Proceedings of EnCon2007
1st Engineering Conference on Energy & Environment
December 27-28, 2007, Kuching, Sarawak, Malaysia

ENCON2007-002

Fuel Penalty from Periodic Rich Combustion of a Diesel Fuelled Engine during Lean NO_X Trap Purging

Ahmad J. Alimin, Stephen F. Benjamin and Carol A. Roberts

Abstract—**Compression ignition engines produce excessive NO_X emissions compare to spark ignition engines. Lean NO_X trap system is currently being investigated as an after-treatment device to suppress the NO_X emissions from compression ignition engines. The application of this after-treatment 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 which consisted of a 4-cylinder light-duty diesel engine, a diesel oxidation catalyst (DOC) and an LNT system. The LNT system purging utilised in-cylinder enrichment method based on DSPACE system, which controlled the engine management system (EMS) and the main engine operating parameters. The enrichment method used open-loop control system, to provide different storage/purge cycles for the LNT system. During enrichment, extra fuelling was needed to produce the required rich exhaust mixture. Emissions test at low operating temperature using this method had shown the capability of this in-cylinder enrichment method to produce the required periodic rich exhaust mixture for the LNT system. Nevertheless, the occurrences of periodic rich combustion also led to the increase in fuel penalty. Therefore, an acceptable trade-off between emissions reduction and fuel penalty is necessary.**

Keywords: diesel engine, NO_X emissions, lean NO_X trap, in-cylinder enrichment method, fuel penalty

I. Introduction

Diesel engines operate under lean conditions and reduction of NO_X to N_2 is difficult due to the presence of excess O2 in the exhaust stream [1]. Various methods of reducing NO_X emissions have been attempted and among them are development of systems to improve fuel mixture and combustion, and development of new post-combustion treatment devices [2]:

Dr. A. J. Alimin is with the Department of Automotive and Plant Engineering, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor (Phone: +6074537868; fax: +6074536080; e-mail: ajais@uthm.edu.my).

Prof. S. F. Benjamin is the Director of Automotive Engineering Applied Research Group, Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry CV1 5FB, UK (e-mail: s.benjamin@coventry.ac.uk).

Dr. C. A. Roberts is a Research Fellow with the Automotive Engineering Applied Research Group, Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry CV1 5FB, UK (e-mail: carol.roberts@coventry.ac.uk).

Lean NO_X trap (LNT) is one of the post-combustion treatment devices that can treat 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 to prolong the performance and durability of the trap, as it has a finite trapping capability [5]. Nevertheless, LNT system is sulphur sensitive and it is difficult to achieve rich exhaust mixture that is necessary for regenerating the trap. 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 H2 [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]-[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 exhaust lambda (λ) value is around 0.87-0.90, 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 of exhaust emissions and fuel penalty from periodic rich combustion experiments of an LNT system, using in-cylinder enrichment method are presented.

II. Experimental Set-up

In 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. 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 Nm 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 sampling points on the exhaust aftertreatment test rig are illustrated in 'figure 2'.

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.

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 Nm. 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. The results from this test are then compared with the findings from previous work.

