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Research Article

Effects of Postinjection Application with Late Partially Premixed Combustion on Power Production and Diesel Exhaust Gas Conditioning

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The effects of postinjection with late partially premixed charge compression ignition (PCCI) were investigated with respect to diesel exhaust gas conditioning and potential power production. Initial tests comparing postinjection application with PCCI to that with conventional diesel high temperature combustion (HTC) indicated the existence of similar trends in terms of carbon monoxide (CO), total unburned hydrocarbon (THC), oxides of nitrogen (NO_x), and smoke emissions. However, postinjection in PCCI cycles exhibited lower NO_x and smoke but higher CO and THC emissions. With PCCI operation, the use of postinjection showed much weaker ability for raising the exhaust gas temperature compared to HTC. Additional PCCI investigations generally showed increasing CO and THC, relatively constant NO_x, and decreasing smoke emissions, as the postinjection was shifted further from top dead center (TDC). Decreasing the overall air-to-fuel ratio resulted in increased hydrogen content levels but at the cost of increased smoke, THC and CO emissions. The power production capabilities of early postinjection, combined with PCCI, were investigated and the results showed potential for early postinjection power production.

1. Introduction

Lean burn diesel engines generally possess an inherent advantage in higher thermal efficiency and lower fuel consumption than their stoichiometric gasoline counterparts [1]. This characteristic makes lean burn diesel engines an attractive option for on-road transportation. However, increasing concerns about the impact of vehicle pollutants on environmental sustainability and human health have caused several governing bodies to implement more stringent vehicle emission regulations [2]. These regulations have forced diesel engine manufacturers to develop technologies to simultaneously reduce the traditionally high oxides of nitrogen and particulate matter (PM) emissions [3, 4]. Contemporary emission reducing technologies can be broadly classified into diesel exhaust after-treatment technologies and in-cylinder technologies which include the concepts of homogeneous charge compression ignition (HCCI) and partially premixed charge compression ignition [2, 5–9].

In diesel homogeneous charge compression ignition, typically, an early multiple injection strategy is utilized which enables an overall lean premixed air-fuel charge, characterized by simultaneously low NO_x and soot emissions [10]. Low soot is enabled due to the premixed homogeneous charge, while the NO_x are minimized due to the low flame temperatures of the lean mixture. However, with the multiple early injection HCCI strategy, the combustion phasing is more dependent on chemical kinetics of the cylinder charge than on the fuel injection timing and is thus more difficult to control [10]. Also, HCCI combustion is typically restricted to low and medium level loads due to combustion instability at higher loads [10].

An alternative to HCCI for achieving low in-cylinder soot and NO_x is partially premixed charge compression ignition. In PCCI, only a part of the fuel is premixed, while the rest undergoes typical diesel combustion [8]. The partial premixing can be achieved by a pilot injection coupled with a main injection close to top dead center. In addition, the use of moderate exhaust gas recirculation (EGR) enables prolonged ignition delay for the main fuel injection, allowing extra time for the injected fuel to mix more homogeneously with the air. Since most of the fuel is injected during the main injection close to TDC, the combustion phasing is usually easier to control than with HCCI combustion [8]. The combustion phasing is typically controllable via main injection timing despite the prolonged ignition delay due to the use of moderate EGR. With partial premixing, PCCI combustion typically achieves lower soot emissions than conventional diesel high temperature combustion. Soot can also be reduced through soot oxidation by the application of a postinjection. The use of moderate EGR levels also reduces the in-cylinder oxygen availability and peak flame temperatures which enable lower NO_x emissions [8]. Thus, compared to HTC, PCCI has a longer ignition delay which allows for partial premixing of the fuel and air and in the present study this was achieved through higher EGR application.

PCCI studies without a pilot injection, henceforth referred to as late PCCI, have also been done [7]. Without a premixed pilot injection, the soot reduction is more dependent on partial premixing through moderate to heavy EGR and on soot oxidation through a postinjection. One of the objectives of the present study was to investigate the impacts of late PCCI postinjection timing on exhaust emissions.

The use of PCCI also has its limitations. At loads above 10 bar, PCCI application can suffer from high soot levels [8]. Since it is not a truly homogeneous combustion, it is possible to produce high smoke values, above 2.5 filter smoke number (FSN), which can be considered as exceeding the suitable threshold in terms of after-treatment [10]. However, the use of diesel after-treatment devices in combination with PCCI has the potential for achieving ultra-low NO_x and PM emissions at all load levels. PCCI has the potential to reduce NO_x and soot emissions coming out of the engine; thus providing less work for the after-treatment devices and potentially enabling reduced after-treatment costs. After-treatment could then be used to further reduce engine-out emissions before they are released to the environment and to reduce the emissions at high loads where PCCI techniques might not be applicable. Therefore, it is of some significance to explore strategies for extending the range of PCCI application to higher loads and for conditioning the engine-out exhaust to conditions favourable for exhaust gas after-treatment applications.

