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Ionization and Ionization rate of a two-stroke HCCI engine fuelled with E85 for control feedback

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Ionisation and Ionisation Rate of a Two-Stroke HCCI Engine Fuelled with E85 for Control Feedback

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ABSTRACT

Homogenous Charge Compression Ignition (HCCI) combustion phasing and stability provides a challenging control problem over conventional combustion technologies of Spark Ignition (SI) and Compression Ignition (CI). Due to the auto ignition nature of the HCCI combustion there are no direct methods for actuation, the combustion and the phasing relies on indirect methods. This in itself creates a nonlinear dynamic problem between the relationships of control actuators and the combustion behavior. In order to control the process, an accurate feedback signal is necessary to determine the state of the actual combustion process.

Ideally to ensure that combustion remains stable and phased correctly an in-cylinder feedback of each cylinder for multi cylinder engines would be preferable. Feedback has been seen in studies using piezoelectric pressure sensors for visually monitoring the pressure in the combustion chamber. This is expensive and requires redesign of the combustion chamber. A potential alternative feedback is to use the conventional spark plug as a sensor. This is achieved by applying a voltage across the spark plug to provide a sensor for ion current. The ions are created through the combustion event, and the current is created by the flow of the ions between the spark plug gap.

The work presented in this paper provides a comparison between ion current feedback and pressure trace for a two stroke HCCI combustion from a control perspective. The emphasis of the work is to show the capability of using the ion current system as feedback for information for the start of combustion, combustion duration, and rate of combustion and estimations on peak pressure magnitude. These key parameters from the signal could be useful when applied as feedback for closed loop control.

INTRODUCTION

HCCI combustion can offer efficiency as high as direct injection compression ignition (DICI) engines while producing low levels of NOx and particulate matter. HCCI can be used in both four stroke and two stroke reciprocating engines and can offer some advantages over spark-ignition and compression-ignition engines while eliminating a number of the disadvantages associated with the two current combustion mechanisms.

The HCCI process combines a number of different parts of CI and SI cycles. The combustion process uses a homogenous air and fuel mixture like the SI engine and the mixture is compression ignited like CI engines. This hybrid combustion leads to auto ignition occurring simultaneously at several sites where local inhomogeneities create warm patches where the temperature can exceed the threshold of the auto ignition temperature for the mixture. These increase the temperature and pressure of the mixture and their ignition lead to a full scale ignition of the charge.

The short combustion duration does not rely on flame propagation to burn the fuel-air mixture, because of this dilution levels can be much higher than in SI or CI. This dilution also keeps the combustion controllable by decreasing knock tendency and lowering combustion peak temperature; it is this that provides the lower NOx emissions (1).

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The NOx emissions can typically be expected to be 90% lower than SI and up to 98% lower than Gasoline Direct Injection (GDI) engines. The particulate emissions are also reduced due to the homogeneity of the mixture being combusted, eliminating rich Air Fuel Ratio (AFR) areas (2).

Two stroke HCCI combustion has a long history and was reported in the first papers on HCCI combustion (3, 4), the inherent scavenging of residuals in the two stroke cycle allowed for the HCCI combustion to be initiated. Since then HCCI combustion has been investigated in both two and four-stroke operations, with four-stroke seen to have had improvements in thermal efficiency at low load conditions(5). Two stroke HCCI has been investigated to stabilize the operation of two stroke engines at part load conditions where fuel consumption and exhaust emissions are a significant drawback. The combustion has been named Active Thermo-Atmosphere Combustion(ATAC) and gave a reduction of 65% in HC emissions and a fuel efficiency increase of 57% under part load(6).

A Two stroke/Four stroke poppet valve engine was studied to investigate the potential of combining the two combustion cycles two/four stroke with SI and HCCI combustion allowing for HCCI to be used for part and low load range and extended it's potential range through the two cycle options(7, 8).

Research has also been conducted into modeling, simulation and optical experiments to determine a better understanding of the flow and combustion process with in the two stroke HCCI combustion(9, 10, 11). One concern with two stroke HCCI is the level of in-homogeneity before ignition that has been reported through CFD(10) and optical diagnostics(9). This causes combustion to usually occur in one half of the cylinder first where exhaust gas residuals and temperatures will be closer to auto ignition requirements. This can create the advantage of reducing rate of heat release giving more control over combustion. However when considering ion current measurement is often local and not global this may create some inaccuracies.

