International Journal of Automotive Technology, Vol. 8, No. 1, pp. 27−31 (2007)

1229−9138/2007/032−04

INJECTION STRATEGY OF DIESEL FUEL FOR AN ACTIVE REGENERATION DPF SYSTEM

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(Received 23 February 2006; Revised 29 December 2006)

ABSTRACT–The number of vehicles employing diesel engines is rapidly rising. Accompanying this trend, application of an after-treatment system is strictly required as a result of reinforced exhaust regulations. The Diesel Particulate Filter (DPF) system is considered as the most efficient method to reduce particulate matter (PM), but the improvement of a regeneration performance at any engine operation point presents a considerable challenge by itself. Therefore, the present study evaluates the effect of fuel injection characteristics on regeneration performance in a DOC and a catalyzed CR-DPF system. The temperature distribution on the rear surface of the DOC and the exhaust gas emission were analyzed in accordance with fuel injection strategies and engine operating conditions. A temperature increase more than BPT of DPF system was obtained with a small amount fuel injection although the exhaust gas temperature was low and flow rate was high. This increase of temperature at the DPF inlet cause PM to oxidize completely by oxygen. In the case of multi-step injection, the abrupt temperature changes of DOC inlet didn't occur and THC slip also could not be observed. However, in the case of pulse type injection, the abrupt injection of much fuel results in the decrease of DOC inlet temperatures and the instantaneous slip of THC was observed.

KEY WORDS : Diesel engine, Diesel oxidation catalyst, Diesel particulate filter, Active regeneration, Fuel injection, Total hydrocarbon Compound

1. INTRODUCTION

Since diesel engines have excellent fuel efficiency and durability, they have been widely used as power source for many commercial vehicles. Moreover, from ongoing carbon dioxide regulations and the anticipated depletion of petroleum fuels, their high fuel efficiency has been drawing attention. For diesel engines, an after-treatment system is indispensable to meet stringent emission regulations. Accordingly, many countries and automobile companies have devoted extensive efforts to the development of low emission engines applying new combustion technologies and aftertreatment systems. In particular, reduction technologies of particulate matter (PM) and nitrogen oxide, which affect the ozone and contribute to smog in large cities, are critical issues related to diesel engines. Although there are many reduction methods for nitrogen oxide, the DPF system is currently the most efficient method to filtrate PM in engine exhaust (Vincent *et al.*, 2002; Konstandopolos and Kostoglou, 2000).

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At present, the key requirement for the DPF system is improvement of the regeneration performance (Konstandopolos and Kostoglou, 2000) in low temperature region. However, there is a limit to lower the light-off temperature of the catalytic system conventionally used in the DPF system (Zheng and Keith, 2004; Kong *et al.*, 2005). Therefore, active regeneration technologies such as burner (Webb *et al.*, 2004; Kong *et al.*, 2004, 2005; Oh *et al.*, 2002), intake throttling (Mayer *et al.*, 2005), the additive method (Richards *et al.*, 2005; Yamane *et al.*, 2005; Suto, 1997), and late injection in the engine (Hiranuma *et al.*, 2003) have been widely investigated. However, these systems are accompanied by some critical drawbacks, including complexity, reliability, costliness, and so on. In response, a regenerating system utilizing hydrocarbon (HC) injection before Diesel Oxidation Catalyst (DOC) has been intensively studied by many researchers (Lee *et al.*, 2005; Guo *et al.*, 2003; Kodama *et al.*, 2005 ; Fayard *et al.*, 2005; Chiew *et al.*, 2005). In this system the heat from the oxidation of injected fuel through DOC is used to oxidize soot particles accumulated in DPF.

In this paper, the evaluation of the effect of fuel injection characteristics on regeneration performance has been carried out in a DOC (cordierite 400 cpsi) and a catalyzed CR-DPF system. The temperature distribution on the rear surface of the DOC and the exhaust gas emission were analyzed in accordance with fuel injection strategies and the engine operating conditions. Through this study, the design parameters were also discussed.

