exhaust temperature. We chose typical working modes of vehicle diesel engine, so as to analyze the effects of intake throttle valve, injection advance angle, and injection pressure and post injection on diesel engine exhaust temperature, and draft an optimum plan to raise exhaust temperature. Using WHTC transient cycle to evaluate the effect of the exhaust temperature raising plan, the result of this research can be a reference for diesel engine exhaust thermal management.

## 2. Experimental setup and method

### 2.1. Experimental setup

The engine used in these experiments was equipped with common rail system of BOSCH. Table 1 and Fig. 1 show the relating specification and detailed information about the test bench, respectively. The experiments were carried out by using Electric dynamometer, Opacimeter, Exhaust gas analyzer, and Precision balance to focus on torque and speed, soot emission, concentration of NOx and $O_2$, and soot weight in DPF, respectively, the details of these equipments were shown in Table 2.

### 2.2. Experimental method

Three working modes of part load condition were selected for this study, as showed in Table 3, which exhaust temperature were comparatively low. Keeping engine speed and torque constant, exhaust temperature is raised and controlled by adjusting the diesel engine parameters. Main methods include: (1) decrease air inflow, and (2) alter combustion condition to increase fuel quantity injected in every cycle to release more heat. To remove EGR valve's effect on exhaust temperature, EGR valve always in closed state throughout this test.

According to petro physical parameter of fuel, heat contained in additional fuel (Q) is:

$$Q = H_{fuel} \times b_{add} \times P \times t \tag{1}$$

where $H_{fuel}$ stands for fuel low calorific value, J/g; $b_{add}$ stands for additional fuel consumption rate, g/(kW h); $P$ stands for power, kW; $t$ stands for time, h.

**Table 1**
Test engine specifications.

| Project | Specification |
|---|---|
| Engine type | 6 Cylinder in-line/inter-cooling |
| Bore × Stroke/mm × mm | 108 × 130 |
| Swept volume/L | 7.14 |
| Compress ratio | 18 |
| Rated power/kW | 200 |
| Rated speed/r/min | 2100 |
| Max torque/N/m | 1100 |
| Idle speed/r/min | 650 |
| EGR type | Electronic control EGR |
| Turbocharger | VGT |
| Emission standard | EURO VI |