Previous work [11] has shown the potential of the use of postinjection, applied in conventional high temperature combustion conditions, to increase the exhaust gas temperature and to produce additional power. Thus, engine tests were conducted to investigate the ability of postinjection, applied with late PCCI combustion, to produce additional power and to create exhaust conditions favourable for diesel after-treatment. Favourable exhaust conditions include exhaust gas temperatures in the range of 400°C, increased hydrogen (H_2) content, and the ability to produce periodically hydrocarbon rich exhaust. The hydrocarbon rich exhaust is periodically needed for diesel particulate trap (DPF) and lean NO_x trap (LNT) regeneration [12, 13]. It could also be beneficial to have a fuel-rich exhaust for the use of exhaust fuel reforming devices [14]. It has been claimed by previous studies [12, 15] that LNTs typically show peak NO_x conversion efficiency around specific exhaust gas temperatures, usually at around 400°C and that the conversion efficiency can dramatically drop as the temperature decreases below this value. Several studies [16–18] have also shown that hydrogen presence improves the desulfation and NO_x conversion performance of NO_x after-treatment devices. Additional preferable exhaust conditions include low NO_x and PM levels to reduce the regeneration frequency and thus the supplemental energy requirements of the after-treatment devices.

Table 1: Research Engine Specifications.

Engine type	Diesel four-stroke direct injection
Displacement (dm^3)	0.767
Bore × stroke (mm)	96 × 106
Compression ratio	14.3 : 1
Fuel injection system	Common rail
Peak injection pressure (MPa)	∼180
Peak cylinder pressure (MPa)	∼20

2. Experimental Setup

The postinjection tests were carried out on a modern single cylinder research engine which was coupled to a DC dynamometer at the Clean Diesel Engine Laboratory at the University of Windsor. The engine specifications and geometry are given in Table 1, and the overall system setup is shown in Figure 1. The testing conditions are presented in Table 2.

This system allowed for both naturally aspirated and simulated boost intake conditions. Clean and dry intake air was provided by a compressor and the intake pressure was precisely controlled by a series of pressure regulators to simulate boost. The exhaust backpressure was controlled through a valve mechanism that could restrict the exhaust flow rate and build up the backpressure. The intake and exhaust systems were independent of each other so that the boost and exhaust backpressures could be controlled separately. An air mass flow meter was placed upstream of the intake surge tank, while cooled EGR was introduced downstream of the tank. The EGR was normally cooled with engine coolant, but there was an existing alternate EGR loop which could utilize other fluids, such as city water, for additional cooling. The EGR ratio was controlled through a combination of EGR valve position and exhaust backpressure control. In-house LabVIEW codes were developed to establish CAN bus communication to the EGR valve and for data acquisition.

In-cylinder pressure measurements were obtained from a pressure transducer connected to a Kistler 5101B charge amplifier. The pressure at each crank angle (CA) was recorded as an average of 200 consecutive cycles. An encoder with a 0.1°CA resolution was utilized to obtain the engine

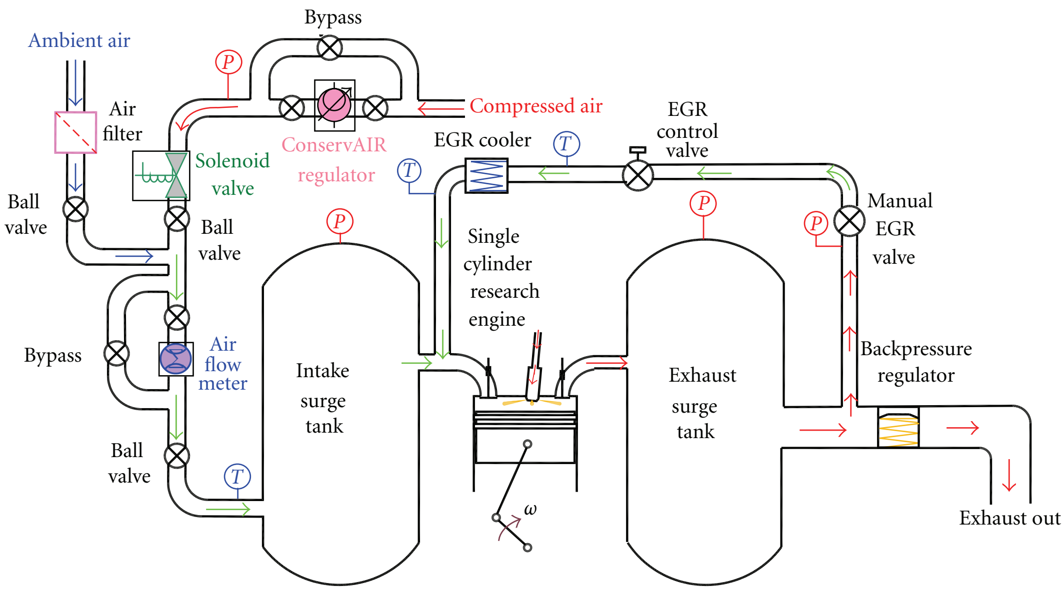

Figure 1: Schematic diagram of the experimental setup at the clean diesel engine laboratory.

Table 2: Testing conditions.