Examples of control over the two stroke HCCI combustion is limited as most control research into HCCI has been focused on four stroke cycle engines, but the findings from these can be considered applicable to two stroke HCCI as the chemistry and physics for initiating and controlling combustion are comparable(5) to such an extent that they can even be run in the same engine (7, 8).

The major concern with control over the HCCI combustion is the lack of direct ignition timing control. Instead this ignition process can be influenced by a number of external technical strategies. These can range from intake heating (12) to full variable compression ratio control(13). The purpose of the external technical strategies is to alter the in-cylinder conditions to allow for ideal temperatures, pressures, concentrations of air, fuel and exhaust gases to give optimal conditions to allow the desired combustion phasing and duration. This indirect method of control adds a major problem of uncertainty if the desired combustion phasing and duration were to be achieved from the given inputs.

The relationships between the inputs and the engine output have a high level of non linear behavior, this means they will vary with respect to changes in certain variables. In fact it was found that the control of combustion timing was not effected by a single variable or by the chosen control system alone but a factor of many variables, often including octane number, engine speed, inlet temperature, fuel quantity and intake pressure to name a few. To get an accurate control it would be important to isolate the different dependences to understand their effects on the relationship of combustion phasing but it is also very difficult to do this, since it is impossible to change parameters individually (14).

Once these relationships can be predicted by a control system combustion phasing and duration should occur where it is supposed to, but as the relationships are extremely difficult to separate a level of error will be certain. The use of a feedback signal to determine the state of the actual combustion process could be used to adjust the control to reduce this error and also reduce any fluctuations that could occur due to external effects.

Feedback signal have been obtained in the past from piezoelectric pressure sensors monitoring the pressure in the combustion chamber, but the combustion pressure sensors have high costs and low long term reliability and require redesign of the combustion chamber. An alternative is using the spark plug as a ion current sensor, since this would offer a low cost in cylinder sensor that already has mounting location(15).

Currently there is limited research into ion current application on two stroke engines, though it is capable of detecting changes in charge variation and misfire over wide operating range of two-stroke SI and HCCI engines. (16, 17).

In literature, relationships with cylinder pressure have been investigated for four-stroke HCCI engines (15 19 20), showing potential as a feedback signal. However there are concerns with ion current as a feedback, as it has been noted that ion current measurement is local, compared to cylinder pressure that is global (18). Inhomogeneous gas composition can affect ion concentration and thus ion current amplitude (23). As mentioned earlier, the two-stroke HCCI combustion tends to have high levels of in-homogeneity, this could alter the reliability of relationships that have been previously observed for four-stroke HCCI. Often ionisation is used to construct predictions of cylinder pressure for feedback information. Comparing ionisation to cylinder pressure

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allows the relationships between ionisation and combustion to be understood. For feedback this offers two possible avenues. Does ionisation need to be related to cylinder pressure for feedback, or can ionisation be used directly? Adaptive feedback control architecture would rely upon a feedback signal that is accurate, reliable and fast. If ionisation can offer reliability to be used directly it could potentially offer a mathematically efficient solution.

The aim of this work is to investigate the capability of the ion current as an efficient feedback signal with information on start of combustion, combustion duration, rate of combustion, and peak pressure magnitude. These were studied on a two-stroke HCCI engine fueled with E85.

EXPERIMENTAL SET- UP

The experimental setup for this work consisted of a single cylinder research engine developed by Lotus Engineering. This engine is capable of running HCCI combustion with multiple fuels and is capable of variable Exhaust Gas Residuals (EGR) trapping, variable compression ratio and direct fuel injection.

The engine is equipped with a spark ignition system that allows for combustion to begin in spark ignition mode and also allows for spark assisted HCCI. This spark plug is used as the sensor for the ionisation circuit. The ionisation circuit was designed such that is could be integrated onto the engine and still allow for spark operation control through the original engine control unit. The ion current circuit would give a voltage output between −10V to 10V that could be recorded via data acquisition

The data acquisition system used was National Instruments LABVIEW, that allowed for a simple program to be written for continuous acquisition for 300 engine cycles that was triggered from the TDC marker, and counted using the engine encoder. Cylinder pressure and rate of ionisation was sampled 600 times per engine rotation.

ION-CURRENT SYSTEM

The ion current circuit was developed by Loughborough University so that it could be used on the two-stroke Lotus engine for sensing of ionisation and still allow for firing of the spark plug for operating the engine.