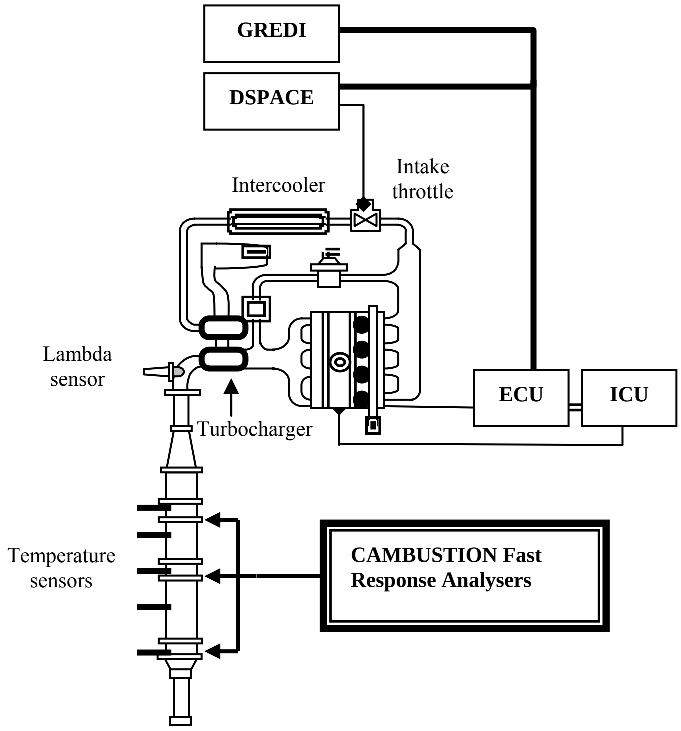


Figure 1. Schematic of the system set-up.

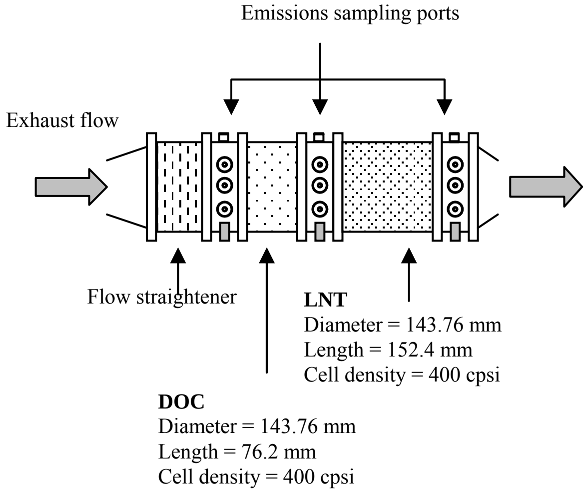


Figure 2. Details of the LNT test rig

III. Results and Discussion

'Figure 3' shows a series of NO_X storage and purging cycles (or lean and rich 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.

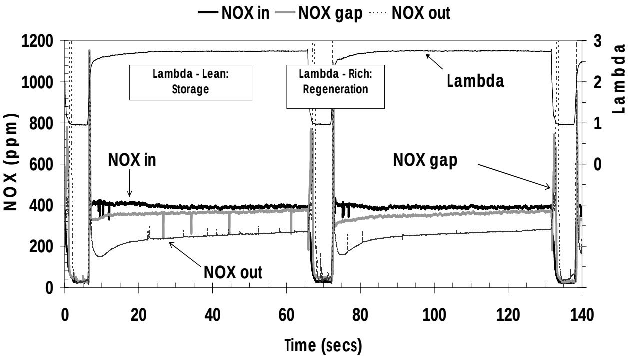


Figure 3. LNT storage and regeneration cycles (peaks NO_X at out are truncated).

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'.

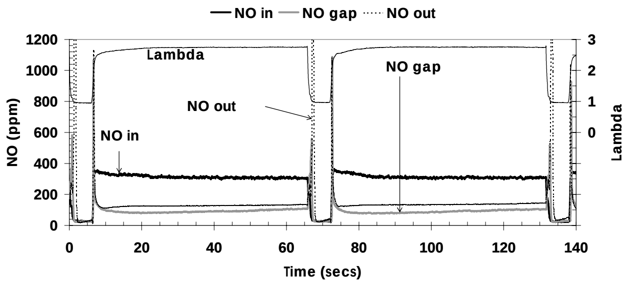


Figure 1. NO emissions during storage and regeneration (peaks NO at out are truncated)

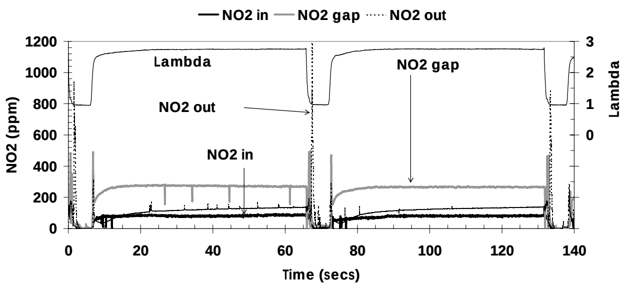


Figure 2. NO_2 emissions during storage and regeneration (peaks NO_2 at out are truncated)

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.

