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# Fuel Effects on Ion Current in an HCCI Engine

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## ABSTRACT

An interest in measuring ion current in Homogeneous Charge Compression Ignition (HCCI) engines arises when one wants to use a cheaper probe for feedback of the combustion timing than expensive piezo electric pressure transducers. However the location of the ion current probe, in this case a spark plug, is of importance for both signal strength and the crank angle position where the signal is obtained. Different fuels will probably affect the ion current in both signal strength and timing and this is the main interest of this investigation. The measurements were performed on a Scania D12 engine in single cylinder operation and ion current was measured at 7 locations simultaneously. By arranging this setup there was a possibility to investigate if the ion current signals from the different spark plug locations would correlate with the fact that, for this particular engine, the combustion starts at the walls and propagates towards the centre of the combustion chamber. The fuels investigated were isooctane, n-heptane, PRF80, gasoline, diesel, ethanol and methanol. A special interest was how the ion current timing was affected by low temperature reactions, which were present with the n-heptane and diesel fuels as well as mixtures of isooctane and n-heptane, i.e. PRF80. The most interesting results were that ion current is both affected by the ion current probe location in the combustion chamber and the fuel used. Fuels with higher octane number seem to provoke ion current more easily, thus with LTR fuels as n-heptane and diesel ion current was only achieved at richer mixtures. The cycle to cycle variations of ion current increased with leaner mixtures. Ion current was also affected by combustion phasing and engine speed.

## INTRODUCTION

The major advantages with Homogeneous Charge Compression Ignition, HCCI, are high efficiency and low NO<sub>x</sub> emissions [1, 2]. The major drawback is the problem of controlling the ignition timing over a wide load and speed range [3, 4]. Another drawback

compared to the Spark Ignition (SI) engine and the diesel engine is higher emissions of unburned hydrocarbons [5].

Auto-ignition timing in an HCCI engine is influenced by numerous operating parameters such as inlet air temperature, air/fuel ratio and Exhaust Gas Recycling (EGR) rate [6, 7, 8]. Therefore a direct timing sensor is needed in order to control the combustion process. This has been conducted in earlier studies using expensive piezoelectric pressure transducers [3, 6].

In SI engines spark plugs have been used for knock and misfire detection for a long time [9, 10, 11]. The basic principle of ion current sensing is that a voltage is applied over an electrode gap inserted in the combustion chamber. The ion current appears only in a reacting, i.e. burning or very hot charge. This means that the ion current reflects the conditions in the gas volume inside the electrode gap.

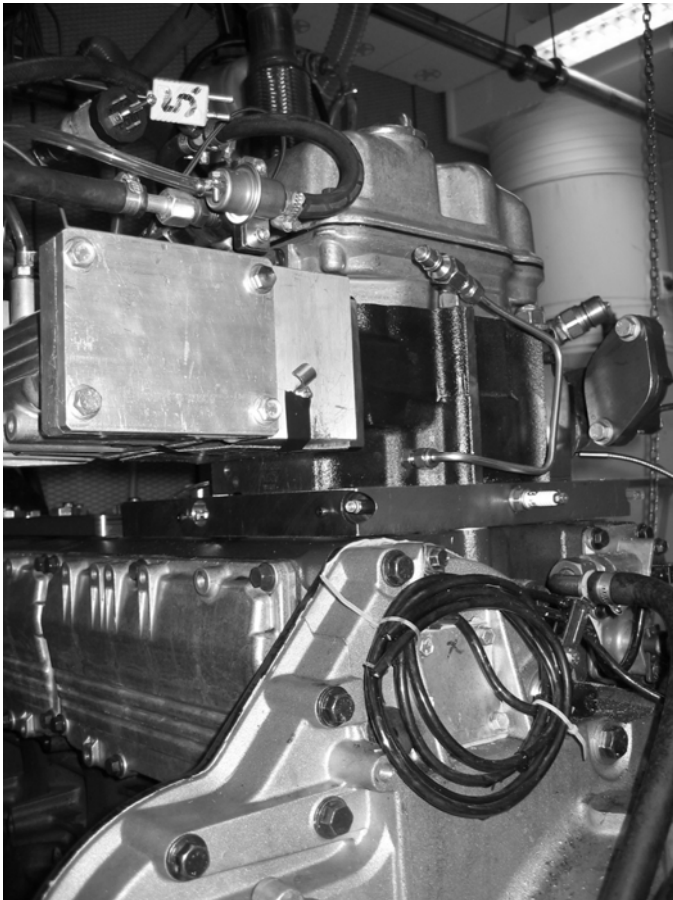
Recent research has revealed that spark plugs can be used as ionization sensors in HCCI engines [9, 12, 13]. They are inexpensive and are appropriate when switching between SI and HCCI combustion. However, the ion current phenomenon in HCCI engines is local in the combustion chamber [9, 12, 13] and is also affected by load. This results in low signal to noise ratios compared to SI engines for isooctane, which was the fuel used in the earlier studies. Therefore an interest arises in this study where the aim is to investigate if ion current can be achieved at lower loads with other fuels and how this would be affected by the ion current probe location inside the combustion chamber. By arranging a setup where multiple ion current sensors are used, there is a possibility to investigate if the ion current signals from the different spark plug locations would correlate with the fact that, for this particular engine, the combustion starts at the walls and propagates towards the centre of the combustion chamber [14]. In SI engines the ion current signal strength is not very dependent on the spark plug location. However, if the spark plug is placed near the centre of the combustion chamber and

good cylinder swirl is present, signal quality seems to improve [10].

## EXPERIMENTAL APPARATUS

### ENGINE

A Scania D12 diesel engine was converted to HCCI operation by using port fuel injection. Only cylinder number 6 was operational and the rest of the cylinders were motored. The combustion chamber was of a disc shaped design. A water cooled Kistler pressure transducer, placed in the center of the combustion chamber, was used for in-cylinder pressure capture. A photo of the engine can be seen in Figure 1 and a table containing some vital engine specifications of the Scania D12 are shown in Table 1.

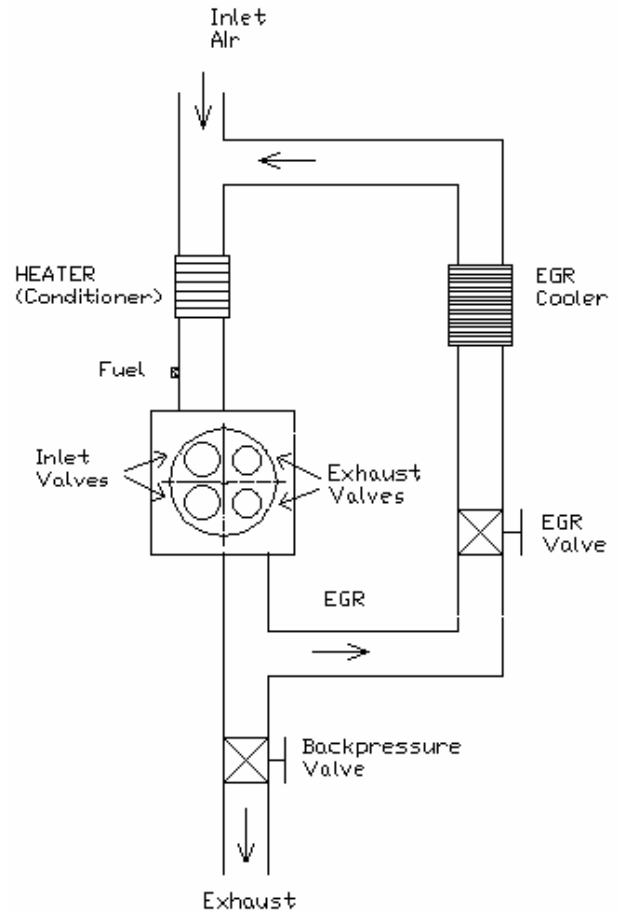


**Figure 1. The modified Scania D12 engine with 3 of the spark plugs visible.**

In order to achieve richer mixtures than  $\lambda$  2.2 dilution with EGR was used. Figure 2 shows the EGR system with cooling. In order to use high EGR rates when having atmospheric pressure conditions in the inlet manifold, the back pressure had to be raised by throttling of the exhaust, thus forcing exhaust gases into the inlet manifold.