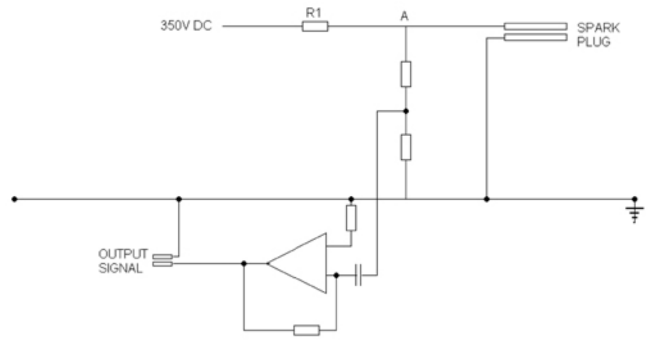

Figure 1. Simplified Ion Current Circuit

Figure(1) shows a simplified circuit diagram of the ion current circuit. The 350 volts DC was produced from a 18v external power supply and was then increased through a transformer to get the 350V. This voltage was then applied to the secondary side of the ignition coil that is isolated from the primary so as to apply a continuous 350V across the spark plug. As ions pass between the earth and the spark plug electrode a current is produced. As the current changes across the spark plug there is a change in the voltage drop across resistor R1. This drop in voltage is then measured by taking the voltage at point A through a potential divider to an amplifier to give an output voltage that is proportional to rate of ionisation.

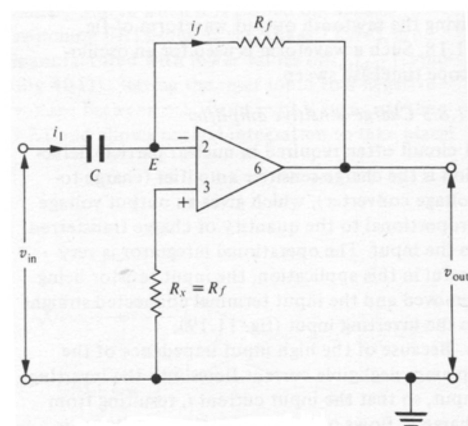

Figure 2. Differential Amplifier (24)

Figure(2) shows the Differential Amplifier configuration used in the circuit. The input voltage is directly proportional to the differential coefficient of the input voltage with respect to time. In other words, the faster the rate of change of the input, the higher the output voltage. Unfortunately this circuit is troublesome because they are very susceptible to any noise in the input circuit, particularly transient interference pulses that maybe picked up from electrical switching. Though the amplitude of the noise maybe low, the rate of change is often very high(24). Noise has been reduced by altering the

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effective gain at high frequencies so that a suitable compromise between noise and sensitivity could be reached.

The differential amplifier circuit was used because the spark plug for sensing was also used for firing the engine during start up. The differential circuit, along with a diode, protect the amplifier from transient high voltages from the spark plug operation during firing. If a separate sensor could be used the differential circuit could be designed out of the system.

ENGINE

The Lotus Omnivore engine operates on the two-stroke cycle with flexi-fuel capability. The engine is equipped with variable charge trapping mechanism to control both trapped charge and residual concentration and has a variable compression ratio mechanism in the cylinder head. This approach allows for individual control between retained and compression heat as inputs to the HCCI combustion process, an ideal situation which is not possible in a traditional fixed compression ratio, variable valve timing 4-stroke engine. For further details on the engine technology and operation capabilities there is a related description paper (25).

Table 1. Omnivore specification.

Bore x stroke	86mm x 86mm
Displacement	499.6cc
Compression ratio	10:1-40:1 (geometric)
Fuel system	Orbital FlexDI air-assist

EXPERIMENT

The experiment was conducted on the Omnivore engine developed by Lotus Engineering. The engine was operated using Ethanol E85[1] fuel. The operating conditions of the tests where ionisation being recorded were;

- compression ratio of 18.5
- engine speed 2000RPM
- Actuator Position of 37% for allowing EGR trapping. EGR is proportional to the actuator position.
- intake pressure of 103.5Kpa at upper Plenum
- Air Inlet Temperature 25 degrees C
- early injection timing at 0 degrees BDC.

During the testing, the fuel injection pulse width was adjusted for each operating point. The durations used were

- 20000 µS
- 19000 µS,
- 16600 µS.

