Periodic rich combustion of a diesel fuelled engine for NOx emissions reduction through engine management system

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Periodic Rich Combustion of a Diesel Fuelled Engine for NO_X Emissions Reduction through Engine Management System

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Abstract. Diesel fuelled engines are known to produce excessive NO_X emissions compare to gasoline fuelled engines. Among the techniques currently being investigated to suppress the NO_X emissions is lean NO_X trap (LNT) system. The application of this aftertreatment device requires alternating lean and rich exhaust gas mixture, in order to produce the necessary reducing agents necessary for purging the LNT system. In this study an engine testbed was set up; comprised a 4-cylinder light duty diesel engine, a diesel oxidation catalyst (DOC) and an LNT system; to investigate the performance of the LNT system under periodic rich combustion. The purging system utilised was in-cylinder enrichment method based on DSPACE system, which controlled the engine management system (EMS) and the main engine operating parameters. This method used open loop control system, to provide different storage/purge cycles for the LNT system. Emissions test at low operating temperature using this enrichment method had shown its capability to produce the required periodic rich exhaust mixture for purging the LNT system. The alternating storage-regeneration events were indicated by the variations in lambda and emissions values.

Keywords: **diesel engines, NO_X emissions, lean NO_X trap, engine management system, DSPACE**

1. INTRODUCTION

Diesel engines operate under lean conditions and reduction of NO_X to N_2 is difficult due to the presence of excess O_2 in the exhaust stream [1]. Various methods of reducing NO_X emissions have been attempted and they can be categorised into the following groups [2]:

- Development of systems to improve fuel mixture and combustion
- Usage of alternative fuels or conventional fuels with additives
- Development and installation of new post-combustion treatment devices

Lean NO_X trap (LNT) is one of the post-combustion treatment devices, which is capable in treating NO_X emissions, as it has certain advantages over other diesel after-treatment devices such as selective catalytic reduction (SCR) and catalysed diesel particulate filter [3, 4]. However, the LNT system requires periodic regeneration under all driving condition, as it has a finite trapping capability. The regeneration process, which is performed during rich condition, also helps to prolong the durability of the trap [5]. Nevertheless, LNT system is sulphur sensitive and it is difficult to achieve rich exhaust mixture that is necessary for regenerating the trap. The rapid switching between lean and rich conditions and the ratio between them are very challenging as far as engine management control and combustion processes are concerned. Previous study has shown that the cost of LNT for diesel fuelled vehicles is much higher than the SCR technology and therefore, optimum system design is critical [6].

LNT catalysts are typically composed of Pt-group metal, which plays an important role in the reduction-oxidation process and a basic adsorbent or base-metal-oxide (BMO) that is responsible for providing the storage capacity. The chemical reactions that occur on the LNT catalyst are very complex and involve the reaction of acidic gas (nitrogen dioxide-NO_2) with the BMO to form nitrate or nitroso-species on the surface of the catalyst, desorption of NO_X during regeneration and reduction with CO or H_2 [1, 4, 7].

The operating factors that can influence the LNT performance, apart from the combinations of the Pt-group metals, are: the composition of the exhaust gas during lean and rich conditions; corresponding air-fuel ratios; exhaust gas temperatures; and also the duration of the lean and rich cycles [7, 8, 9, 10, 11, 12].

For the LNT system to operate effectively, it requires optimisation of key engine operating parameters as part of the reduction process, since there are insufficient reducing agents in the rich pulse that are able to completely reduce the NO_X levels. Integrated control of exhaust gas recirculation (EGR) and turbocharging has been shown to augment the reduction of NO_X emissions [13]. It has been reported that the recommended desorption and reduction of NO_X is when the equivalence ratio, Φ=1.15 (λ=0.870), where higher CO levels give shorter desorption times [14]. Previous study, on the expected emission control technologies that will be implemented in the coming years, has indicated that LNT will play an important role in curbing the NO_X emissions, especially for the application in light-duty vehicles [17].

In this paper, the results from periodic rich combustion experiments on the performance of an LNT system, using in-cylinder enrichment method based on the control of the engine management system (EMS), are presented.

2. EXPERIMENTAL SET-UP

For the experimental works, a 4-cylinder diesel engine was used, equipped with a common rail injection system, an EGR system, and an intake throttle body. The EMS, which was comprised an engine control unit (ECU) and an injection control unit (ICU), and the throttle body were connected to the DSPACE control tool to enable the generation of the periodic rich combustion. The EMS was also connected to a GREDI system that served as the calibration tool. Throughout the tests, the engine used a very low sulphur diesel fuel supplied by PETROCHEM. The engine specification is given in Table 1.

TABLE 1. Specifications of the test engine.