**Table 1. Geometric properties of the Scania D12 engine.**

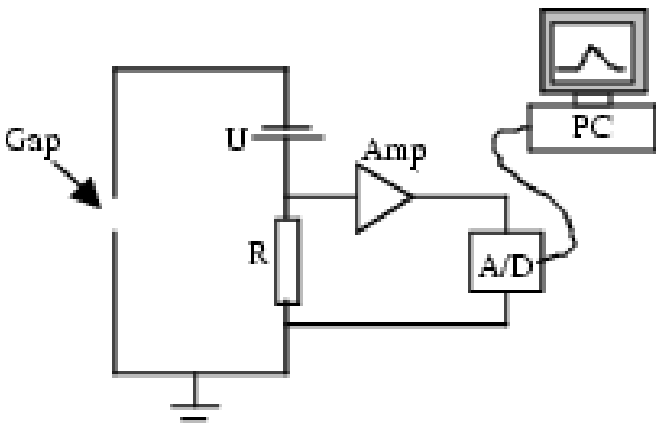
<i>Displaced volume</i>	1966 cc
<i>Stroke</i>	154 mm
<i>Bore</i>	127.5 mm
<i>Connecting Rod</i>	255 mm
<i>Compression ratios</i>	11.5:1, 16.5:1 and 18:1
<i>Number of Valves</i>	4
<i>Exhaust Valve Open</i>	34° BBDC @ 0.15 mm lift
<i>Exhaust Valve Close</i>	6° BTDC @ 0.15 mm lift
<i>Inlet Valve Open</i>	2° BTDC @ 0.15 mm lift
<i>Inlet Valve Close</i>	29° ABDC @ 0.15 mm lift
<i>Valve Lift Exhaust</i>	14.1 mm
<i>Valve Lift Inlet</i>	14.1 mm
<i>Inlet Valve Diameter</i>	45 mm
<i>Exhaust Valve Diameter</i>	41 mm



**Figure 2. The EGR system used for the Scania D12 engine.**

## ION CURRENT SENSING SYSTEM

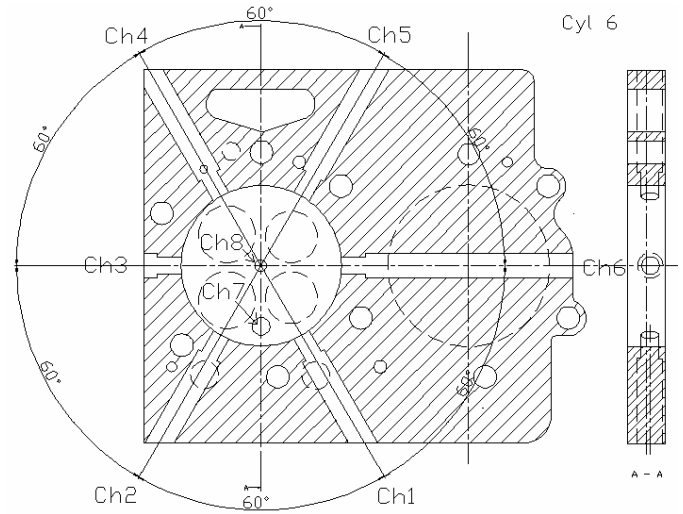
In SI engines ion current measurements are limited by the spark duration, since the actual measurement takes place after ignition [15]. Since auto ignition is used in HCCI engines this limitation does not exist.



**Figure 3. Schematic of the ion current measuring system.**

Figure 3 shows the principal ion current measuring system, used for each ion current measuring position. A DC voltage ( $U$ ) of 85 volts was applied over the spark plug gap. The ion current was measured by measuring the voltage over a resistance of  $100\text{k}\Omega$ , inserted in the electrical circuit. Since the ion current signal is low,  $\mu\text{A}$  or lower, it had to be amplified 11 times (Amp) before it was A/D converted and sampled by the PC. The sampling system consisted of a DAP 5400a/627, which had an individual A/D converter for each of the 8 channels. The system had a theoretical capacity of  $1.2\text{MHz}$ , but during these test a sample frequency of  $30\text{kHz}$  was used.

In a previous study several spark plugs were used in order to monitor the ion current at several locations in the combustion chamber with good results [12]. Strategic placement of the spark plugs throughout the combustion chamber allowed a correct analysis of the local ion current phenomena. In order to measure ion current simultaneously at several locations a spacer was designed which was placed between the engine block and the engine head. This setup allowed 6 spark plugs to be mounted in the spacer and one additional spark plug in the cylinder head. A piezo electric pressure transducer was placed in the centre of the combustion chamber in order to simultaneously measure pressure and ion current. This enabled a comparison between the combustion phasing in terms of Crank Angle of 50% burned fuel (CA50) and the appearance of the ion current signal. The spark plug arrangement in the spacer can be seen in Figure 4.



**Figure 4. Drawing of the spacer with seven ion current measuring positions and one pressure measuring position (ch8). The angular separation between the spark plugs is 60 degrees.**

Modified spark plugs were used as ionization sensors where the side electrodes have been removed in order to measure ion current in a larger gas volume. This modification has resulted in higher signal strength in earlier studies [9, 12]. To ensure that there were no manufacturing defects or variances in the spark plugs themselves, the spark plugs were switched to different locations. The spark plugs used in this study were NGK BCPR5ES.

## FUELS

The fuels used for the experiments and their properties can be seen in table 2. Since the fuels have different auto ignition characteristics three different compression ratios were used in order to be able to run the engine at about the same inlet air temperatures.

**Table 2. Fuel specifications and corresponding Compression Ratios (CR) [16].**

Fuel	Octane or Cetane no.	$T_{Boil} [^{\circ}\text{C}]$	CR
N-heptane	RON0	98.4	11.5:1
Diesel	Cetane54	280 (95%)	11.5:1
Gasoline	RON98	34-213	16.5:1
PRF80	RON80	114.1	16.5:1
Iso-octane	RON100	118	18:1
Ethanol	RON107	78	18:1
Methanol	RON106	65	18:1

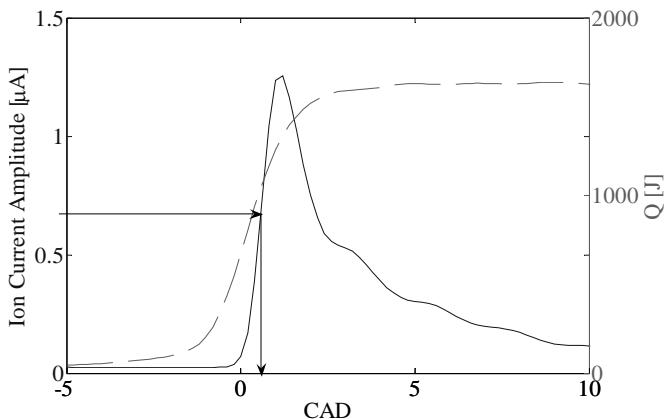
## EXPERIMENTS

The engine was mainly run at 1000 rpm with the dilution of air and/or EGR. Three lambda sweeps were conducted for each fuel; Two of these sweeps were performed by changing the fuel amount with either 0 or 40% EGR. The figures of the 40% EGR case can be found in appendix. In the third lambda sweep the fuel amount was kept constant and the EGR rate was varied between 55 and 0% EGR. CA50 was kept at 1 CAD ATDC for the fuels where Low Temperature Reactions (LTR) was absent in order to achieve a good ion current signal and acceptable combustion efficiency. For the cases with LTR (PRF80, N-heptane and Diesel) CA50 was  $2 \pm 0.5$  CAD BTDC. The combustion phasing was controlled by changing the inlet air temperature. Three different engine speeds were tested for the PRF80 case and an auto ignition timing sweep was conducted for the isoctane case. An overview of the operational parameters can be seen in Table 3.

**Table 3. Operational Parameters.**

Engine Speed	1000 – 1400 rpm
Lambda	1 – 5
Inlet Air Temperature	25 – 200°C
EGR Rates	0 – 55 %
Inlet Air Pressure	1 Bar Absolute
Fuels	Gasoline, Iso-octane, N-heptane, Diesel, Methanol, Ethanol, PRF80

Ion current timing (ION50) is defined as 50% of ion rise (the crank angle where the ion current has risen to half of its full amplitude). An example of an ion current trace and a cumulative heat release trace can be seen in Figure 5. The ION50 is marked with an arrow in the figure.