2. EXPERIMENTAL SETUP

Figure 1 is a photograph of the devised experimental apparatus. A Euro-2, 3.3 liter TCI engine was used in this study. It is good to develop a regenerating system of DPF for a retrofit because of the characteristics of high PM emission and low exhaust gas temperature. The aftertreatment system of PM used in this study consists of DOC (cordierite 400 cpsi) and catalyzed CR-DPF (Continuous Regeneration DPF, cordierite 200 cpsi). The concept of this system is that fuel injected into the exhaust stream is oxidized through DOC, resulting in a gas temperature that is sufficiently high (> 500°C) to burn the soot deposited within DPF by residual oxygen (Lee, 2005). The detailed specifications of this system are shown in Table 1.

Figure 2 shows a schematic diagram of experimental

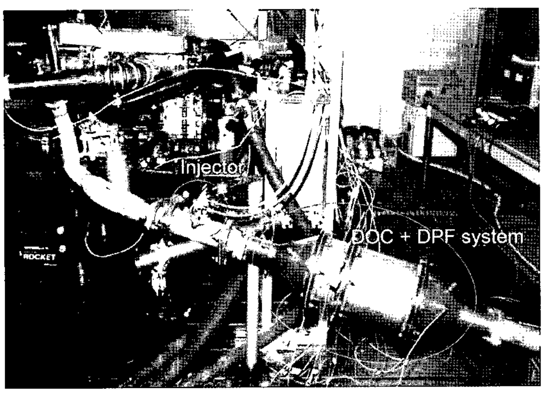

Figure 1. Photograph of system setup.

Table 1. Specifications of engine and aftertreatment system.

Engine type	EURO-2, TCI
Displacement volume	3298 cc
Max. torque	30/1800 (kg·m/rpm)
Max. power	120/3000 (PS/rpm)
Fuel	ULSD
DPF	Catalyzed CR-DPF (Cordierite 200 cpsi) 7.5×8 inches, PMG loading
DOC	Cordierite 400 cpsi 7.5×4.8 inches PMG loading

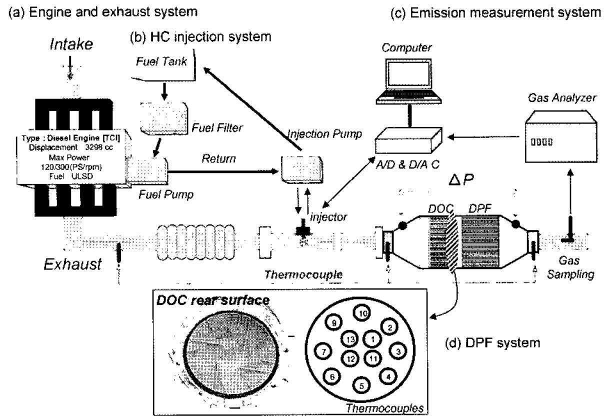

Figure 2. Schematic diagram of experimental setup.

setup in this study. The experimental setup consists of four parts, an engine and exhaust system, an injection part, an aftertreatment system, and an emission measurement system. Three thermocouples are located at the exhaust manifold, the preceding DOC, and the DPF outlet in order to observe the exhaust gas temperatures. In addition, in order to measure the temperature distribution on the DOC outlet (or DPF inlet) after fuel (HC) injection, 12 thermocouples are placed at the DOC rear surface, as shown in Figure 2-(d).

An AVL 250 KW EC dynamometer was used for control of engine speed and load (exhaust gas temperature) and a Horiba Mexa-9100D was used to analyze engine emissions, specially THC slip. The injection part consists of a fuel tank, an injection pump (3 bar), a commercial injector, and a duty controller. The amount of HC injection was controlled by duty rate (frequency = 20 Hz) calibrated via the gravimetric method (10% duty → 17 cc/min) and two type injection methods which are a gradually increasing type (multi-step injection) and pulse type were used in this study. Signals were collected by an ADC (Analog to Digital Converter) simultaneously.

3. EXPERIMENTAL CONDITIONS AND BASE TEST

Figure 3(a) shows PM emission at the full load condition according to engine speed. As can be seen here, a gradually increasing tendency is displayed for PM emission above 2,200 rpm. Therefore, engine speeds below 2,200 rpm, such as 1,500, 1,800, and 2,000 rpm were selected as test points in order to observe heating of exhaust gas by HC injection while minimizing interference of PM oxidation through DOC. Figure 3(b) shows the results of BPT (Balance Point Temperature) tests of the DPF system used in this study.