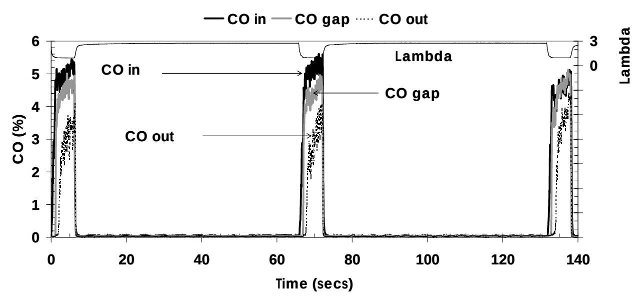


Figure 3. CO emissions during storage and regeneration

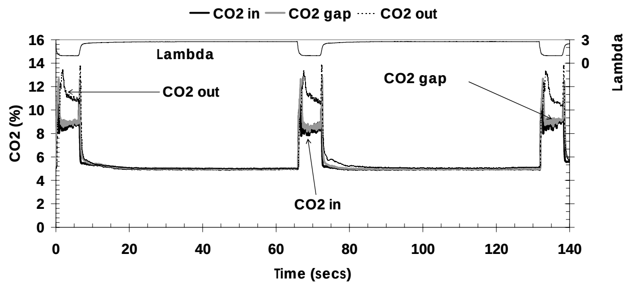


Figure 4. CO_2 emissions during storage and regeneration

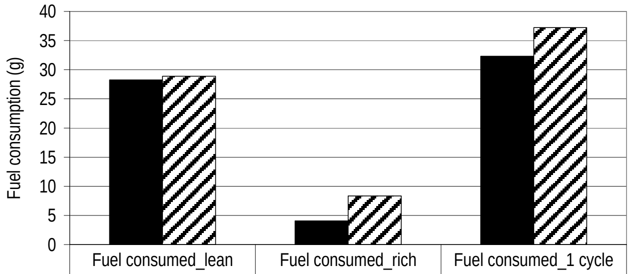
Referring to the NO and NO_2 plots, ('figures 5 and 6') all the individual plots shown are repetitive, which indicate the capability of the LNT system to store and reduce the incoming NO_X emissions. Although there are some cycle to cycle variations, similar features are repeatable and identifiable during 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].

CO_2 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.

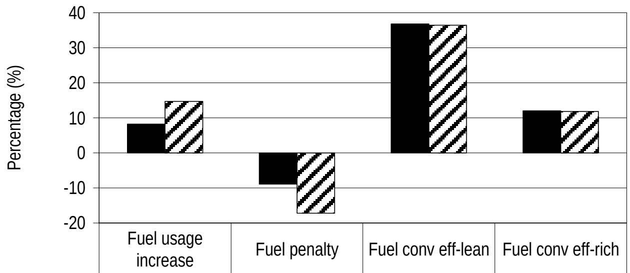
Fuel usage analysis during lean, rich and in a complete lean/rich cycle for the test condition described above (60L6R) and test at 60 seconds lean and 3 seconds (60L3R), which has been described previously [19], are depicted in 'figure 8'. In this figure, the term *'Fuel consumed_1 cycle'* refers to the combined fuel consumption during lean and rich periods for a particular lean/rich cycle. As can be seen, the total amount of fuel being consumed was also increased as the regeneration period became longer.



	Fuel consumed_lean	Fuel consumed_rich	Fuel consumed_1 cycle
60L3R	28	4	32
60L6R	29	8	37

Figure 5. Fuel consumption during lean, rich and a complete lean/rich cycle under different test conditions

Using the information on 'figure 8', an analysis on the fuel penalty for each test condition was performed and the results are as shown in 'figure 9'. The fuel penalty is defined as the ratio between the additional fuel consumption due to regeneration during a complete lean/rich cycle duration to the total fuel consumption during the same duration but with the engine running in lean condition only. The effect of periodic lean/rich cycle on the overall engine fuel conversion efficiency (or thermal efficiency) is also illustrated in 'figure 9'. In this analysis, the term *'Fuel conv eff-lean'* refers to the fuel conversion efficiency of the engine during the storage period and was calculated based on the fuel specific consumption when the engine was running lean only. Similarly, the term *'Fuel conv eff-rich'* indicates the fuel conversion efficiency during regeneration only and was calculated using the fuel specific consumption of the engine when it was running rich.