**Figure 5. Example of an ion current trace (solid line) and a cumulative heat release trace (dotted line).**

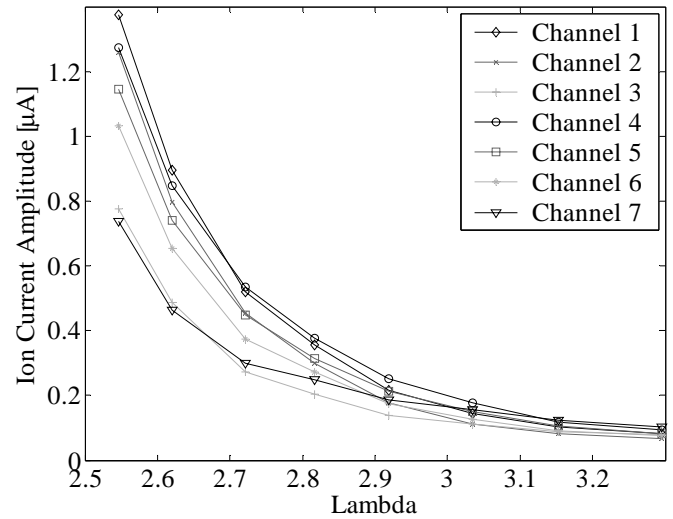
## RESULTS

### DIFFERENCES BETWEEN CHANNELS

#### Ion Current Amplitude

The mean ion current amplitudes for 500 cycles can be seen in Figure 6 for a lambda sweep between 2.55 and 3.30. The engine speed was 1400 rpm and the engine was run with PRF80 as fuel. The amplitude increases as the mixture becomes richer [9, 12].

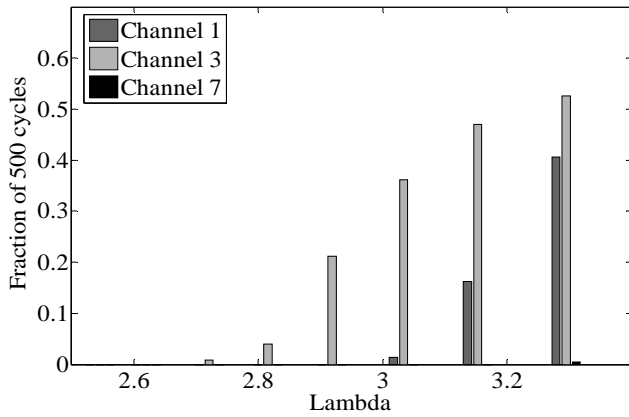
There seems to be a systematic difference in amplitude between the measurement locations. Locations 1 and 4 have the highest amplitude for richer mixtures. Locations 3 and 7 seem to have the lowest amplitudes.



**Figure 6. Ion current amplitudes for a lambda sweep without EGR. Engine speed of 1400 rpm and PRF80.**

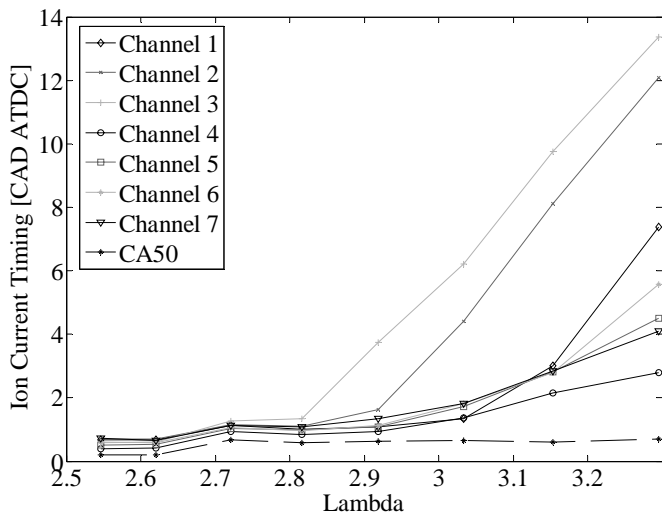
#### Ion Current Timing

When one wants to use ion current for feedback control of the combustion process, the signal to noise ratio is of importance in order to find the ION50. In this study ION50 is calculated for cycles where the signal to noise ratio is at least 1.5. For the lambda sweep in Figure 6 it is of interest how many of the 500 measured cycles for each lambda that fail to fulfill this criterion. This is displayed in Figure 7 for the ion current locations 1, 3 and 7. These locations were chosen since number 7 was placed in the bulk of the combustion chamber and among the locations in the topland volume number 1 had the least amount of inadequate cycles and number 3 had the most amount of inadequate cycles. It is noticed that even if ion current location number 7 had the weakest amplitude in Figure 6 it has the least amount of inadequate cycles for combustion feedback.



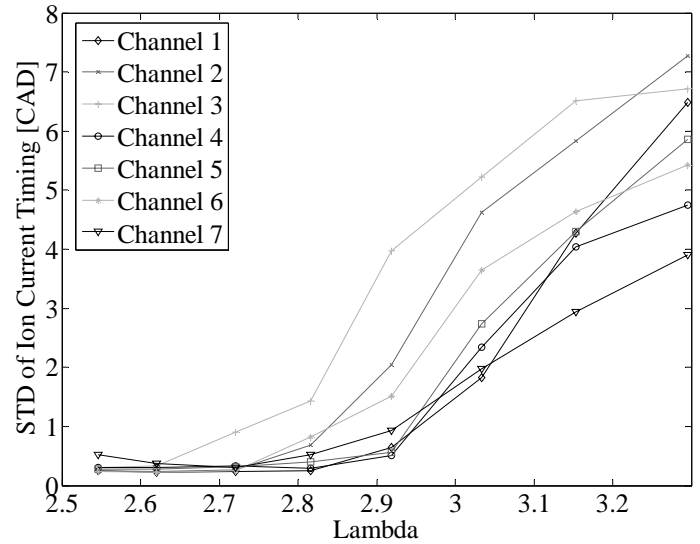
**Figure 7. Fractions of 500 cycles where the signal strength is not adequate for timing calculations.**

In Figure 8 the ION50 is displayed for all 7 channels as function of lambda. CA50 as function of lambda is also present in the figure. One can note that the correlation between ION50 and CA50 is pretty good but when reaching leaner mixtures the signal to noise ratio decreases and thus the signal is not so reliable for combustion phasing feedback. Location number 4 has the best correlation to CA50 even at leaner mixtures. Location number 7 which was placed in the bulk of the combustion chamber have the latest ion current timing at richer mixtures but is among the better locations at the leaner points where the signal to noise ratios are decreasing. Thus it can be concluded that for these test conditions the ion current is appearing a bit later in the bulk of the combustion chamber compared to the locations in topland volume, close to the cylinder walls. This conclusion correlates with the fact that the combustion starts at the walls in this particular engine according to LIF measurements conducted by Anders Hultqvist et. al. [14]. The reason for the differences between different ion current measuring locations is probably inhomogenities or differences in cylinder wall temperature.



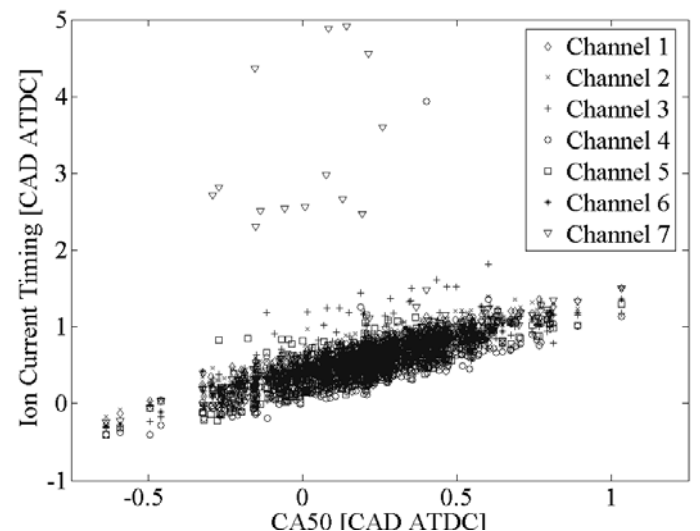
**Figure 8. Ion current timing as function of Lambda. The dotted line is CA50. Engine speed of 1400 rpm and PRF80 as fuel. Mean values of 500 cycles.**

In Figure 9 the standard deviations of the timing information for the lambda sweep in Figure 8 are plotted. As expected the standard deviation of the timing increases with leaner mixtures as the signal to noise ratio decreases.