Items	Description
Engine capacity	1998 cc
Rated power output	96 kW at 3800 rpm
Rated torque	330 N-m at 1800 rpm

The turbo outlet of the engine was linked to an exhaust aftertreatment test rig that consisted of a long diffuser followed by a flow straightener upstream of a diesel oxidation catalyst (DOC) and an LNT system. Both the DOC and LNT used Pt-group metal as the main catalytic compounds. Figure 1 shows the layout for the experimental set-up and the details of the exhaust aftertreatment test rig are illustrated in Figure 2.

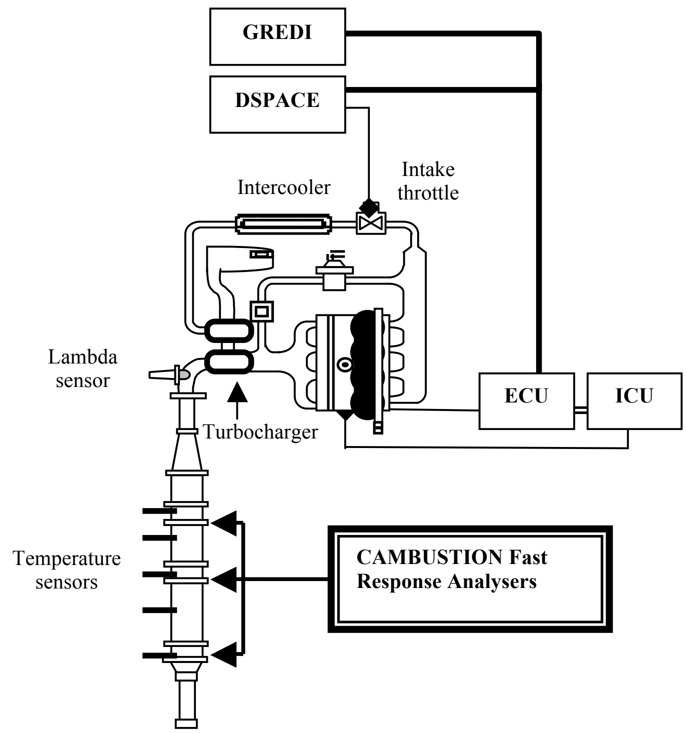

FIGURE 1: **Schematic of the system set-up**

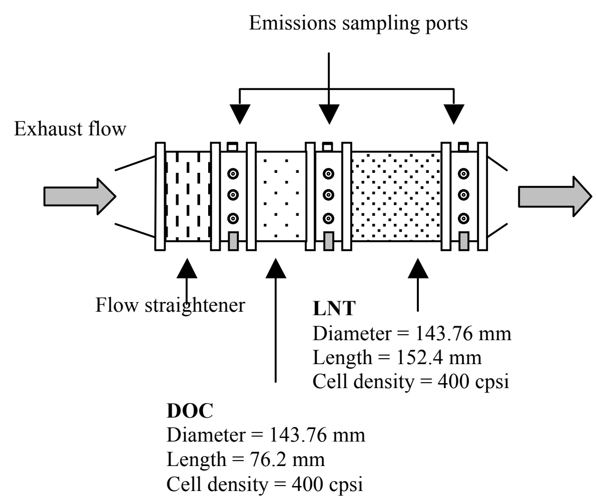

FIGURE 2: Details of the LNT test rig

The control algorithm set-up within the DSPACE system allowed the control on the intake throttle body, EGR, fuel injection quantities and timings for each of the Pilot, Main and Post injections. In addition to that, it can also produce different cyclic regeneration sets (different durations of alternating lean and rich operations), even though only in open-loop condition. For characterising the exhaust emissions, CAMBUSTION fast response analysers were used during each storage and regeneration phases, with response time of less than 10 milliseconds. Data logging for all the measurements from the engine and the emissions analysers was performed concurrently at frequency of 50 Hz, using Froude-Consine TEXCEL data logger.

Engine's fuel injection properties were also logged simultaneously using GREDI. An NDIR500 (Non-Dispersive Infra-Red) analyser was used for sampling the CO and CO2 and a CLD500 (Chemiluminescence) analyser was used to measure NO and total NO_X. The sampling probe without a NO_X converter was used to measure NO and with the converter to measure total NO_X, thus allowing for measurement of NO_2. BOSCH wide band lambda measuring system was used to record the exhaust's lambda value. Temperatures were measured in front, within and after the DOC, inside the LNT and after the LNT. Three separate emission sampling positions were chosen: IN (before the DOC), GAP (between DOC and LNT) and OUT (after the LNT).