	Fuel usage increase	Fuel penalty	Fuel conv eff-lean	Fuel conv eff-rich
60L3R	8	-9	37	12
60L6R	15	-17	36	12

Figure 6. The percentage fuel usage increase, fuel penalty and engine fuel conversion efficiency due to regeneration for a complete storage/regeneration cycle under different test conditions

From the figure above, significant increase in fuel usage was observed for both tests, 60L3R and 60L6R, which caused fuel penalty of 9% and 17% respectively. During lean the engine produced comparable fuel conversion efficiency for all test conditions, between 34 – 38% during lean and around 11 – 12% during rich. The addition of a regeneration stage caused the engine fuel conversion efficiency to drop. This was due to the fact that the periodic in-cylinder enrichment system for the emission tests used high amount of fuel to purge the LNT.

The results from the tabulated data can be interpreted together with their LNT system instantaneous trapping efficiencies, shown in 'figure 10'.

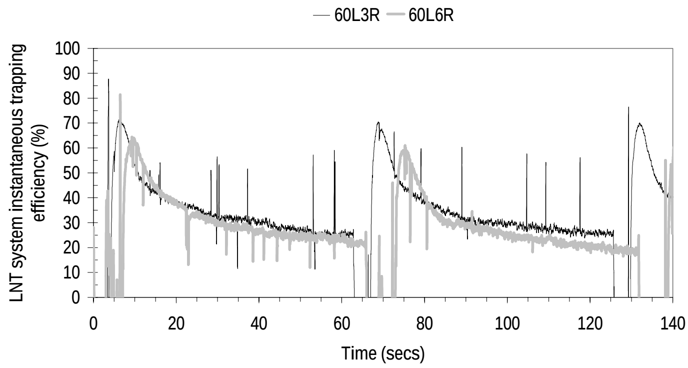


Figure 7. LNT system instantaneous trapping efficiency for 60L3R and 60L6R tests

From 'figure 10', both emission tests were operating at system trapping efficiency of within 20 – 70%. The trapping efficiency was the highest immediately after regeneration before it began to drop gradually with time, during the storage period. Although large amount of fuel was added during the regeneration period in test 60L6R, the system trapping efficiency was still at a comparable level with the system trapping efficiency of test 60L3R. This would indicate that adding extra fuel or increasing the fuel injection duration would not necessarily improve the LNT system trapping performance.

IV. Conclusion

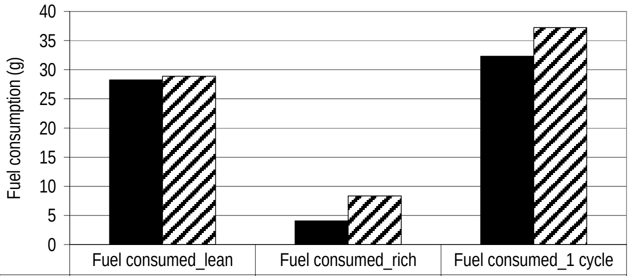
The experimental results have shown the ability of the in-cylinder enrichment method to provide periodic lean and rich combustion, required for the operation of the LNT system. The approach used in developing the in-cylinder enrichment technique for this study, which was based on the fuel injections properties and intake air throttling, was only one of many possible options for generating rich combustion but was used because it was the simplest.

The fast response emissions analysers had also effectively displayed the detail of the events that occurred during the storage and regeneration periods, particularly during the lambda changeover, either from lean to rich or from rich to lean.

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. Nevertheless, fuel penalty analysis has implied that if the in-cylinder enrichment technique was chosen to purge the LNT system, appropriate fuel injection properties must be used. This is important to avoid excessive loss in the fuel conversion efficiency, as well as to achieve the acceptable trade-off between LNT system performance and fuel penalty.

started to switch from rich to lean.