**Figure 9. Standard deviation of ion current timing as function of lambda for a lambda sweep without EGR.**

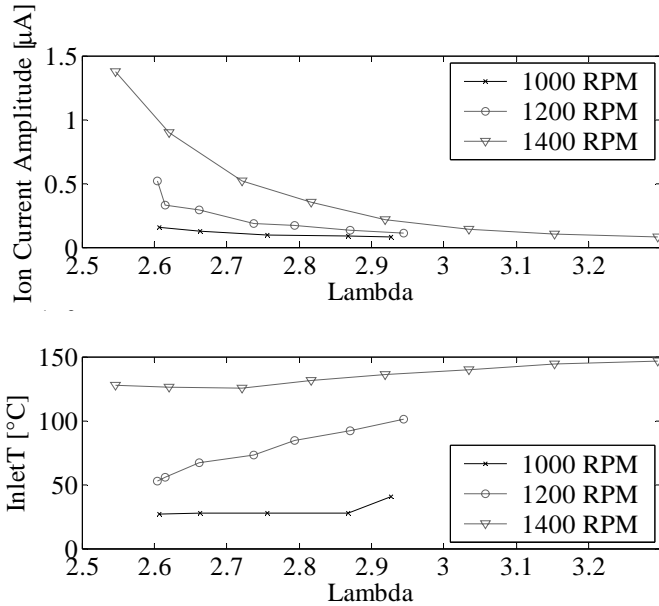
In Figure 10 the richest case of the lambda sweep ( $\lambda$  2.55) is displayed in terms of ION50 as function of CA50 for all 500 cycles. In this case the signal to noise ratio is high and thus the correlation between CA50 and ION50 is adequate. But some cycles measured by ion current location 7 which was placed in the center of the combustion chamber has measured late timing even if the combustion phasing according to the pressure data is within the mean of the 500 cycles. An explanation to this could be inhomogenities with locally leaner mixtures resulting in lower and later heat release at this spark plug location.



**Figure 10. Ion current timing information for 500 cycles as function of CA50. Engine speed of 1400 rpm and PRF80. Lambda was 2.55.**

## THE EFFECT OF ENGINE SPEED

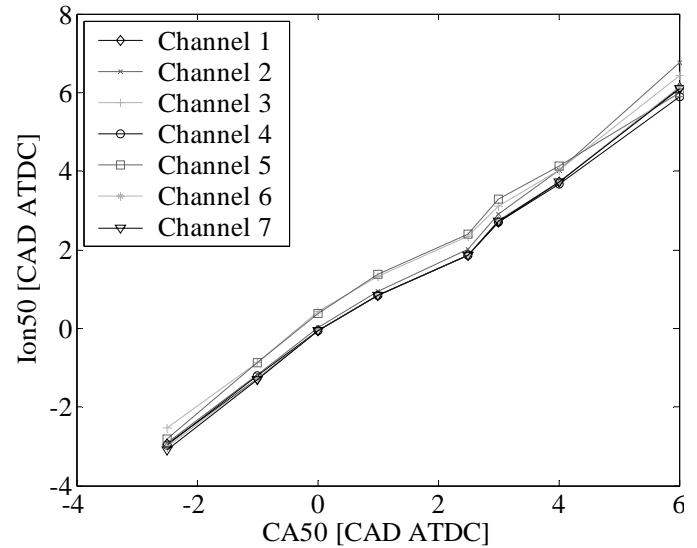
Ion current amplitude and corresponding inlet air temperature can be seen in Figure 11. During the Lambda sweeps the fuel amount was adjusted in order to obtain richer mixtures. In order to keep CA50 at 1 CAD ATDC the inlet air temperature was also adjusted. The fuel used was PRF80. As can be seen the inlet air temperature had to be increased with higher engine speed due to less time for the reactions to take place. When the engine speed increased and thus inlet air temperature the ion current amplitude also increased due to higher peak in-cylinder temperatures.



**Figure 11. Ion current amplitude and inlet air temperature as function of Lambda for 1000, 1200 and 1400rpm. Mean values of 500 cycles.**

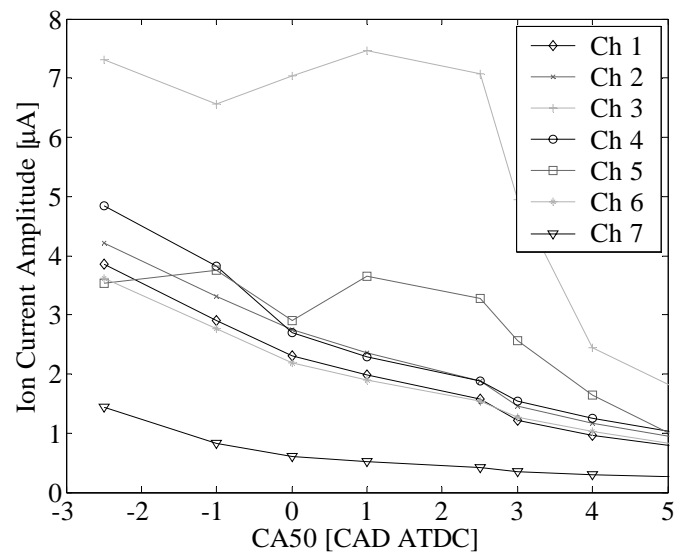
## THE EFFECT OF COMBUSTION PHASING

Figure 12 shows the mean ion current timing for 500 cycles as function of CA50%. The engine speed was 1000 rpm and  $\lambda$  2.5. The amount of fuel (isooctane) was kept constant and the combustion advancement was achieved by increasing the inlet air temperature. As can be seen there is a good correlation between ION50 and CA50. Locations 3 and 5 have later ION50 compared to the other locations .



**Figure 12. Ion current timing information for a combustion phasing sweep. 1000 RPM and  $\lambda$  2.5.**

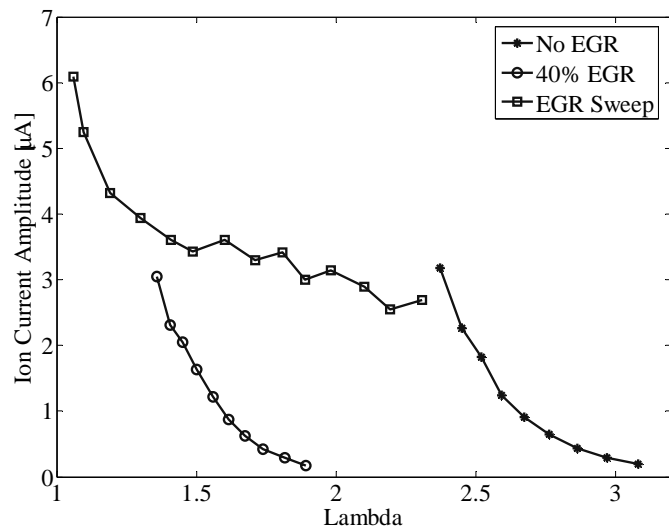
In Figure 13 one can see the corresponding ion current amplitudes for the same combustion phasing sweep as in Figure 12. As can be seen the ion current amplitude increases with earlier combustion phasing due to higher peak in-cylinder temperatures. However other channels have higher ion current amplitudes compared to the case in Figure 6. This is probably due to damaged spark plugs which were a result from heavy knocking combustion. Note that this problem has not affected the ion current timing in Figure 12. One can also note that location number 7 which is inside the bulk of the combustion chamber has low ion current amplitude but still good correlation between ION50 and CA50.



**Figure 13. Ion current amplitudes for a combustion phasing sweep. 1000 RPM and  $\lambda$  2.5.**

## COMPARISONS BETWEEN DIFFERENT FUELS

For the comparison between different fuels three lambda sweeps were conducted for each fuel; Two of these sweeps were performed by changing the fuel amount with either 0 or 40% EGR. The figures of the 40% EGR case can be found in appendix. In the third lambda sweep the fuel amount was kept constant and the EGR rate was varied between 55 and 0% EGR. In Figure 14 ion current amplitudes for location number 4 can be seen for the three different sweeps of either amount of fuel or EGR. As have been seen before the ion current amplitude increases with increased amount fuel. The increment is about the same for both cases of constant EGR rates. For the EGR sweep the ion current amplitude is increasing in a slower rate but is rapidly reaching high levels when moving towards lambda 1.



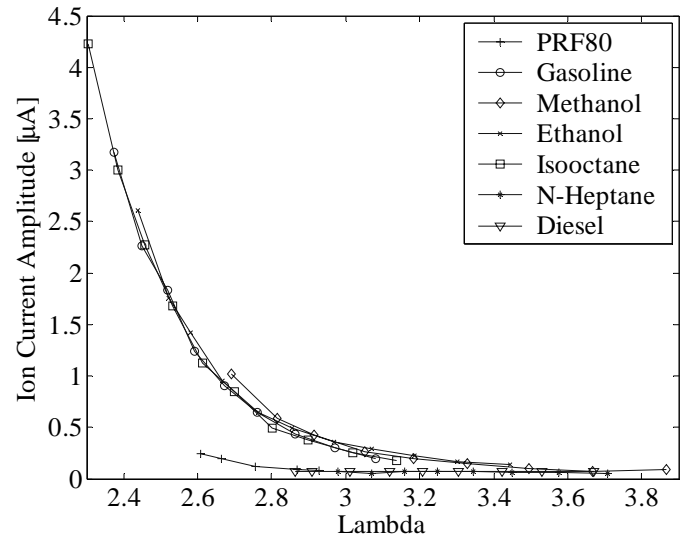
**Figure 14. EGR dependence on ion current amplitude when using gasoline as fuel. The engine speed was 1000 rpm and ion current location displayed is number 4.**

In this section of the paper the EGR sweep and the fuel sweep without EGR will be presented for the effect on ion current amplitude, ion current timing, NOx emissions and in-cylinder temperature.