Which delivers the air to fuel ratio (AFR) of 11.33, 11.75 and 13.3, and corresponding loads 17Nm, 16Nm and 13.4 Nm.

The data allows us to investigate relationships between the cylinder pressure and the ion current for combustion characteristics.

EXPERIMENTAL DATA ANALYSIS

During the running of the Lotus Omnivore Engine it was possible to measure the rate of ion current signal and pressure trace under steady conditions for HCCI combustion for three different AFRs. The purpose of the following investigation is to investigate the relationships between ion current and pressure trace for combustion characteristics for the potential of it to be used for a feedback signal for control. Although the ion current circuit only produced an output of rate of ionisation, it is possible to integrate this signal to gain a set of data for ionisation. Both will be used in the investigation as they show different characteristics of the ion current and by investigating them both it will show if either hold advantages for giving information on combustion characteristics.

DEFINING DATA OF INTEREST

The pressure trace is currently used widely for gathering information on in-cylinder conditions, and allows for feedback on peak pressure position, peak pressure magnitude and detection of knock. The pressure trace can be used further in predictive calculations for useful combustion properties such as mass fraction burnt (MFB) and rate of heat release. The pressure trace is formed from a combination of pressure change due to volume change through compression and expansion of a gas and pressure change due to combustion. This makes it difficult to predict the start of combustion from the pressure trace. However it is possible to estimate the MFB profile from the pressure trace using a method established by Rassweiler and Withrow (26). This allows for an estimation to be made on the start of combustion from the start of MFB that is calculated from the following equations.

$$\Delta p = \Delta p_c + \Delta p_v$$

$$p_i V_j^n = p_j V_j^n \qquad (4)$$

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1 E85 is 85% by volume Ethanol in bulk Gasoline. Stoichiometty for E85 is 9.7:1

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$$\Delta p_v = p_j - p_i = \left[\left(\frac{V_i}{V_j}\right)^n - 1\right]$$

(5)

$$\frac{m_{b(i)}}{m_{b(total)}} = \frac{\sum_0^i \Delta p_c}{\sum_o^N \Delta p_c}$$

(6)

Equations 4,5,6 developed by Rassweiler and Withrow for calculation of MFB (21).

This method is widely used, though it contains several approximations. Heat transfer effects are included only to the extent that the polytropic exponent *n* differs approximately from the adiabatic isentropic exponent *y* which is the ratio of specific heats for a gas. The pressure rise due to combustion is proportional to the amount of fuel chemical energy released rather than the mass of mixture burned. Also the polytropic exponent *n* is not constant during combustion(21). The prediction of the start of combustion will therefore only be as reliable as the polytropic exponents used to predict the compression and expansion processes.

Figure(3) shows a comparison for a typical averaged cylinder pressure, a typical averaged rate of ionisation signal and a typical averaged ionisation signal. From the data acquisition system only two signals where collected; the pressure trace and the rate of ionisation. The rate of ionisation signal acquired from the circuit is the first differential of ionisation, to obtain the ionisation signal in fig(3) the signal of rate of ionisation had to be integrated. From this figure it is possible to highlight the following points of interest in this investigation.

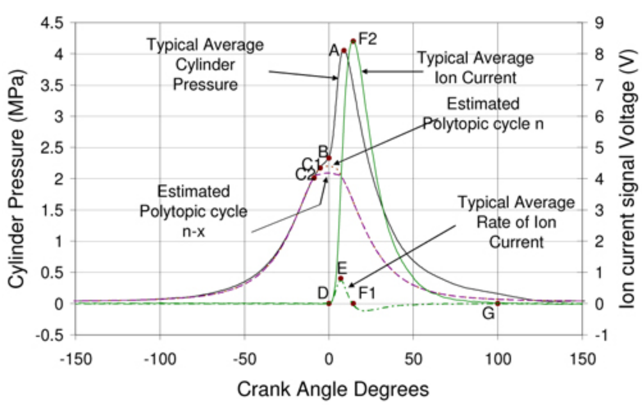

Figure 3. Typical Averaged Cylinder Pressure and Rate of ionisation and Ionisation signals.

It is possible to see several points of interest marked out from A to G.

Point (A) shows the peak pressure position, this allows us to gain information on location of peak pressure and magnitude of peak pressure, this can be used for phasing the combustion and understanding the quality of the combustion.