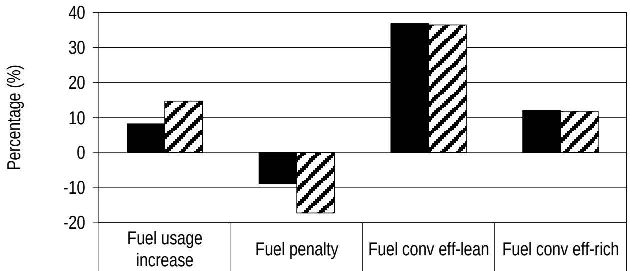
Fuel usage analysis during lean, rich and in a complete lean/rich cycle for the test condition described above (60L6R) and test at 60 seconds lean and 3 seconds (60L3R), which has been described previously [19], are depicted in 'figure 8'. In this figure, the term *'Fuel consumed_1 cycle'* refers to the combined fuel consumption during lean and rich periods for a particular lean/rich cycle. As can be seen, the total amount of fuel being consumed was also increased as the regeneration period became longer.



	Fuel consumed_lean	Fuel consumed_rich	Fuel consumed_1 cycle
60L3R	28	4	32
60L6R	29	8	37

Figure 5. Fuel consumption during lean, rich and a complete lean/rich cycle under different test conditions

Using the information on 'figure 8', an analysis on the fuel penalty for each test condition was performed and the results are as shown in 'figure 9'. The fuel penalty is defined as the ratio between the additional fuel consumption due to regeneration during a complete lean/rich cycle duration to the total fuel consumption during the same duration but with the engine running in lean condition only. The effect of periodic lean/rich cycle on the overall engine fuel conversion efficiency (or thermal efficiency) is also illustrated in 'figure 9'. In this analysis, the term *'Fuel conv eff-lean'* refers to the fuel conversion efficiency of the engine during the storage period and was calculated based on the fuel specific consumption when the engine was running lean only. Similarly, the term *'Fuel conv eff-rich'* indicates the fuel conversion efficiency during regeneration only and was calculated using the fuel specific consumption of the engine when it was running rich.



	Fuel usage increase	Fuel penalty	Fuel conv eff-lean	Fuel conv eff-rich
60L3R	8	-9	37	12
60L6R	15	-17	36	12

Figure 6. The percentage fuel usage increase, fuel penalty and engine fuel conversion efficiency due to regeneration for a complete storage/regeneration cycle under different test conditions

From the figure above, significant increase in fuel usage was observed for both tests, 60L3R and 60L6R, which caused fuel penalty of 9% and 17% respectively. During lean the engine produced comparable fuel conversion efficiency for all test conditions, between 34 – 38% during lean and around 11 – 12% during rich. The addition of a regeneration stage caused the engine fuel conversion efficiency to drop. This was due to the fact that the periodic in-cylinder enrichment system for the emission tests used high amount of fuel to purge the LNT.

The results from the tabulated data can be interpreted together with their LNT system instantaneous trapping efficiencies, shown in 'figure 10'.

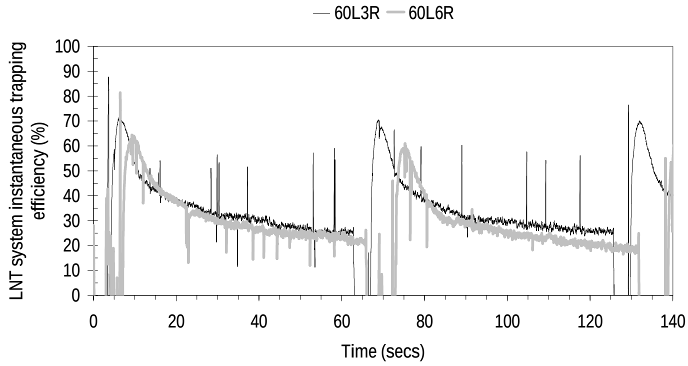


Figure 7. LNT system instantaneous trapping efficiency for 60L3R and 60L6R tests

From 'figure 10', both emission tests were operating at system trapping efficiency of within 20 – 70%. The trapping efficiency was the highest immediately after regeneration before it began to drop gradually with time, during the storage period. Although large amount of fuel was added during the regeneration period in test 60L6R, the system trapping efficiency was still at a comparable level with the system trapping efficiency of test 60L3R. This would indicate that adding extra fuel or increasing the fuel injection duration would not necessarily improve the LNT system trapping performance.

IV. Conclusion

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

The fast response emissions analysers had also effectively displayed the detail of the events that occurred during the storage and regeneration periods, particularly during the lambda changeover, either from lean to rich or from rich to lean.