### Ion Current Amplitude

#### Lambda Sweep without EGR

In Figure 15 ion current amplitudes for location number 4 as function of lambda is plotted for all the different fuels tested. In this lambda sweep no EGR was used and the fuel amount was changed in order to achieve richer mixtures. Meanwhile the inlet air temperature had to be decreased in order to keep CA50 1 CAD ATDC.

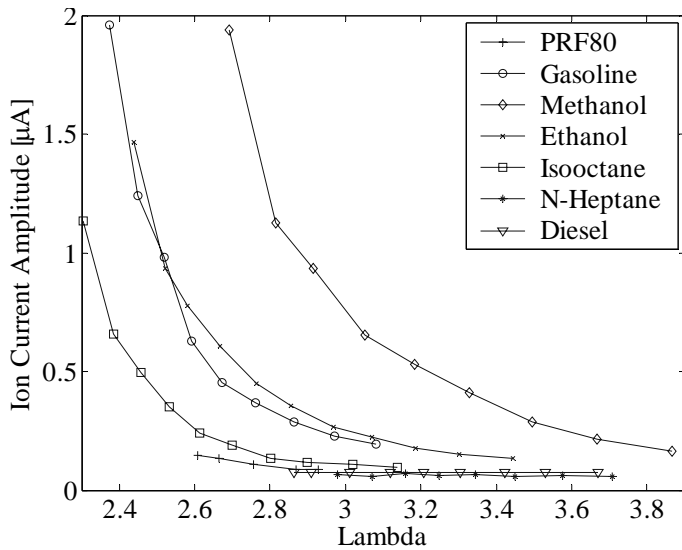


**Figure 15. Ion current amplitude for location number 4 as function of lambda for different fuels.**

The rich running limits for the fuels were due to high pressure derivatives and depending on the fuels different characteristics the load range in terms of lambda overlap between the fuels. Isooctane and gasoline were the fuels that enabled richest mixtures for these conditions and therefore generated the highest amplitudes. The alcohols, ethanol and especially methanol were limited by load at lambda 2.45 and lambda 2.6 respectively. A conclusion is that the non LTR fuels generate about the same ion current amplitudes. For the LTR fuels, PRF80, n-heptane and diesel, low ion current amplitudes were achieved compared to the non LTR fuels due to lower peak in-cylinder temperatures.

However for the ion current probe location number 7 which was placed inside the bulk of the combustion chamber the situation is different. This can be seen in Figure 16. The overall maximum amplitudes are lower but the main differences are between the different fuels. Gasoline and ethanol seem to have about the same conditions and generate about the same amplitudes for the overlap load regime. However methanol seems to provoke higher amplitudes for lower loads and isooctane seem to provoke less ion current for higher loads. The LTR fuels, PRF80, n-heptane and diesel seem to have about the same amplitudes when comparing the locations 4 and 7. An explanation to this behavior between the different locations is inhomogeneties and thus locally richer or leaner mixtures generating higher or lower heat release at the specific locations. Another explanation or a combination with the one above could be locally different cylinder wall temperatures.





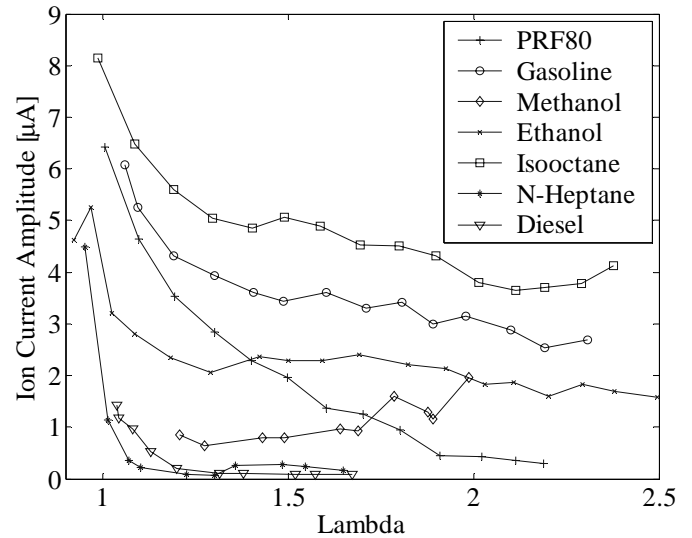
**Figure 16. Ion current amplitude for location number 7 as function of lambda for different fuels.**

#### EGR Sweep with Constant Amount of Fuel

In this lambda sweep the amount of fuel was kept constant and the amount of EGR was increased from 0 to 55% in order to obtain richer mixtures. Meanwhile the inlet air temperature had to be increased in order to maintain the same combustion phasing.

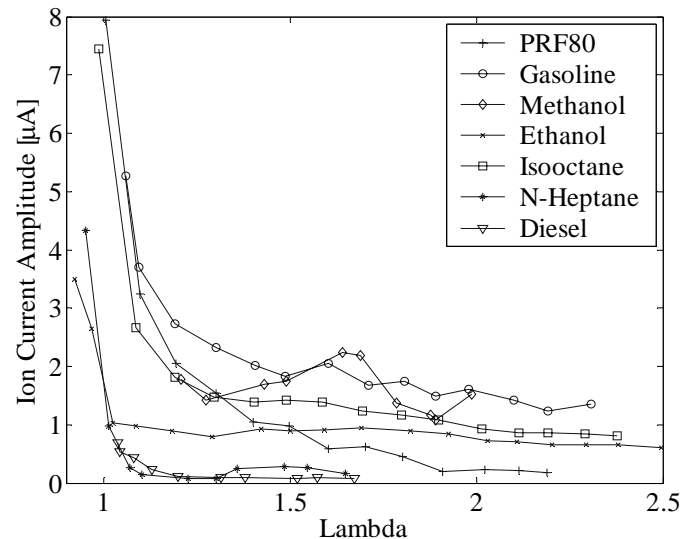
In Figure 17 the ion current amplitudes for location number 4 are displayed. One can note that the amplitude is still dependent on lambda but the differences are not so large when the fuel amount is kept constant in comparison to the cases where the dilution of EGR is kept constant and the fuel amount is changed. Under these conditions there are large differences in amplitude between the fuels tested. For the non LTR fuels the amplitude order from lowest to highest is methanol, ethanol, gasoline and isooctane.

When reaching lambda 1 the LTR fuels seem to improve much regarding ion current amplitude. Especially for PRF80 which reaches almost to the same amplitudes as for the gasoline and isooctane. Diesel doesn't seem to provoke ion current easily but n-heptane seems to achieve higher amplitudes at richer mixtures, especially when moving towards the rich side of stoichiometric. During these rich running conditions with high amounts of EGR the inlet air temperature were in the range of 200 °C and thus the LTR are not present anymore. A conclusion to this behavior is that LTR don't seem to provoke ion current.



**Figure 17. Ion current amplitude for location number 4 as function of lambda for different fuels. EGR rates from 55% at lambda 1 to 0% at lambda 2.5.**

For the case with ion current location number 7 plotted in Figure 18 the difference is not as large as for location number 4 plotted in Figure 17. But the order in which the fuels generate ion current is different. The LTR fuels seem to have about the same behavior as for location number 4 where high amplitudes are achieved at lambda 1. Among the alcohols methanol seems to produce higher amplitudes than ethanol. PRF80, gasoline and isooctane have about the same amplitudes for the richest mixtures but for leaner mixtures gasoline followed by isooctane and PRF80 have the highest amplitudes for the same load conditions. The difference in ion current amplitude depending on measuring location and fuel is probably due to locally different charge or wall temperatures.