In this research work, the experiment was conducted under steady-state condition, at an engine speed of 1500 rpm and a torque setting of 48 N-m. Emissions were sampled after the engine temperature and the catalyst beds temperatures had approximately stabilised. The exhaust gas temperature was around 250-280 ^{O}C. The lean and rich durations, for trap storage and regeneration, were set at 60 seconds and 6 seconds respectively.

3. RESULTS AND DISSCUSSION

Figure 3 shows a series of NO_X storage and purging cycles, which are repetitive and indicate the capability of the in-cylinder enrichment system to periodically purge the LNT system. The LNT purging events are indicated by the cyclic changes of the exhaust lambda values.

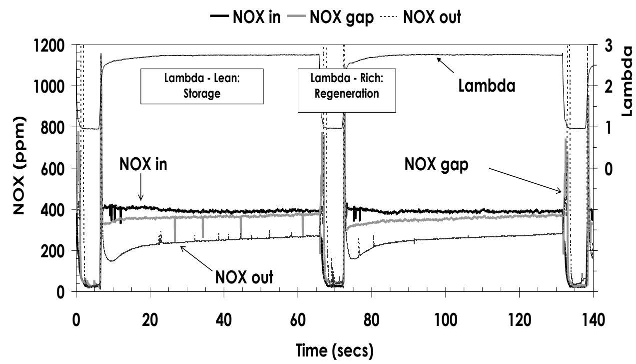

FIGURE 3: LNT storage and regeneration cycles (peaks NO_X at out are truncated)

The individual plots for NO, NO_2 CO and CO_2 emissions, during storage and regeneration, are shown respectively in figures 4, 5, 6 and 7.

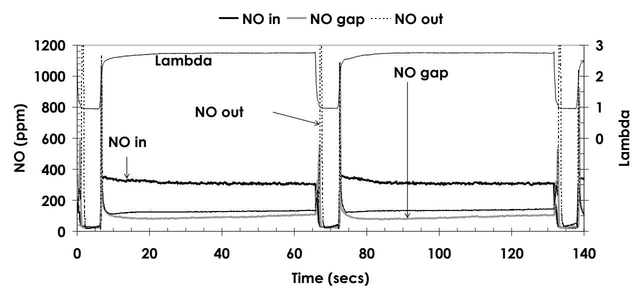

FIGURE 4: NO emissions during storage and regeneration (peaks NO at out are truncated)

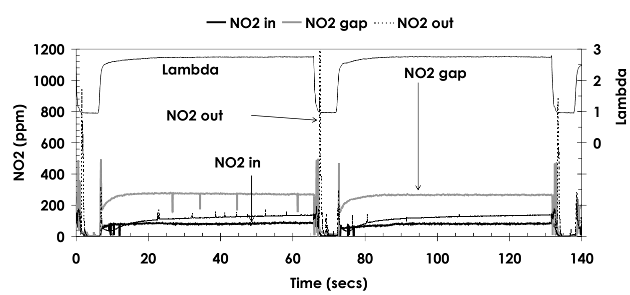

FIGURE 5: NO_2 emissions during storage and regeneration (peaks NO_2 at out are truncated)

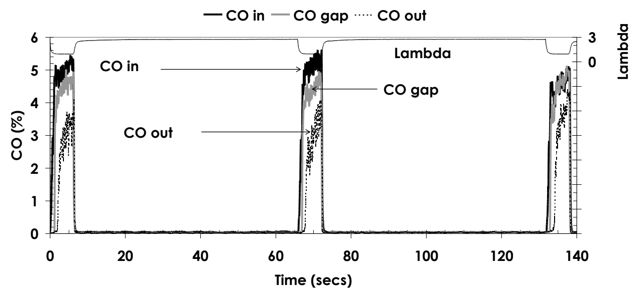

FIGURE 6: CO emissions during storage and regeneration

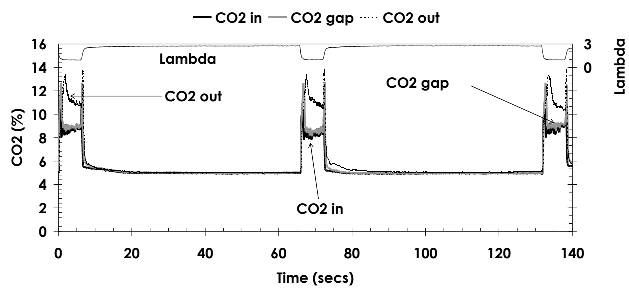

FIGURE 7: CO_2 emissions during storage and regeneration

Immediately after purging, NO_X emissions after the LNT increased steadily before starting to stabilise after around 15 seconds, as the trap was started to fill. On average the amount of NO_X emitted by the engine during lean operation was around 430-450 ppm and consisted mostly of NO (see Figure 4). During the storage period, almost half of the total NO_X that went into the LNT system, around 200-250 ppm, was successfully stored.