Type of test	Late postinjection PCCI	Late postinjection HTC	Late postinjection H_2 reforming	Early postinjection power production	
Engine speed (rpm)	1200	1200	1200	1200	1200
Baseline IMEP (bar)	8	8	8	8	8
Average lambda	1.46	1.40	1.17	1.19–1.62	1.46–1.66
EGR (%)	~42	~25	~45	~47	~47
Intake pressure (bar abs)	1.75	1.50	1.50	2.00	2.50
P_{inj} (bar)	1200	1200	1200	1200	1200
Duration_{main} (μs)	520	540	530	510	510
Timing_{main} (°CA)	355	356	354	355	355
Duration_{post} (μs)	250	250	200	200–350	200–250
Timing_{post} (°CA)	390–420	390–420	390–420	385	385

position. The injection pressure and scheduling were tightly controlled through a pair of embedded real-time (RT) controllers and field programmable gate array (FPGA) devices. EFS IPoD piezo injector drivers were utilized for energizing the injectors. The intake and exhaust gas measurements were obtained from a dual-bank emissions bench. One bank was utilized for measuring the intake oxygen (O_2) and carbon dioxide (CO_2) and the other bank was used for measuring the exhaust oxygen, carbon dioxide, carbon monoxide, unburned hydrocarbons, and oxides of nitrogen. An AVL 415S smoke meter was used to measure the filter smoke number in order to characterize the soot emissions. A V&F H-Sense analyzer was utilized to measure the exhaust hydrogen content.

3. Emission Comparison of Late PCCI and HTC Postinjection

Preliminary tests were conducted to determine the strategy for the late PCCI investigation. The results showed similar trends to what was concluded in previous work [11]; namely, that an early postinjection event was more beneficial for producing power while a late postinjection event was more beneficial for exhaust gas conditioning. Based on these findings, subsequent tests investigated the effects of late postinjection with PCCI regimes on exhaust gas conditioning and attempts were made to compare these results to those obtained for postinjection with HTC regimes with low EGR.

Figure 2 shows the heat release rate curves for the late PCCI regime tests with and without postinjection. From these curves, it was easy to identify the postinjection curves due to the additional heat release of the postinjection for the cases of 390°CA, 400°CA, and 410°CA. However, it was noticed that as the postinjection timing was delayed, the ignition delay of the postinjection increased and the heat release rate from the postinjection decreased. This was most obvious at a postinjection at 420°CA, where a distinctive postinjection heat release arc was not observed. This could be attributed to the reduced in-cylinder temperature at late postinjection timings. Since at 420°CA a heat release arc

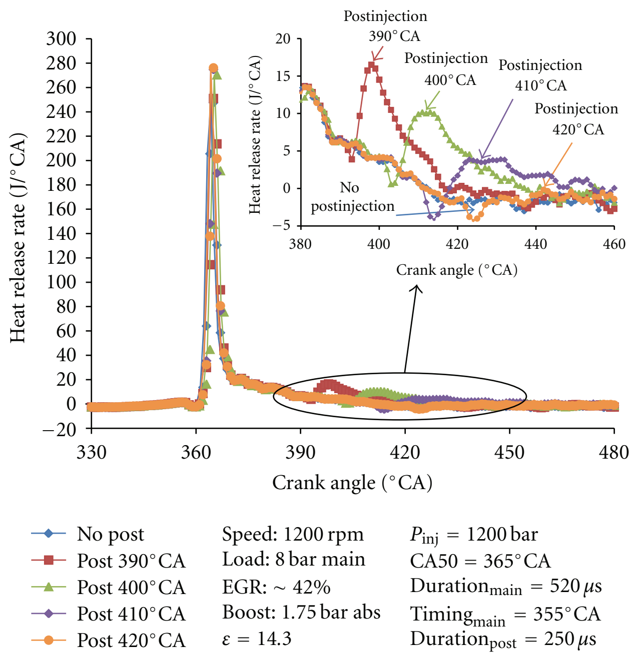

FIGURE 2: Heat release-rate for postinjection with late PCCI.

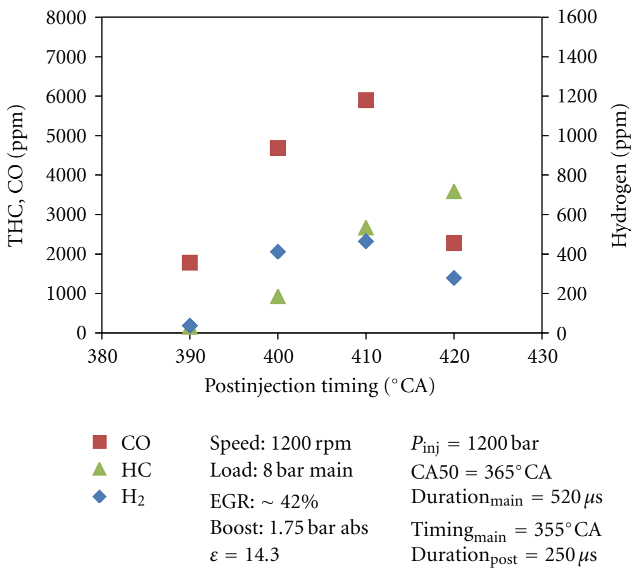

FIGURE 3: Effect of postinjection timing on THC, CO, and hydrogen exhaust content with late PCCI.

was not observed, it was hypothesized that most of the postinjected fuel did not oxidize but was simply released into the exhaust. Thus, high hydrocarbon readings were expected.