**Figure 18. Ion current amplitude for location number 7 as function of lambda for different fuels.**

## Ion Current Timing

### Lambda Sweep without EGR

In Figure 19 and 20 the ION50 is plotted as function of lambda for ion current measuring locations 4 and 7 respectively. CA50 was kept at  $1 \pm 0.5$  CAD ATDC for the fuels without LTR in order to achieve a good ion current signal and acceptable combustion efficiency. For the cases with LTR CA50 was kept at  $2 \pm 0.5$  CAD BTDC. As expected the ION50 correlates well with CA50 as long as the ion current signal to noise ratio is adequate. For gasoline both locations resulted in ION50 timings of 0.5 CAD ATDC even though the signal to noise ratio was low at leaner mixtures. For isooctane the correlation with CA50 is good for the measuring location number 4 but for number 7 ION50 is retarded in the case of leaner mixtures. Regarding the alcohols the correlation between ION50 and CA50 is adequate for the richer mixtures. The LTR fuels generate too weak ion current signals in order to achieve adequate ION50 calculations and thus the ion current timing is late for these cases.

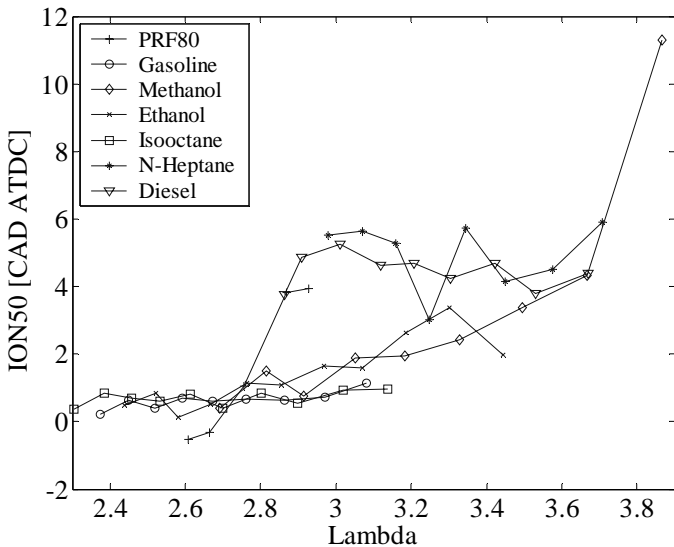


Figure 19. . ION50 at ion probe location 4 as function of lambda for a lambda sweep without EGR.

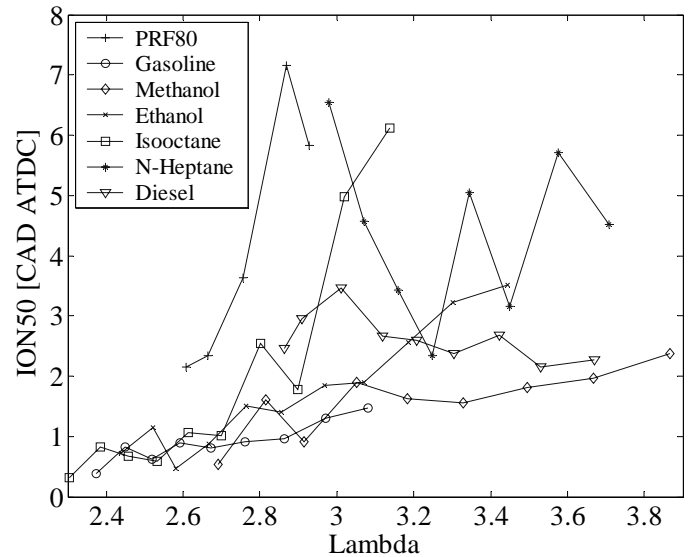


Figure 20. ION50 at ion probe location 7 as function of lambda for a lambda sweep without EGR.

### EGR Sweep with Constant Amount of Fuel

When running the engine with much fuel and changing the EGR rate the ion current signal strength is mainly good. This results in better ion current timing estimations for the fuels with higher octane number. This can be seen in Figure 21 and 22 for the measuring locations number 4 and 7. The ion current for the LTR fuels, diesel and n-heptane, still has inaccurate timing information for the leaner mixtures but for richer mixtures the ION50 is BTDC. Due to the cool flames produced by these fuels the CA50 was  $2 \pm 0.5$  CAD BTDC and the ION50 is still a few CAD off. For the high octane fuels the ION50 is between 0 to 1 CAD ATDC, a good correlation to CA50 which was  $1 \pm 0.5$  CAD ATDC. An exception was the ion current when running on ethanol. For this fuel the ION50 is 1 CAD ahead of CA50.

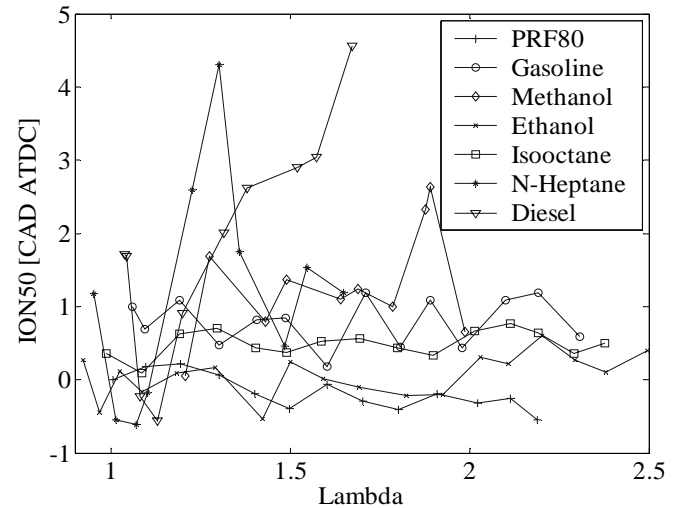
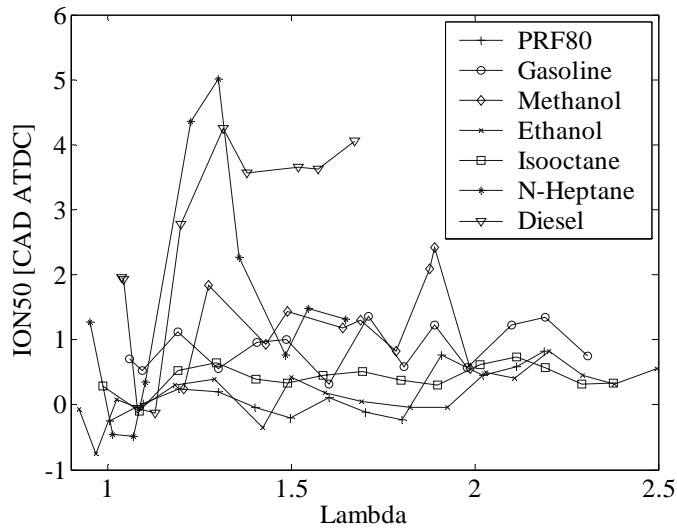


Figure 21. ION50 at ion current probe location 4 as function of lambda for a EGR sweep with constant amount of fuel.

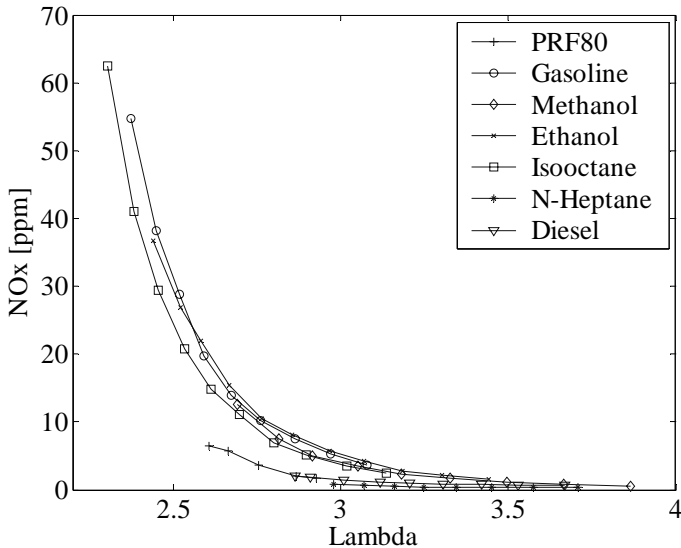


**Figure 22. ION50 at ion current probe location 7 as function of lambda for a EGR sweep with constant amount of fuel.**

NOx Emissions and Peak In-Cylinder Temperature

Lambda Sweep without EGR

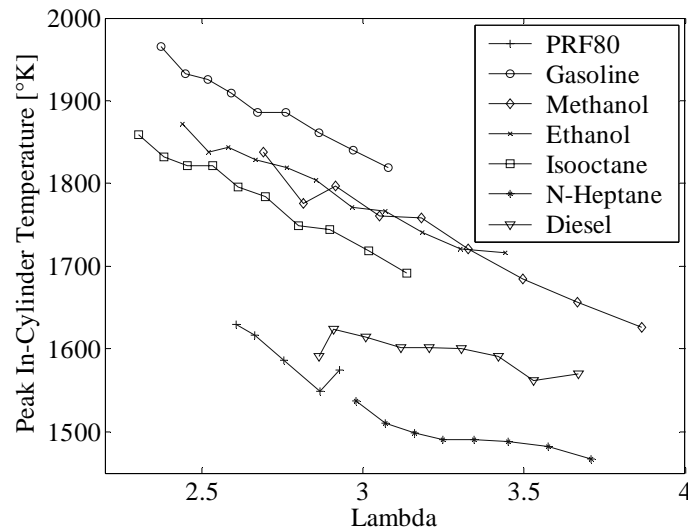
In Figure 23 the NOx emissions are plotted as function of lambda. One can note that the shape of the curves are similar to the ion current amplitudes in Figure 15 and a suspicion could be that it is the maximum in-cylinder temperature that generates both NOx emissions and ion current.