Referring to the NO and NO_2 plots, (figures 5 and 6) all the individual plots shown are repetitive, which indicate the capability of the LNT system to store and reduce the incoming NO_X emissions. Although there are some cycle to cycle variations, similar features are repeatable and identifiable during the storage and purging events. The large amount of NO from the engine was oxidised into NO_2 by the DOC as shown by the increase of NO_2 to around 280-300 ppm and reduction of NO to around 100-120 ppm, measured at the gap (post DOC before LNT). The lower NO_2 trace observed post LNT suggests that almost all the incoming NO_2 from the DOC has been stored by the LNT during the lean period, whereas, the LNT was not storing the NO emission from the DOC in both cases, as the levels for both the NO inside the gap and at out (post LNT) are almost similar. Hence, the DOC proved its capability to oxidise the NO from the engine and the LNT functioned by storing mainly the NO_2 emission during the lean period.

During the regeneration events, two significant NO_X breakthroughs or spikes were observed after the LNT (refers to figure 3). These were observed at the start and the end of every regeneration period, during the changeover from rich to lean and vice versa, and were present in every cycle. The NO_X breakthroughs consisted mainly of NO, rather than the NO_2. Theis et al. [12] stated that at operating temperatures around 250 ^{O}C, the NO_X release can be ascribed to low NO_X reduction activity. The existences of these NO_X spikes during regeneration were not detected in previous studies on LNT, for example in the studies from Theis et al. [12], Bögner et al. [15] and Li et al. [16].

Throughout the lean period, the CO level was very low and only increased drastically during the regeneration period (refers to figure 6). CO emissions were much lower after the LNT than after the DOC during regeneration, and the CO was partially consumed at the beginning of the regeneration period before starting to increase again, although not reaching the same level as the incoming CO from the DOC. The significant consumption of CO emissions during the regeneration indicates that the CO acts as a primary reductant for the purged NO_X. This is comparable to the findings from the study by West et al. [17], as well as previous lab-scaled studies on the roles of CO as the reducing agent by Abdulhamid et al. [18].

CO2 emissions were almost equal during the lean period at each sampling point, before they started to rise only during the rich period; see figure 7. The increase of CO_2 emissions at the beginning of the regeneration period could be associated to the partial consumption of CO and at that particular time. CO_2 emissions began to drop after that time and started to increase again as the combustion mixture started to switch from rich to lean.

The presence of signal noises in the emissions measurements (figures 3, 4, 5, 6 and 7) were caused by small particles or carbon soot temporarily blocking the sampling passage from the sample probe heads to the analysers' service units. As a result, the analysers became dirty in a very short time and required frequent cleaning. Moreover, it has limited the sampling duration that could be made during an experiment

Figure 5 shows the LNT system instantaneous efficiency, which is defined as follows:

$$Efficiency = \left[\frac{(NO_X)_{IN} - (NO_X)_{OUT}}{(NO_X)_{IN}} \right] \times 100 \qquad (1)$$

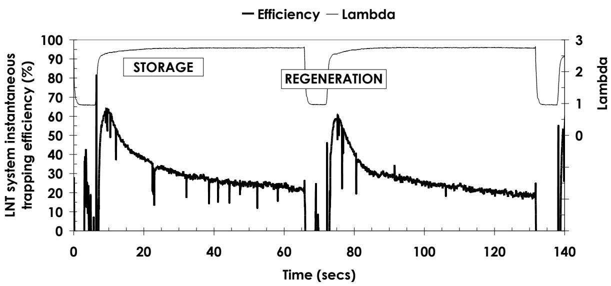

FIGURE 8: LNT system efficiency

The plot shows that as the storage period increases the efficiency drops, as the trap started to fill up. This LNT system operated with maximum efficiency of only around 65-70% and this implies that the implemented regeneration strategy can be improved further. The negative efficiencies are due to presence of NO_X spikes.

4. CONCLUSION

The experimental results have shown the ability of the in-cylinder enrichment method that was based on the control of the EMS, to provide periodic lean and rich combustion, required for the operation of the LNT system.

From those emissions results, it can be confirmed that the NO_X storage and reduction process had been successfully carried out using the developed in-cylinder enrichment method. The fast response emissions analysers had also effectively displayed the detail of the events that occurred during the storage and regeneration periods. The analysers were, in particular, able to detect and measure the emissions traces during the lambda changeover, either from lean to rich or from rich to lean.

The approach used in developing the in-cylinder enrichment technique for this study, which was based on the fuel injections properties and intake air throttling, was only one of many possible options for generating rich combustion but was used because it was the simplest.

It is recommended that future work in this area, should involve further experiments under different engine operating conditions.

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