The BPT of this system is about 345°C, and the conditions of exhaust gas temperature before DOC are deter-

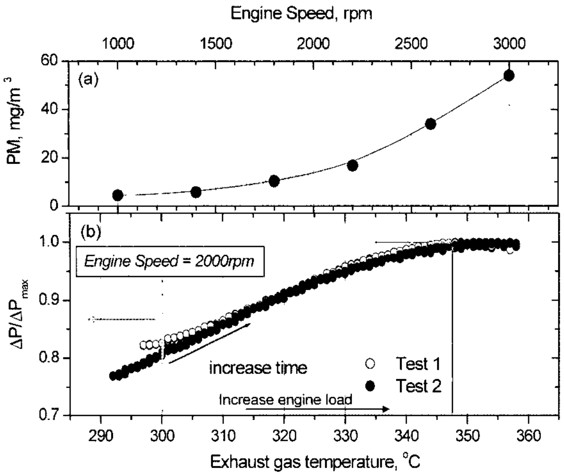

Figure 3. Experimental conditions (a) PM emission according to engine speed; (b) BPT test of DPF system.

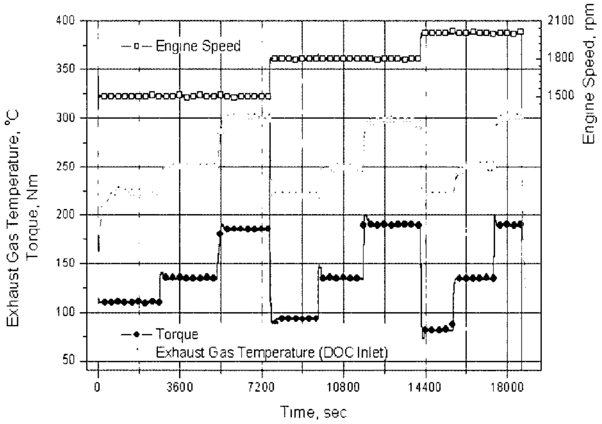

Figure 4. Engine operating condition in this experiment.

mined below BPT, i.e., 220, 250, and 300°C, achieved by adjusting the engine load. Figure 4 shows the engine operating conditions of this study.

4. RESULTS AND DISCUSSION

In order to simulate an active regeneration process in the low temperature region, the temperature at the entrance of the after-treatment system and the exhaust gas flow rate are important experimental parameters. Therefore, three engine speeds (1,500, 1,800, 2,000 rpm) were selected and the exhaust temperatures at the entrance of the DOC were adjusted by varying the engine load condition at 220°C, 250°C and 300°C for each engine speed, as previous described. When the exhaust temperature was selected by adjusting the engine load, a defined amount of fuel was injected by a control loop (multi-step injection and pulse type injection), as shown in Figure 5.

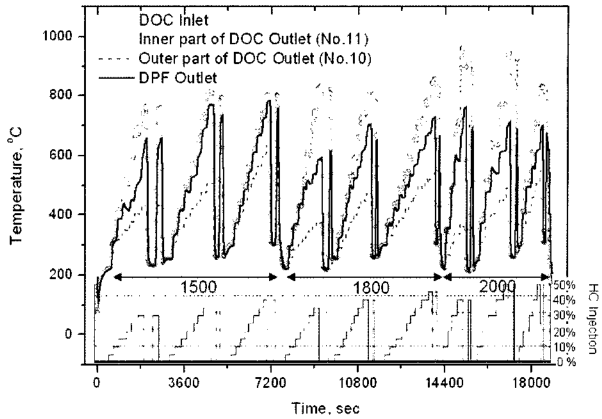

Figure 5. Temperature profile of each position due to HC injection.

Increase in the temperature of the inner and outer part of the DOC outlet and DPF outlet was observed in accordance with HC injection pattern simultaneously.