**Figure 23. NOx emissions as function of lambda for a lambda sweep without EGR.**

In Figure 24 the approximate peak in-cylinder temperatures are plotted. As one could expect the fuels with lower octane number including PRF80 have generated lower peak temperatures for the present conditions. Even though the temperatures for the diesel case are in the same range as the PRF80 it has not generated any similar ion current amplitudes or NOx emissions. At lambda 2.6 gasoline followed by ethanol

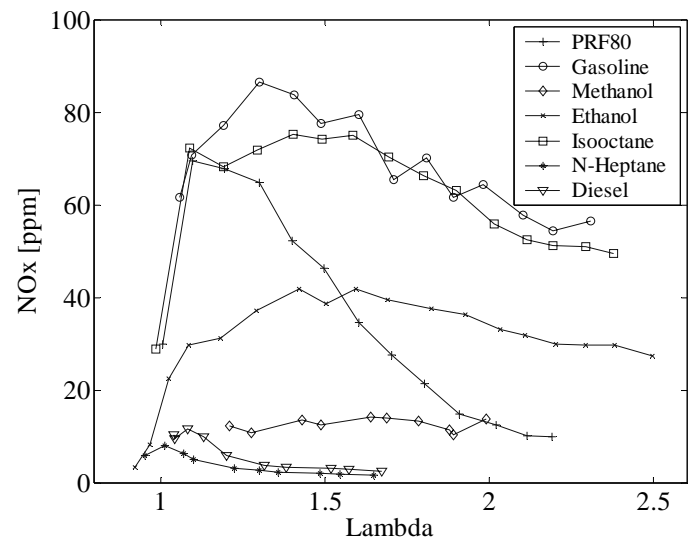
and isooctane have the highest peak temperatures which correlate well with the NOx emissions in Figure 23. This is also the case for the ion current amplitudes at location number 7 in Figure 16. But at lambda 2.5 ethanol has higher ion current amplitudes than gasoline for this measuring location.



**Figure 24. Peak in-cylinder temperature as function of lambda for a lambda sweep without EGR.**

EGR Sweep with Constant Amount of Fuel

The NOx emissions are plotted in Figure 25 as function of lambda. The LTR fuels seem to generate a lower combustion temperature and this results in low NOx emissions. The alcohols, ethanol and methanol, generate less NOx than isooctane, gasoline and PRF80, probably due to the cooling effect of the alcohols. The NOx emissions drop on the rich side of stoichiometric for all the fuels due to the lack of oxygen.

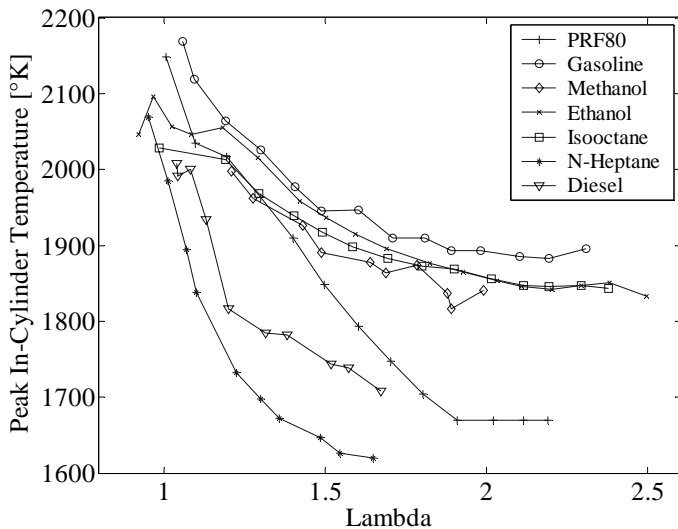


**Figure 25. NOx emissions as function of lambda for a EGR sweep with constant amount of fuel.**

In Figure 26 one can note that the peak in-cylinder temperatures increase above 1900 K when reaching

lambda 1 and also during these conditions the ion current amplitude increases rapidly. For the high octane fuels gasoline followed by ethanol, isooctane methanol and, at richer mixtures PRF80, have the highest peak temperatures. Even though ethanol seems to have high peak temperatures it hasn't produced as high ion current amplitudes as the other fuels in the same temperature range. The explanation to the high ion current amplitudes for PRF80 at rich mixtures can be the rapid increase in peak temperature.

One can also note that when reaching lambda 1 the peak in-cylinder temperature is still rising for all the fuels and that behavior is also seen in the ion current amplitudes but not in the NOx emissions. For these lambda sweeps it has been seen that NOx and ion current are connected by peak in-cylinder temperature but NOx doesn't seem to produce ion current. This has also been seen in another study by O. Stenlås and P. Einewall where ion current were studied with and without NO addition to the intake air in an SI engine [17].



**Figure 26. Peak in-cylinder temperature as function of lambda for a EGR sweep with constant amount of fuel.**

## SUMMARY AND CONCLUSIONS

Ion current was measured at several locations simultaneously for different fuels in an HCCI engine. The fuels tested were isooctane, gasoline, PRF80, methanol, ethanol, n-heptane and diesel. Three lambda sweeps were conducted where 2 of those were conducted by changing the fuel amount at different EGR rates, 0 and 40% EGR. The last lambda sweep was conducted by keeping the fuel amount constant and changing the EGR rate. The effects of combustion phasing and engine speed were also investigated.

1. As concluded in earlier studies [9, 12, 13], the ion current is a local phenomenon and thus the location of the ion current probe is of importance in order to obtain good signals.

- The ion current amplitude is affected by both lambda and combustion phasing but the ion current timing is only affected by the combustion phasing.
- Higher ion current amplitudes are obtained with higher engine speed since the charge has to be preheated to a higher temperature in order to maintain the combustion phasing.
- High ion current cycle to cycle variations in terms of ION50 were experienced at low loads mainly due to low signal to noise ratios.
- The ion current is appearing a bit later in the bulk of the combustion chamber compared to the measuring locations in the topland volume, due to the fact that the combustion starts at the walls in this particular engine.
- Fuels with LTR, especially diesel, doesn't provoke ion current easily but when reaching rich mixtures especially at lambda 1 the ion current amplitude increases rapidly. At these rich running conditions with high amounts of EGR no LTR were present. The conclusion to this is that LTR doesn't provoke ion current.
- Fuels with higher octane number provoke ion current even at lower loads.
- The difference in ion current amplitude between fuels when measuring in the topland volume is not that large but when measuring for the same load conditions in the bulk of the combustion chamber, methanol provokes higher amplitudes and isooctane lower amplitudes. An explanation to this behavior between the different locations is inhomogeneties and thus locally richer or leaner mixtures generating higher or lower heat release at the specific locations. Another explanation or a combination with the one above could be locally different cylinder wall temperatures.
- When running the engine with a high amount of fuel the non LTR fuels are not so affected by EGR rate even though the signal increases slowly with decreasing lambda. Under these conditions gasoline and PRF fuels with high octane number provoke higher ion current amplitudes than the alcohols, ethanol and methanol, followed by the LTR fuels n-heptane and diesel due to higher peak in-cylinder temperatures.
- NOx emissions and ion current signal strength seems to be related through peak in-cylinder temperature but NOx doesn't seem to provoke ion current [16].
- For the high octane fuels the ION50 correlated well with CA50 except for ethanol which seemed to have too advanced ion current timing compared to the

other fuels. The LTR fuels have later ION50 compared to CA50.

## ACKNOWLEDGMENTS

This work has been performed within the Centre of Competence for Combustion Processes at Lund Institute of Technology, Sweden. The authors would like to thank the financial sponsors and the engine lab staff.