Comparing the results from postinjection application with late PCCI, shown in Figure 3, to those obtained for postinjection with HTC, shown in Figure 4, it was observed that with late PCCI the CO and THC emissions were typically higher. Even with slightly higher boost pressure, PCCI still produced higher CO and THC. While higher

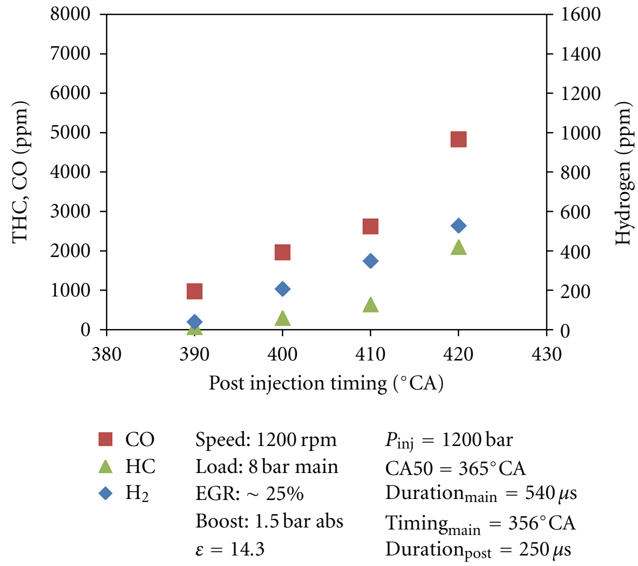

FIGURE 4: Effect of postinjection timing on THC, CO, and hydrogen exhaust content with HTC.

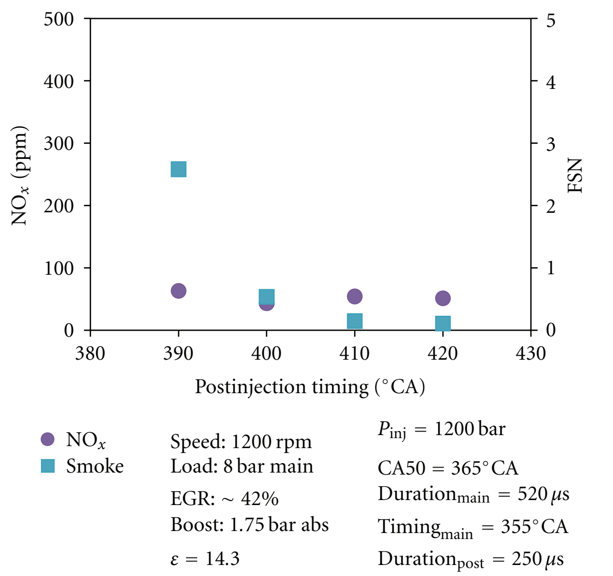

FIGURE 5: Effect of postinjection timing on NO_x and smoke exhaust content with late PCCI.

THC and CO emissions could have benefits for diesel after-treatment, such as for fuel-reforming and after-treatment regeneration, it should be noted that extremely high levels of THC could be an indicator of poor fuel efficiency and could also be dangerous for after-treatment equipment because of the potential for the hydrocarbons to ignite and cause dangerously high temperatures in excess of 1200°C. Continuous temperature at this level could cause physical damage to the after-treatment equipment [12, 13, 19].

Examining the NO_x and smoke emissions, shown in Figures 5 and 6, similar trends were noticed. The NO_x emissions seemed to be independent of the late postinjection

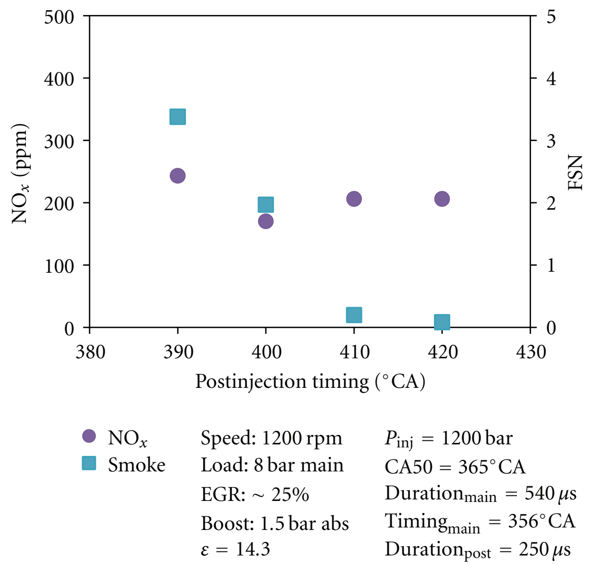

Figure 6: Effect of postinjection timing on NO_x and smoke exhaust content with HTC.