Point (B) is an inversion on the cylinder pressure trace and is due to the change in pressure as the piston begins its expansion stroke at top dead centre. This inversion will be more or less obvious depending on the location of ignition. The start of ignition for this pressure trace will have been before this point, the further before the point the less predominant the inflection will be as the pressure due to combustion will have a more dominating effect.

Point (C1 & C2) is the approximate location of start of ignition, this is difficult to locate exactly using pressure trace or the method for finding MFB as demonstrated in the diagram, as the value of polytropic index *n* changes the height of the pressure change due to compression and expansions changes. This therefore changes the location of where the pressure curve leaves the predicted polytrophic curve (point C1-C2). It is also known to be very difficult to accurately estimate a appropriate value for *n* as it is known to vary during combustion (26).

Point (D) is the start of ionisation, this can be seen to be later than start of predicted combustion and resemble more closely TDC. Potentially this could be due to the variability in the start location of combustion in the cylinder volume and the location for where the measurement is taken.

Point (E) is the peak of the rate of change of ionisation. As the ion current circuit amplifier is differential, the trace represents the first differential of the ionisation and therefore the peak of this trace does not represent the peak value or location of ionisation but the peak change in ionisation.

Point (F1 F2) is the actual peak of ionisation where it crosses zero on the rate of ionisation(F1). At this point the rate of positive increase in ionisation has reached its maximum, as the value drops below zero is the negative rate of change in ionisation.

Point (G) is therefore the end of the ionisation signal. Where there is no longer any rate or change positive or negative and will be the end of ionisation detection of the products of combustion.

There appears to be relationships between the pressure and the ion current but these relationships maybe unclear as ion current gives a local reading of a product of combustion reaction, whereas cylinder pressure is a accumulative averaged reading from pressure rise due to combustion and volume change. It will now be investigated further to see if some of the key points highlighted from the pressure trace can be matched to some of the key points of the ion signal.

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DIRECT ION CURRENT ANALYSIS

From the acquired signals the first investigation was to determine if the ionisation signal acquired had any relationships or correlation with points of interest with pressure trace. But first the acquired signal required a level of processing.

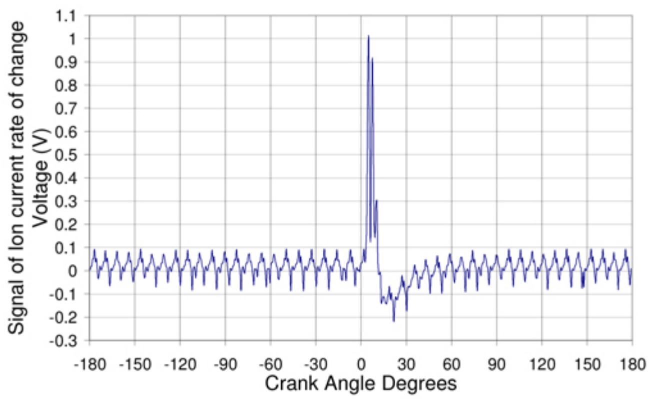

Figure 4. Typical Unprocessed Rate of Ionisation Signal

Figure(4) shows a Typical Unprocessed Rate of ionisation signal. There is significant baseline noise and this makes it difficult to accurately pinpoint a start, a peak value and an end. The only value that could be defined would be where the signal crosses zero, previously described as point (F1). Although this can become unclear if the noise level increased. The problems found with noise can be improved in future work by having better screening on high voltage cables. This data can be filtered and averaged to improve the clarity of the signal and make finding points of interest more reliable.

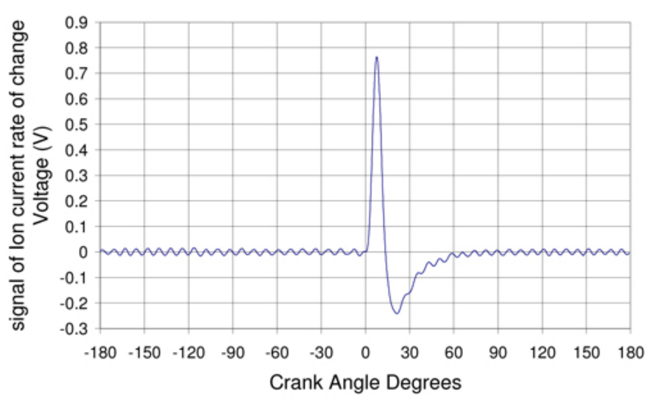

Figure 5. Typical Processed Rate of Ionisation signal

Figure(5) shows a typical processed rate of ionisation signal. The processed signal is formed from averaging ten consecutive cycles then removing noise through the Wavelet Toolbox in Matlab. The processed signal has a much more defined start location, peak location, zero crossing point and end. By averaging and using Wavelet Toolbox for filtering the signal it has made it possible for further analysis to be carried out for comparison with cylinder pressure for combustion characteristics.