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## ABBREVIATIONS

**ABDC**: After Bottom Dead Center  
**ATDC**: After Top Dead Center  
**BBDC**: Before Bottom Dead Center  
**BTDC**: Before Top Dead Center  
**CA50**: Crank Angle of 50% burned fuel  
**CAD**: Crank Angle Degree  
**EGR**: Exhaust Gas Recycling  
**HCCI**: Homogeneous Charge Compression Ignition  
**ION50**: 50% of Ion rise  
**LTR**: Low Temperature Reactions  
**SI**: Spark Ignition  
**STD**: Standard Deviation  
**PRF80**: Primary Reference Fuel octane number 80

# APPENDIX

RESULTS FROM THE TEST CASE WITH 40% EGR.

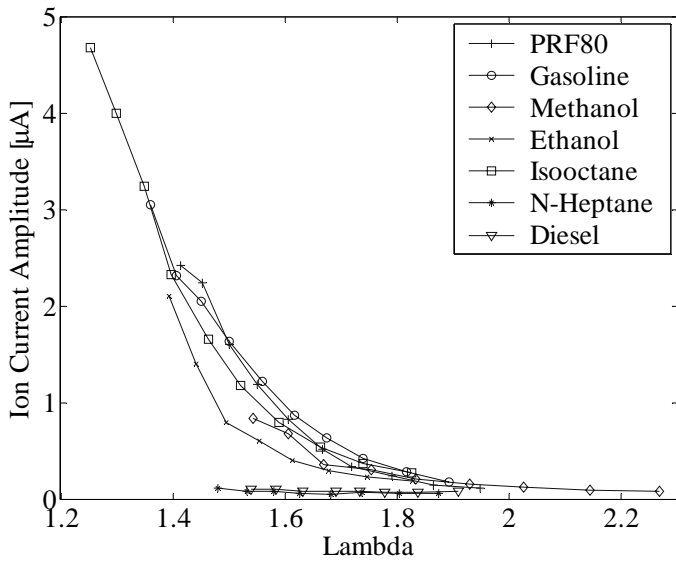


Figure 27. Ion current amplitude for location number 4 as function of lambda for different fuels.

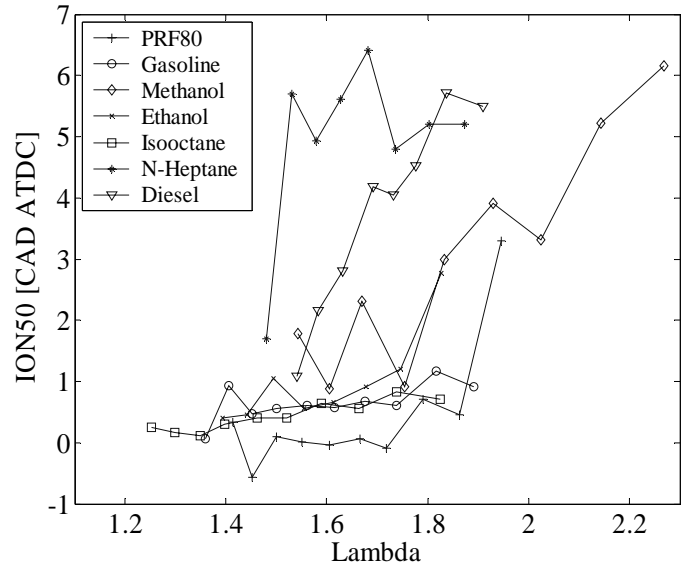


Figure 29. ION50 at ion probe location 4 as function of lambda.

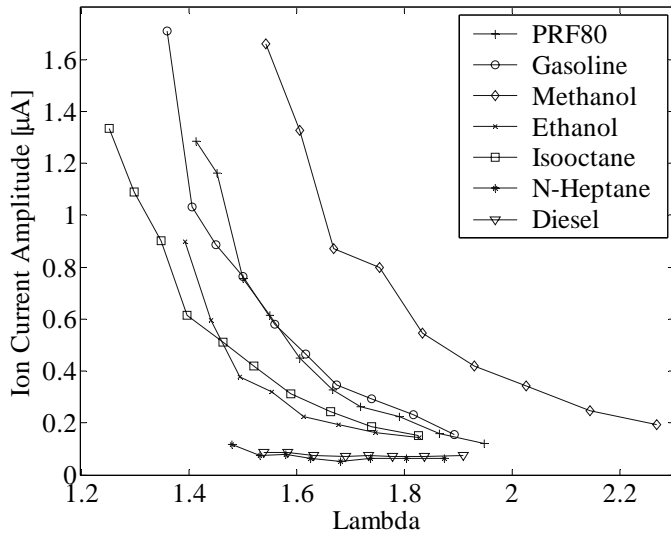


Figure 28. Ion current amplitude for location number 7 as function of lambda for different fuels.

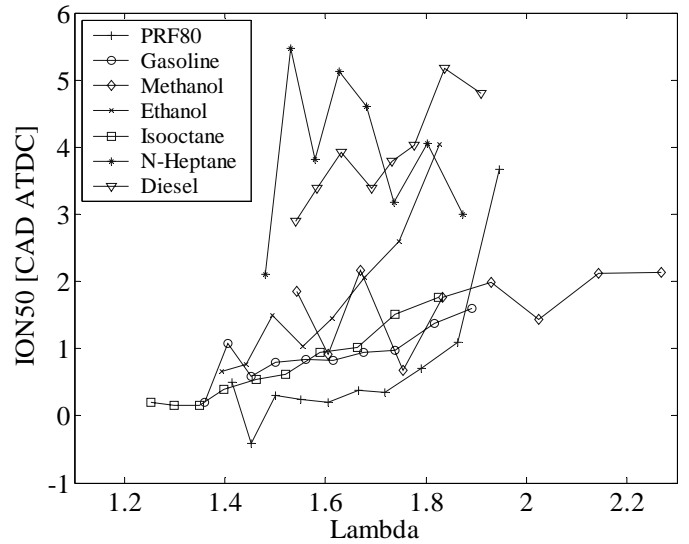


Figure 30. ION50 at ion probe location 7 as function of lambda.

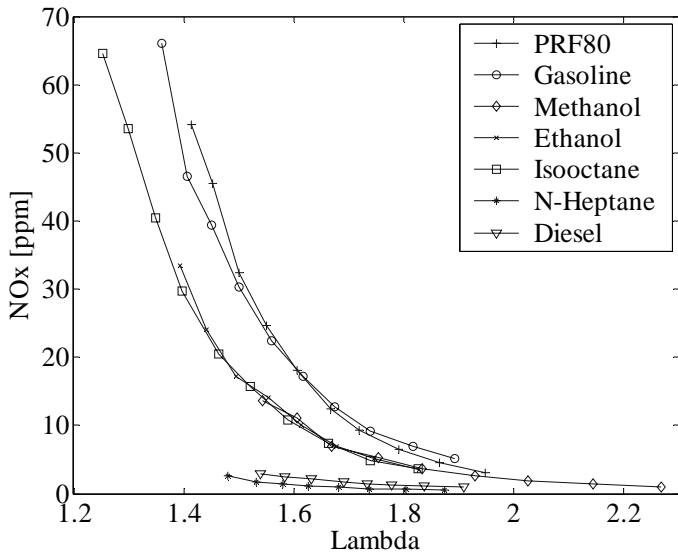


Figure 31. NOx emissions as function of lambda.

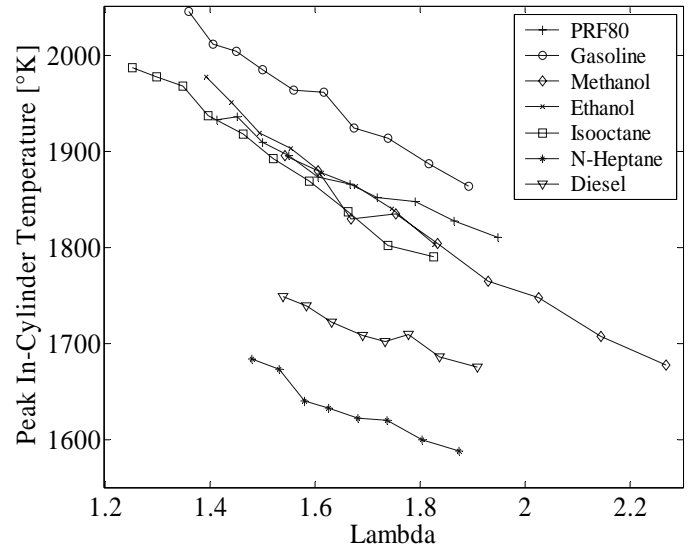


Figure 32. Peak in-cylinder temperature as function of lambda.