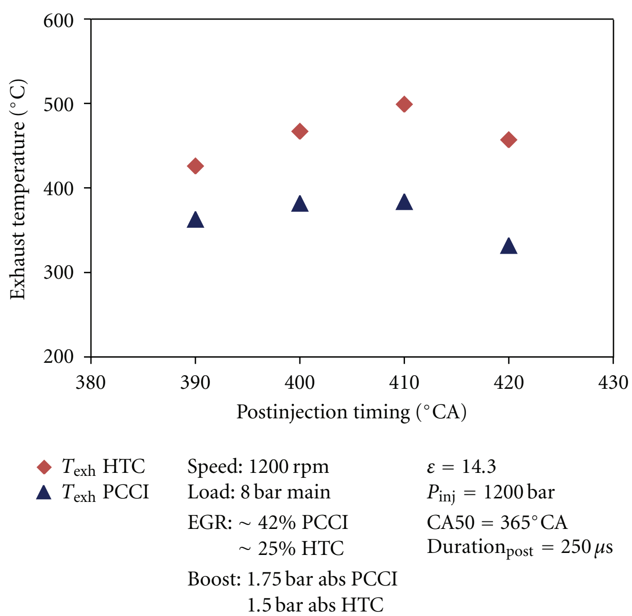

Figure 7: Effect of postinjection timing on the exhaust temperature with late PCCI and HTC.

timing while the smoke number appeared to decrease. However, as is typical of PCCI regimes, the postinjections with late PCCI produced lower NO_x and smoke levels compared to the HTC tests. Although the average lambda for the late PCCI tests was slightly higher than that for the HTC tests (Table 2), this difference was mostly due to the postinjections at 410°CA and 420°CA at which the lambda for the PCCI tests was higher by a value of about 0.1 than that for the HTC tests. Furthermore, the lambda for the HTC test with postinjection at 390°CA was higher than that for the PCCI test but the PCCI test still produced lower smoke

Table 3: Baseline results without postinjection.

Load (bar)	8.14
H_2 (ppm)	0
CO (ppm)	881
THC (ppm)	103
Smoke (FSN)	0.104
NO_x (ppm)	130
Exhaust temperature (°C)	324

emissions. Thus, the lower smoke emissions at 390°CA and 400°CA of the PCCI tests should not be attributed to a difference in air-to-fuel ratio but to the improved air-fuel mixing of PCCI regimes. The lower NO_x and smoke which are characteristic of PCCI regimes could be viewed as a potential benefit from a diesel after-treatment point of view, because the lower NO_x and smoke would reduce the work load of their respective after-treatment devices.

These potential benefits do seem to be accompanied by a penalty in exhaust gas temperature. The effects of late postinjection on the exhaust gas temperature are shown in Figure 7. Similar trends were observed with peak exhaust temperature occurring at the same postinjection crank angle. However, the HTC peak exhaust temperature was about 100°C higher than the peak exhaust temperature for late PCCI. Postinjection with HTC regimes seemed to be more effective in raising the exhaust gas temperature compared to the case without postinjection. For HTC without postinjection, the exhaust gas temperature was about 365°C. From Figure 7, the ability of the postinjection to raise the HTC exhaust gas temperature was obvious with the peak temperature nearing 500°C. This was a significant increase over the 365°C baseline. Conversely, the PCCI postinjection was not able to raise the exhaust gas temperature more than 60°C compared to the main injection baseline test. Thus, the ability of the postinjection to raise the exhaust gas temperature appeared to be diminished when used with late PCCI regimes compared to HTC regimes. The lower exhaust gas temperatures for PCCI could have a negative effect on the performance of the exhaust after-treatment where higher temperatures might be needed.

4. The Influence of Postinjection Timing with Late PCCI Regimes on Emissions

The effects of postinjection timing with PCCI regimes were investigated. Figure 3 shows the effects of postinjection timing on THC, CO, and hydrogen exhaust gas content. It was observed that as the postinjection timing was delayed from 390°CA to 420°CA, the THC and CO emissions and the hydrogen content generally increased. The postinjection at 420°CA showed decreasing CO and hydrogen content; however, the evidence was not conclusive enough to confirm this trend since other tests showed constant or slightly increasing levels of CO and H_2. Comparing the postinjection results with the baseline data when no postinjection was utilized, shown in Table 3, it was concluded that the additional fuel supplied during the expansion cycle by the postinjection was responsible for the increased THC and CO emissions. With late postinjection, the fuel is injected when the cylinder temperature has started to decrease and the oxygen content has been reduced due to the main combustion. This could have potentially lead to the production of incomplete combustion products from the postinjection.