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. Nevertheless, fuel penalty analysis has implied that if the in-cylinder enrichment technique was chosen to purge the LNT system, appropriate fuel injection properties must be used. This is important to avoid excessive loss in the fuel conversion efficiency, as well as to achieve the acceptable trade-off between LNT system performance and fuel penalty.

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

ACKNOWLEDGMENT

The authors would like to thank ArvinMeritor, Ford, Jaguar Land Rover and Johnson Matthey, for their technical and financial support.

REFERENCES

[1] Epling, William S., Parks, James E., Campbell, Greg C., Yezerets, Aleksey, Currier, Neal W. and Campbell, Larry E. (2004) - *Further evidence of multiple NO_X sorption sites on NO_X storage/reduction catalysts*, Catalysis Today, 96, 21-30, available online www.elsevier.com/locate/cattod.

[2] Armas, O; Baltesteros, R; Martos, F.S. and Agudelo, J.R. (2004) - *Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel*, Fuel, Vol. 84, Number 7-8, available online www.sciencedirect.com.

[3] West, Brian H. and Sluder, C. Scott (2000) - *NO_X adsorber performance in a light-duty diesel vehicle*, SAE2000-01-2912, International Fall Fuels and Lubricants, Meeting and Exposition, Baltimore, Maryland, 16-19th October 2000.

[4] Fang, Howard L.; Huang, Shyan C.; Yu, Robert C., Wan, C.Z. and Howden, Ken (2002) - *A fundamental consideration on NO_X adsorber technology for diesel application*, SAE2002-01-2889, Powertrain and Fluid Systems, Conference and Exhibition, San Diego, California, USA, 21-24th October 2002.

[5] Guyon, M.; Blanche P.; Bert, C.; Phillippe, L. and Messaoudi, I. (2000) - *NO_X-Trap system development and characterization for diesel engines emission contro*l, SAE 2000-01-2910, SAE International Fall Fuels and Lubricants, Meeting and Exhibition, Baltimore, USA, 16-19th October 2000.

[6] Warren, James P. (2001) - *Diesel aftertreatment systems: 2004-2007, A Cost Assessment*, SAE2001-01-1948, International Spring Fuels and Lubricants, Meeting and Exhibition, Orlando, Florida, 7-9th 2001.

[7] Olsson, Louise; Fridell, Erik; Skoglundh, Magnus and Andersson, Bengt (2002) – *Mean field modelling of NO_X storage on $Pt/BaO/Al_2O_3$*, Catalysis Today, Vol. 73, pp263-270.

[8] Takahashi, Naoki; Shinjoh, Hirofumi; Iijima, Tomoko; Suzuki, Tadashi; Yamazaki, Kiyoshi; Yokota, Koji; Suzuki, Hiromasa; Miyoshi, Naoto; Matsumoto, Shin-ichi; Tanizawa, Tsuneyuki; Tanak, Toshiaki; Tateishi, Syu-shi and Kasahara, Kouichi (1996) – *The new concept 3-way catalyst for automotive lean-burn engine: NO_X storage and reduction catalyst*, Catalysis Today, Vol. 27, pp 63-69.

[9] Kobayashi, Takeshi; Yamada, Teiji and Kayano, Kunihide (1997) – *Study of NO_X trap reaction by thermodynamic calculation*, SAE970745, SAE International Congress and Exposition, Detroit, Michigan, USA, 24-27th February 1997.

[10] Fridell, Erik; Skoglundh, Magnus; Westerberg, Björn; Johansson and Smedler, Gudmund (1999) – *NO_X storage in barium-containing catalysts*, Journal of Catalysis, Vol. 183, pp196-209.

[11] Mahzoul, H.; Brilhac; J.F. and Gilot, P. (1999) – *Experimental and mechanistic study on NO_X adsorption over NO_X trap catalysts*, Applied Catalysis B: Environmental, Vol. 20, pp47-55.

[12] Theis, Joseph R.; Ura, Justin A.; Li, John J.; Surnilla, Gopichandra G.; Roth, John M. and Goralski Jr., Christian T. (2003) – *NO_X release characteristics of lean no_x traps during rich purges*, SAE2003-01-1159, SAE World Congress, Detroit, Michigan, USA, 3-6th March 2003.