However, there is a difference in temperature on the rear surface of the DOC. In this figure, the temperature at No.11 position (inner and bottom of DOC) was greater than that at No. 10 position (outer and top of DOC). This discrepancy arises from the injecting direction, vaporization, and mixing process. That is, HC is injected downwards and then collides against the surface of the exhaust pipe, where main vaporization occurs in this system. Although this inhomogeneity was observed, these increases of temperature at each point are meaningful results given that the BPT of the DPF system is 345°C.

Figure 6 shows the temperature contour of the DOC outlet in accordance with the engine speed and HC injection rate. When the engine speed is 1,500 rpm and the injection rate is 0%, the temperature distribution is symmetric. However, the high temperature region is biased downward after HC injection. This results from

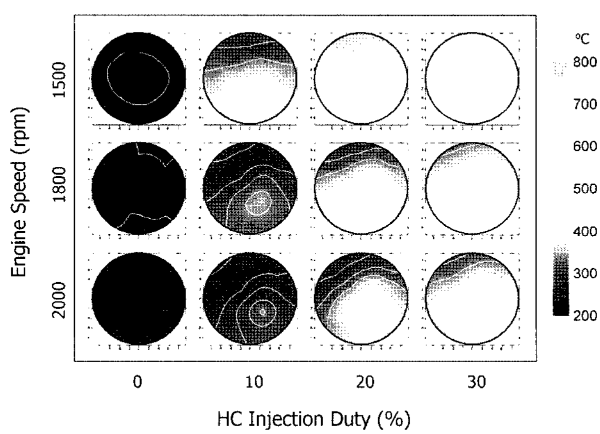

Figure 6. Temperature contour of DOC outlet according to HC injection rate (T_{exh}=220°C).

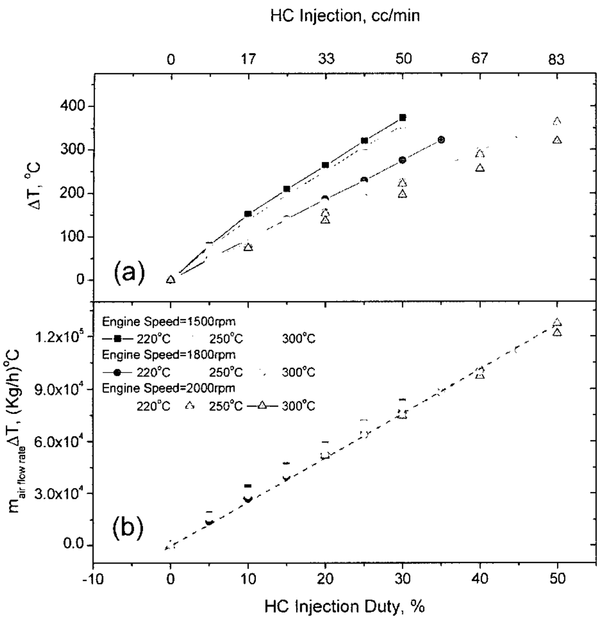

Figure 7. Heat generation from HC dosage in various engine operating conditions; (a) temperature increase; (b) heat generation according to the amount of HC injection.

the direction of injection and the mixing process, as previously described. As the engine speed increases, that is, as the exhaust gas flow rate increases, the increase of temperature gets small and the high temperature region moves toward the center. This results from enhanced mixing between HC and exhaust flow and smaller penetration length due to the increase of main flow velocity (exhaust gas flow).

Temperature increase caused by HC injection is measured as the mean temperature difference between before and after HC injection on the DOC rear surface. Figure 7 shows the increase of temperature according to the HC injection rate for various engine operating conditions. We can see that an HC dosage of roughly 40 cc/min (at DOC inlet temperature = 220°C, 2,000 rpm) resulted in a higher temperature than BPT to regenerate the DPF system, regardless of engine conditions (Figure 7(a)). As the engine speed and load increase, the mass flow rate of the exhaust gas increases, therefore, the heat generation caused by HC oxidization normalized by the increase of flow rate linearly increases according to the amount of HC injection, as shown in Figure 7(b). This means that the HC dosage is almost oxidized and the amount of HC injection can be determined by the exhaust gas flow rate and target temperature. Generally, the low regeneration temperature of DPF at low speed and load is considered a major barrier to the commercialization of CR-DPF for the general public. However, the present results provide a means of resolving this problem. The temperature increase at the inlet of DPF (> 600°C) is also significant in that the