Figure 5 shows the effects of postinjection timing on NO_x and smoke. Here, it was noted that the NO_x seemed to be unaffected by the postinjection timing, staying at a nearly constant value of about 50 ppm. A possible reason for the apparently constant NO_x emissions could be that the in-cylinder temperature at the time of postinjection combustion was not high enough to produce NO_x. Conversely, the smoke emissions were significantly reduced as the postinjection timing was moved further away from top dead centre although initially the smoke emissions did increase compared to the baseline (Table 3) with the peak observed at 390°CA. The higher smoke of earlier postinjections compared to the baseline was attributed to the additional postinjected fuel being introduced into an oxygen reduced atmosphere, due to the consumption of oxygen from the main combustion, and the higher temperatures compared to later postinjection. Thus, with early postinjection, the reduced oxygen level was responsible for a reduced soot oxidation rate but the temperature seemed to be still high enough for soot formation to occur. As the postinjection was delayed, the in-cylinder temperature correspondingly decreased so that the postinjected fuel was injected into a lower temperature atmosphere. Therefore, with delayed postinjection, the oxygen content was still low, leading to low soot oxidation, but the temperatures seemed to have been reduced enough so that soot formation was restricted as well. Also, as the postinjection was delayed, the ignition delay for the postinjection became longer (Figure 2) allowing for better air-fuel mixing, and thus reduced smoke emissions.

The late postinjection effect on smoke has been previously explored by other authors [20–22], where it was concluded that smoke was reduced due to the increased soot oxidation during the expansion stroke. The increased soot oxidation was attributed to several factors. Yun and Reitz [21] attributed the reduction in soot to improved late cycle air-fuel mixing caused by the introduction of the postinjection into the combustion chamber. Other authors [22, 23] have claimed that the final soot reduction was due to the higher late cycle temperatures compared to the case without postinjection. However, there was not enough evidence from the current results to adopt these conclusions.

5. Ability of Postinjection with Late PCCI Regimes for Hydrogen Production

The use of postinjection seemed to enable noticeable hydrogen production. Without postinjection, see Table 3, 0 ppm of hydrogen was measured but up to 460 ppm of hydrogen was produced with the use of postinjection, as shown in Figure 3. This could be attributed to the fact that the postinjection fuel was supplied to the cylinder once the oxygen content was already depleted by the main combustion. With reduced oxygen, the postinjected fuel was more likely to undergo hydrogen producing reactions such as partial oxidation, shown below. It was intriguing that the pattern of CO emissions and H_2 exhaust content was very well correlated, with the R^2 value exceeding 0.85 in the majority of the tests. This appeared to indicate that the in-cylinder hydrogen production could be attributed to mechanisms that simultaneously produce both CO and H_2 such as partial oxidation and steam reforming

$$\text{Steam Reforming} \quad C_\alpha H_\beta + \alpha H_2O \longrightarrow \alpha CO + \left(\alpha + \frac{\beta}{2}\right) H_2, \tag{1}$$

$$\text{Partial Oxidation} \quad C_\alpha H_\beta + \frac{\alpha}{2} O_2 \longrightarrow \alpha CO + \frac{\beta}{2} H_2. \tag{2}$$

The ability to produce hydrogen inside the cylinder would be a very beneficial characteristic in terms of exhaust after-treatment. Studies [16–18] have shown that the presence of hydrogen content within diesel exhaust could provide very beneficial effects for de-NO_x after-treatment devices. Thus, further tests were carried out in an attempt to produce higher hydrogen levels through postinjection with late PCCI. These tests were carried out at a similar EGR level, approximately 45%, but with a slightly reduced boost pressure, 1.5 bar absolute, in order to decrease the overall air-to-fuel ratio. Additionally, the postinjection quantity was also adjusted in order to reduce the overall excess air-to-fuel ratio from about 1.46 to about 1.17. The results are shown in Figures 8 and 9. Reducing the overall air-to-fuel ratio seemed to promote hydrogen production, as shown in Figure 8. With the reduced air-to-fuel ratio, hydrogen content increased from about 460 ppm to about 1560 ppm. However, the increased hydrogen production was accompanied by a penalty in increased THC and CO emissions. The CO emissions were again very well correlated with the H_2, with the R^2 value over 0.85. The THC and CO emission increase was attributed to the observation that with reduced air-to-fuel ratios, oxidation of the postinjected fuel appeared to deteriorate, leading to an increase in incomplete combustion products. With the reduced air-to-fuel ratio, the exhaust oxygen content was also reduced to about 3.5% from about 7.5%. Low exhaust oxygen along with increased CO and THC emissions could be beneficial for downstream fuel reforming, which could further increase the exhaust hydrogen content.

The NO_x emissions did not seem to be affected by the reduced air-to-fuel ratio, staying below 50 ppm throughout these tests. On the other hand, a noticeable increase in smoke was observed as shown in Figure 9. With 390°CA postinjection, the peak smoke number increased from 2.5 to about 3.0 FSN. Moreover, as the postinjection was delayed from TDC, with a higher air-to-fuel ratio the smoke dropped to below 0.5 FSN (Figure 5) but when the air-to-fuel ratio was reduced, the smoke stabilized at about 2.0 FSN (Figure 9). The higher FSN was attributed to two conditions. Due to the reduced air-to-fuel ratio, the main combustion generated higher smoke and due to the lower oxygen content available