[13] Capobianco, M. (2001) - *Optimum control of an automotive direct injection diesel engine for low exhaust emissions*, Proc. Inst. Mech. Engineers-Part D, Journal of Automobile Engineering, Vol. 215, 2001

[14] Johnson, Timothy V. (2002) - *Diesel emission control: 2001 in Review*, SAE2002-01-0285, SAE 2002 World Congress, Detroit, Michigan, 4-7th March, 2002.

[15] Bögner, W.; Krämer, M.; Krutzsch, B.; Pischinger, S.; Voigtländer, D.; Wenninger, G.; Wirbeleit, F.; Brogan, M.S.; Brisley, R.J. and Webster, D.E. (1995) – *Removal of nitrogen oxides from the exhaust of a lean-tune gasoline engine*, Applied Catalysis B: Environmental, Vol. 7, pp153-171.

[16] Li, Yuejin; Roth, Stan, Yassine, Mahmoud, Beutel, Tilman, Dettling, Joe and Sammer, Chris (2000) – *Study of factors influencing the performance of a NO_X trap in a light-duty diesel vehicle*, SAE2000-01-2911, SAE International Fall Fuels and Lubricants, Meeting and Exhibition, Baltimore, USA, 16-19th October 2000.

[17] West, Brian; Huff, Shean; Parks, James; Lewis, Sam; Choi, Jae-Soon; Partridge, William and Storey, John (2004) – *Assessing reductant chemistry during in-cylinder regeneration of diesel lean NO_X traps*, SAE2004-01-3023, Powertrain and Fluid Systems Conference and Exhibition, Tampa, Florida USA, 25-28th October 2004.

[18] Abdulhamid, Hussam; Fridell, Erik and Skoglundh, Magnus (2005) – *The reduction phase in NO_X storage catalysis: Effect of type of precious metal and reducing agent*, Applied Catalysis B: Environmental, Vol. 62, pp319-328.

[19] A. J. Alimin, C.A. Roberts and S. F. Benjamin (2006) – *A NO_X trap study using fast response emission analysers for model validation*, SAE2006-01-0685, Special Publication, SP2023, Society of Automotive Engineers, April 2006.

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

ACKNOWLEDGMENT

The authors would like to thank ArvinMeritor, Ford, Jaguar Land Rover and Johnson Matthey, for their technical and financial support.

REFERENCES

[1] Epling, William S., Parks, James E., Campbell, Greg C., Yezerets, Aleksey, Currier, Neal W. and Campbell, Larry E. (2004) - *Further evidence of multiple NO_X sorption sites on NO_X storage/reduction catalysts*, Catalysis Today, 96, 21-30, available online www.elsevier.com/locate/cattod.

[2] Armas, O; Baltesteros, R; Martos, F.S. and Agudelo, J.R. (2004) - *Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel*, Fuel, Vol. 84, Number 7-8, available online www.sciencedirect.com.

[3] West, Brian H. and Sluder, C. Scott (2000) - *NO_X adsorber performance in a light-duty diesel vehicle*, SAE2000-01-2912, International Fall Fuels and Lubricants, Meeting and Exposition, Baltimore, Maryland, 16-19th October 2000.

[4] Fang, Howard L.; Huang, Shyan C.; Yu, Robert C., Wan, C.Z. and Howden, Ken (2002) - *A fundamental consideration on NO_X adsorber technology for diesel application*, SAE2002-01-2889, Powertrain and Fluid Systems, Conference and Exhibition, San Diego, California, USA, 21-24th October 2002.

[5] Guyon, M.; Blanche P.; Bert, C.; Phillippe, L. and Messaoudi, I. (2000) - *NO_X-Trap system development and characterization for diesel engines emission control*, SAE 2000-01-2910, SAE International Fall Fuels and Lubricants, Meeting and Exhibition, Baltimore, USA, 16-19th October 2000.

[6] Warren, James P. (2001) - *Diesel aftertreatment systems: 2004-2007, A Cost Assessment*, SAE2001-01-1948, International Spring Fuels and Lubricants, Meeting and Exhibition, Orlando, Florida, 7-9th 2001.