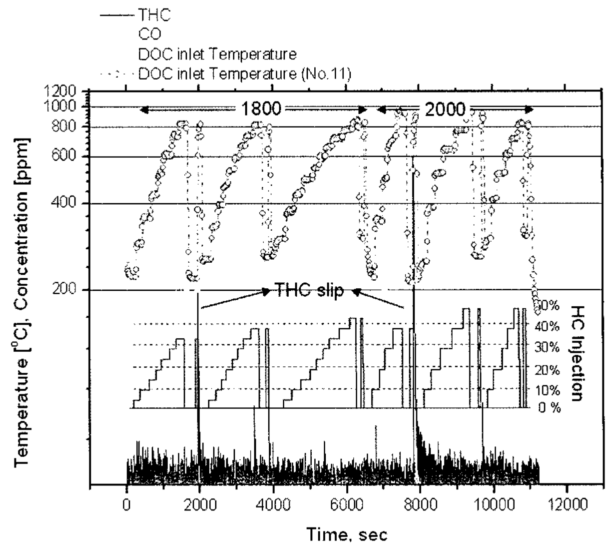

Figure 8. THC slip according to injection methods (engine speed: 1800 and 2000 rpm).

deposited PM in DPF can be oxidized by only O_2 independent of NO_2. In addition, this temperature induces complete oxidation of accumulated soot.

Figure 8 shows the composition of exhaust gas and the temperature of the DOC outlet in accordance with HC injection. The THC emission (black solid line) in this graph represents the instantaneous slip phenomena.

In the case of multi-step injection, that is, as the injection rate gradually increases, the DOC inlet temperatures decrease due to adsorption of vaporization heat of fuel. But in this case, the abrupt temperature changes of DOC inlet did not occur and THC slip also could not be observed. However, in the case of pulse type injection, the abrupt injection of much fuel results in the decrease of DOC inlet temperatures and an instantaneous THC slip was observed as shown in Figure 8. This abrupt increase of fuel caused the mixture to form a locally fuel rich zone, and thus incomplete oxidization occurred in the case of relatively low DOC inlet temperature (220°C) and non-uniformity of the temperature distribution was observed at DOC and DPF. This non-uniformity may cause the DPF system to fracture by thermal cracking (Nakane *et al.*, 2005). These results show that a temperature increase inlet to oxidize soot completely at the DPF can be obtained by fuel injection, and the dosage of fuel should be gradually increased in order to obtain endurance and low THC slip.

5. CONCLUSIONS

The temperature distribution of DOC and the exhaust gas composition were observed in a diesel fuel (HC) injection type regeneration system according to the engine operating conditions in an effort to improve the regeneration performance in low temperature region. The following observations were made during this study.

(1) The high temperature region is biased downward after HC injection. This results from the direction of injection and the mixing process. As the exhaust gas flow rate increases, the increase in temperature is small and the high temperature region moves toward the center because of enhanced mixing between HC and exhaust flow.

(2) A temperature increase more than BPT of DPF system was obtained with a small amount of fuel injection (about 40 cc/min → loss of fuel consumption=0.9%*) when the exhaust gas temperature was low (at 220°C, engine speed = 2000 rpm). This increase of temperature at the DPF inlet can oxidize soot completely by O_2.

(3) In the case of multi-step injection, the abrupt temperature changes of DOC inlet didn't occur and injection rate gradually increases, and the large peak of THC slip also could not be observed. However, in the case of pulse type injection, the abrupt injection of much fuel results in the decrease of DOC inlet temperatures and the instantaneous slip of THC was observed. Therefore, the dosage of fuel should be gradually increased in order to obtain endurance and minimize THC slip.

*the reference for calculating the fuel consumption
PM emission= 0.15 g/km (2000 year, 3.0~3.5 ton)
Fuel consumption~7 km/liter
The injection duration for regenerating DPF=10 min

REFERENCES

Chiew, L., Kroner, P. and Ranalli, M. (2005). Diesel vaporizer: An innovative technology for reducing complexity and costs association with DPF regeneration. *SAE Paper No.* 2005-01-0671.