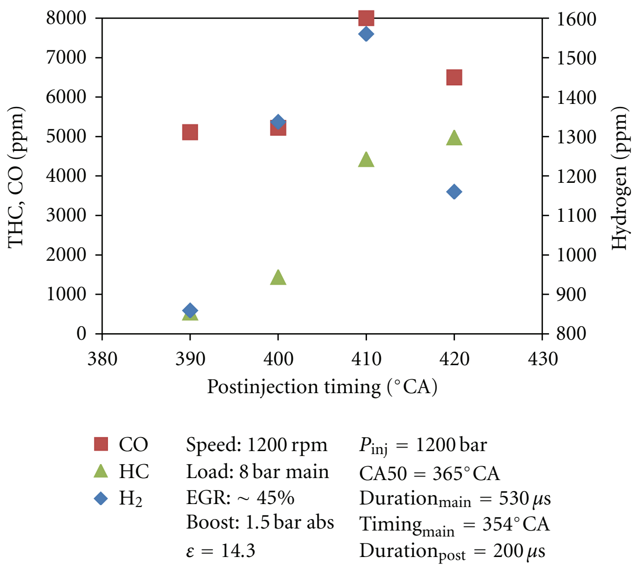

FIGURE 8: Effect of postinjection timing on THC, CO, and hydrogen exhaust content with late PCCI and a reduced air-to-fuel ratio.

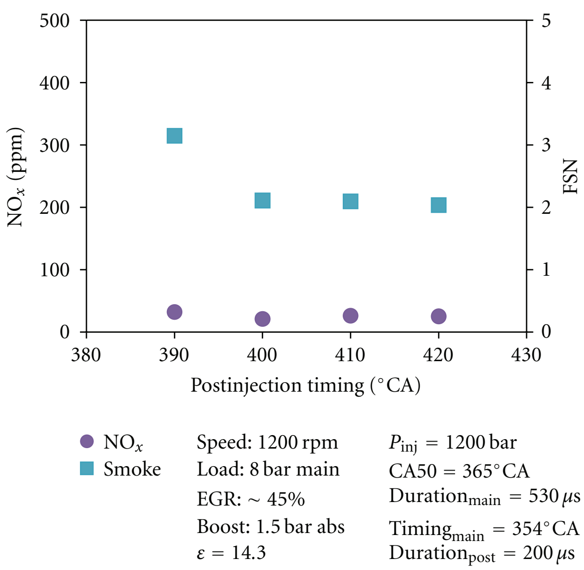

FIGURE 9: Effect of postinjection timing on NO_x and smoke exhaust content with late PCCI and a reduced air-to-fuel ratio.

at the time of postinjection, the soot oxidation of the post seemed to be reduced. This hypothesis was supported by the observed reduction in the measured exhaust oxygen content. The exhaust gas temperature was also slightly, but not significantly, higher when the air-to-fuel ratio was closer to stoichiometric. With and without postinjection, the exhaust gas temperature appeared to fluctuate around 400°C, a temperature suitable for exhaust gas after-treatment but not near the levels achieved with HTC regimes.

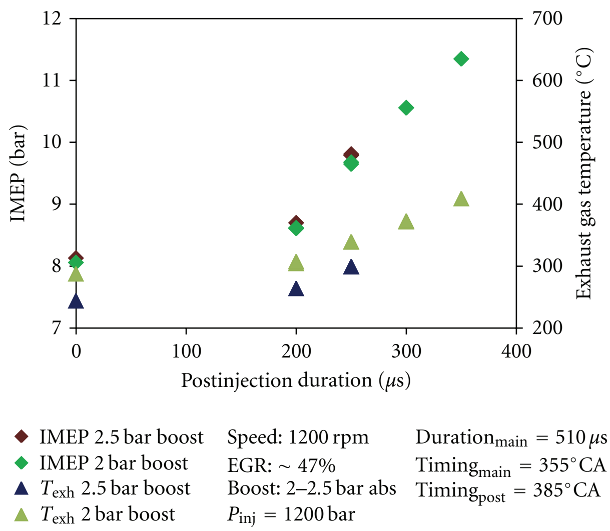

FIGURE 10: Early postinjection power generation with late PCCI.

6. Postinjection Power Production with Late PCCI

Power production from early postinjection was studied and the results are shown in Figure 10. In this test, the main injection duration and timing were kept constant so as to produce a constant 8 bar indicated mean effective pressure (IMEP) from the main injection. The EGR was kept at around 47%. Subsequently, an early postinjection was added at 385°CA. The postinjection duration was then continually increased to determine the capability of the postinjection for power production. From the data presented in Figure 10, it was observed that an early postinjection was able to generate up to an additional 3 bar load in PCCI conditions. The IMEP increase from the early postinjection was more prominent when the postinjection duration was prolonged. From the same figure, it was also observed that as the early postinjection was prolonged, the exhaust gas temperature seemed to increase, a condition favourable for exhaust gas after-treatment.