[7] Olsson, Louise; Fridell, Erik; Skoglundh, Magnus and Andersson, Bengt (2002) – *Mean field modelling of NO_X storage on $Pt/BaO/Al_2O_3$*, Catalysis Today, Vol. 73, pp263-270.

[8] Takahashi, Naoki; Shinjoh, Hirofumi; Iijima, Tomoko; Suzuki, Tadashi; Yamazaki, Kiyoshi; Yokota, Koji; Suzuki, Hiromasa; Miyoshi, Naoto; Matsumoto, Shin-ichi; Tanizawa, Tsuneyuki; Tanak, Toshiaki; Tateishi, Syu-shi and Kasahara, Kouichi (1996) – *The new concept 3-way catalyst for automotive lean-burn engine: NO_X storage and reduction catalyst*, Catalysis Today, Vol. 27, pp 63-69.

[9] Kobayashi, Takeshi; Yamada, Teiji and Kayano, Kunihide (1997) – *Study of NO_X trap reaction by thermodynamic calculation*, SAE970745, SAE International Congress and Exposition, Detroit, Michigan, USA, 24-27th February 1997.

[10] Fridell, Erik; Skoglundh, Magnus; Westerberg, Björn; Johansson and Smedler, Gudmund (1999) – *NO_X storage in barium-containing catalysts*, Journal of Catalysis, Vol. 183, pp196-209.

[11] Mahzoul, H.; Brilhac; J.F. and Gilot, P. (1999) – *Experimental and mechanistic study on NO_X adsorption over NO_X trap catalysts*, Applied Catalysis B: Environmental, Vol. 20, pp47-55.

[12] Theis, Joseph R.; Ura, Justin A.; Li, John J.; Surnilla, Gopichandra G.; Roth, John M. and Goralski Jr., Christian T. (2003) – *NO_X release characteristics of lean no_x traps during rich purges*, SAE2003-01-1159, SAE World Congress, Detroit, Michigan, USA, 3-6th March 2003.

[13] Capobianco, M. (2001) - *Optimum control of an automotive direct injection diesel engine for low exhaust emissions*, Proc. Inst. Mech. Engineers-Part D, Journal of Automobile Engineering, Vol. 215, 2001

[14] Johnson, Timothy V. (2002) - *Diesel emission control: 2001 in Review*, SAE2002-01-0285, SAE 2002 World Congress, Detroit, Michigan, 4-7th March, 2002.

[15] Bögner, W.; Krämer, M.; Krutzsch, B.; Pischinger, S.; Voigtländer, D.; Wenninger, G.; Wirbeleit, F.; Brogan, M.S.; Brisley, R.J. and Webster, D.E. (1995) – *Removal of nitrogen oxides from the exhaust of a lean-tune gasoline engine*, Applied Catalysis B: Environmental, Vol. 7, pp153-171.

[16] Li, Yuejin; Roth, Stan, Yassine, Mahmoud, Beutel, Tilman, Dettling, Joe and Sammer, Chris (2000) – *Study of factors influencing the performance of a NO_X trap in a light-duty diesel vehicle*, SAE2000-01-2911, SAE International Fall Fuels and Lubricants, Meeting and Exhibition, Baltimore, USA, 16-19th October 2000.

[17] West, Brian; Huff, Shean; Parks, James; Lewis, Sam; Choi, Jae-Soon; Partridge, William and Storey, John (2004) – *Assessing reductant chemistry during in-cylinder regeneration of diesel lean NO_X traps*, SAE2004-01-3023, Powertrain and Fluid Systems Conference and Exhibition, Tampa, Florida USA, 25-28th October 2004.

[18] Abdulhamid, Hussam; Fridell, Erik and Skoglundh, Magnus (2005) – *The reduction phase in NO_X storage catalysis: Effect of type of precious metal and reducing agent*, Applied Catalysis B: Environmental, Vol. 62, pp319-328.

[19] A. J. Alimin, C.A. Roberts and S. F. Benjamin (2006) – *A NO_X trap study using fast response emission analysers for model validation*, SAE2006-01-0685, Special Publication, SP2023, Society of Automotive Engineers, April 2006.