Fayard, J.-C., Joubert, E. and Seguelong, T. (2005). A new active DPF system for stop & go duty cycle vehicle: durability and improvements. *SAE Paper No.* 2005-01-1754.

Guo, G., Xu, N., Laing, P. M., Hammerle, R. H. and Maricq, M. M. (2003). Performance of a catalyzed diesel particulate filter system during soot accumulation and regeneration. *SAE Paper No.* 2003-01-0047.

Hiranuma, S., Takeda, Y., Kawatani, T., Doumeki, R. and Nagasaki, K. (2003). Development of DPF system for commercial vehicle-Basic characteristic and active regeneration performance. *SAE Paper No.* 2003-01-3182.

Kodama, K., Hiranuma, S., Doumeki, R. and Takeda, Y. (2005). Development of DPF system for commercial vehicles (2nd Report)-Active regenerating function in various driving condition. *SAE Paper No.* 2005-01-3694.

Kong, Y. T., Huffmeyer, C., Johnson, R., Taylor, B., Crawley, W. and Hayworth, G. (2004). Applications of an active diesel particulate filter regeneration system. *SAE Paper No.* 2004-01-2660.

Kong, Y., Kozakiewicz, T., Johnson, R., Huffmeyer, C., Huckaby, J., Abel, J., Baurley, J. and Duffield, K. (2005). Active DPF regeneration for 2007 diesel engines. *SAE Paper No.* 2005-01-3509.

Konstandopoulos, A. G. and Kostoglou, M. (2000). Reciprocating flow regeneration of soot filter. *Combustion and Flame*, **121**, 488–500.

Lee, C.-H., Lee, C.-B., Kim, D.-J., Oh, K.-C., Kang, J.-H., Choi, J.-M., Jo, J.-D., You, Y.-H. and Cho, T.-D. (2005). The experimental study of diesel fuel injection for active regeneration of DPF system. *Proc. 13th Int. Pacific Conf. Automotive Engineering. Paper No.* 81, Gyeongju, Korea.

Mayer, A., Kany, S., Richards, P., Andreassen, L., Sem, T. (2005). Retrofitting TRU-diesel engines with DPF-systems using FBC and intake throttling for active regeneration. *SAE Paper No.* 2005-01-0662.

Nakane, T., Ikeda, M., Hori, M., Bailey, O. and Mussmann, L. (2005). Investigation of the aging behavior of oxidation catalysts developed for active DPF regeneration systems. *SAE Paper No.* 2005-01-1759.

Oh, S. K., Baik, D. S. and Han, Y. C. (2002). performance and exhaust gas characteristics on diesel particulate filter trap, *Int. J. Automotive Technology* **3, 3**, 111–115.

Richards, P., Vincent, M. and Chadderton, W. J. (2005). Service application of a novel fuel borne catalyst dosing system for DPF retrofit. *SAE Paper No.* 2005-01-0669.

Suto, H. (1997). Regeneration method using a cerium based fuel additive on SiC honeycomb DPF-self regeneration at low exhaust temperature. *JSAE Review* **18, 2,** 202.

Vincent, M. W., Richards, P. J. and Rogers, T. J. (2002). Effective particulates reduction in diesel engines through the use of fuel catalyzed particulate filter. *Int. J. Automotive Technology* **3, 1**, 1–8.

Webb, C. C., Weber, P. A. and Thornton, M. (2004). Achieving tier 2 bin 5 emission levels with a medium duty diesel pick-up and a NO_x adsorber, diesel particulate filter emissions system-exhaust gas temperature management. *SAE Paper No.* 2004-01-0584.

Yamane, K., Yuuki, R., Kawasaki, K., Asakawa, T., Numao, H. and Komori, M. (2005). Characteristics of DPF for diesel engine fueled with biodiesel fuel-2nd report: Exhaust gas emission characteristics at self-regeneration of DPF. *SAE Paper No.* 2005-01-2198.

Zheng, H. and Keith, J. M. (2004). Ignition analysis of wall-flow monolith diesel particulate filters. *Catalysis Today*, **98**, 403–412.