However, from Figure 11 it was observed that the early postinjection had negative impacts on the engine-out smoke emissions. Without a postinjection, both NO_x and smoke were at tolerably low levels with NO_x at around 50 ppm and smoke at about 0.8 FSN. Once an early postinjection was added, NO_x emissions remained fairly constant but a moderate increase in smoke was observed and as the postinjection duration was prolonged, the smoke emissions continued to increase. Therefore, even though the early postinjection was obviously able to generate power and increase the IMEP, its use was accompanied by an increased smoke penalty. Further tests were performed at a slightly higher boost pressure in an attempt to suppress smoke emission formation. The test results suggested that an increased boost pressure was able to reduce the smoke penalty while retaining the power generation capability of the early postinjection. A disadvantage of the increased boost

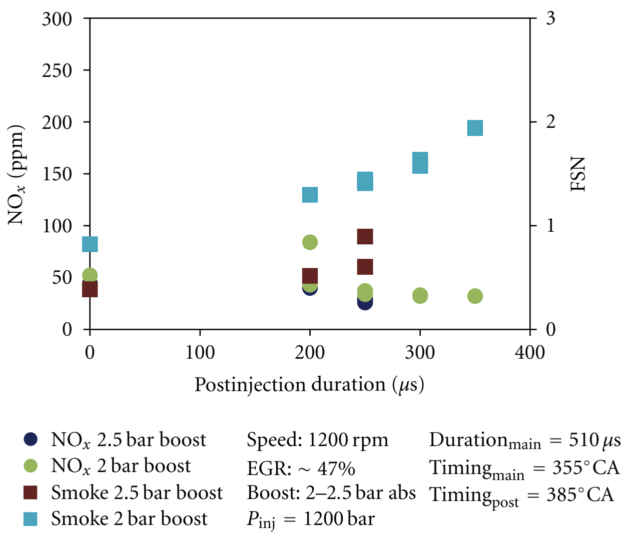

Figure 11: Early postinjection NO_x and smoke emissions with late PCCI.

seemed to be that the exhaust gas temperature was reduced, an unfavourable circumstance in terms of exhaust gas aftertreatment.

7. Conclusions

The effects of postinjection in combination with late PCCI on power generation and exhaust gas conditioning were investigated. The initial tests compared the effects of late postinjection with HTC and late PCCI regimes. From these tests it was observed that postinjection with late PCCI, compared to postinjection with HTC, produced higher THC and CO emissions but lower NO_x and PM emissions, a result completely in agreement with expected PCCI operation. However, it was also observed that the ability of the postinjection to raise the exhaust gas temperature was much weaker with late PCCI compared to HTC. With respect to postinjection scheduling, it was observed that both HTC and late PCCI exhibited similar patterns. The THC and CO emissions tended to increase, the NO_x emissions appeared to remain constant, and the smoke emissions decreased as the postinjection was pushed further away from TDC. This was potentially attributed to low oxygen availability and the decreasing in-cylinder temperatures as the postinjection was delayed. With lower temperatures and low oxygen availability, the fuel oxidation of the late postinjections is expected to be weaker, thus producing more incomplete combustion products such as THC and CO, while the smoke formation due to the postinjection would be decreased due to the lowered temperatures. Oxides of nitrogen appeared to be unaffected by the postinjection timing, and this could be attributed to the low postinjection combustion temperatures which were probably low enough to suppress NO_x formation.

The subsequent tests attempted to explore the ability of postinjection for hydrogen production by reducing the overall air-to-fuel ratio. The results indicated that with a lowered air-to-fuel ratio, hydrogen production increased significantly but at the expense of increased smoke, THC, and CO emissions. These findings were accredited to the reduced oxygen content at the time of postinjection. With reduced oxygen content, hydrogen producing reactions such as partial oxidation and steam reforming tended to be more favoured than with oxygen rich conditions. This conclusion was confirmed by the strong correlation between carbon monoxide and hydrogen, both species being products of the aforementioned reactions.

The final tests investigated the potential for power production of postinjection with late PCCI. It was concluded that an early postinjection was capable of significant power production, increasing the IMEP by as much as an additional 3 bar over the 8 bar baseline. However, it was also observed that with early postinjections, the power production came with an increased smoke penalty. The smoke penalty was partially mitigated by increasing the boost pressure; however, this came at the expense of lowered exhaust gas temperatures, an undesirable characteristic in terms of exhaust gas aftertreatment.

Nomenclature

CA:	Crank angle
CA50:	Crank angle of 50% heat release
CO:	Carbon monoxide
DPF:	Diesel particulate filter
$Duration_{main}$:	Main injection duration
$Duration_{post}$:	Postinjection duration
EGR:	Exhaust gas recirculation
FSN:	Filter smoke number
H_2:	Hydrogen
HCCI:	Homogeneous charge compression ignition
HTC:	High temperature combustion
IMEP:	Indicated mean effective pressure
LNT:	Lean NO_x trap
NO_x:	Oxides of nitrogen
O_2:	Oxygen
PCCI:	Partially premixed charge compression ignition
Pinj:	Injection pressure
PM:	Particulate matter
TDC:	Top dead centre
T_{exh}:	Exhaust gas temperature
THC:	Total unburned hydrocarbons
$Timing_{main}$:	Main injection timing
$Timing_{post}$:	Postinjection timing
abs:	Absolute pressure
ppm:	Parts per million
rpm:	Revolutions per minute
ε:	Compression ratio.

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