KNOCK COMPARISON

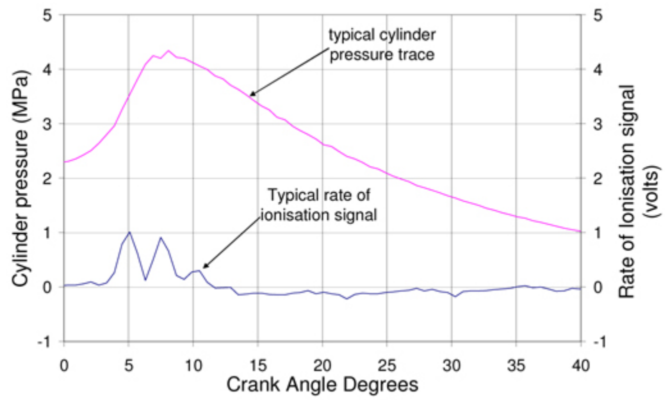

Figure 6. Comparison between typical unprocessed Rate of Ionisation signal and Typical Cylinder Pressure Trace.

Figure(6) shows a comparison between typical unprocessed rate of ionisation signal with the typical cylinder pressure trace. The pressure trace shows a small level of knock indicated by the spikes beginning to show at the top of the pressure trace peak. This is a indicator that auto ignition is taking place. The rate of ionisation also shows multiple peaks from the combustion showing rapid changes in rate of ionisation. The multiple peaks could be due to the nature of the rapid combustion of HCCI representing knock. It has been reported that ionisation is capable of detecting knock (27)

PHASING CARACTERISTICS

To investigate the characteristics of the timing of ionisation with combustion timing, comparisons have been made between points along the ionisation and rate of ionisation signals with peak pressure position. Points of interest investigated are; the start of the signal, peak location of the signals and points at 15% 50% and 75% of the rising edge. Relationships between these points could represent a relationship with combustion timing.

When relationships are compared for accuracy, Microsoft Excel Function "VARP" is used to describe the spread of data.

$$\frac{\sum (x-\bar{x})^2}{n} \qquad (7)$$

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where x is the sample mean average and n is the sample size. VARP calculates the variance based on the entire population n.

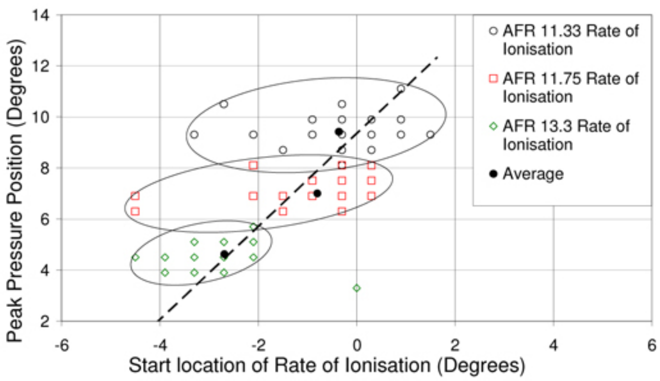

Figure 7. Correlation between Averaged Peak Pressure Position and Averaged Start Location of Rate of Ionisation

Figure(7) shows the Correlation between Averaged Peak Pressure Position and Averaged Start Location of Rate of ionisation for three different AFRs. As the AFR becomes leaner the peak pressure position advances as well as the start timing for rate of ionisation. This indicates that as the AFR becomes leaner the start of combustion is becoming earlier and is represented in both the Peak pressure Position and the Start location of Rate of ionisation. The ignition becomes earlier as there is less fuel in the cylinder, leading to less energy used in heating the fuel. Therefore during compression the temperature/pressure requirements for auto ignition to initiate occur earlier in the cycle. The variability of the peak pressure position shows that start of ignition is variable at each of the AFR operations. There is however a larger variation of 1.12 for start location of ionisation compared to Peak Pressure Position variation of 0.3. When combustion begins in HCCI it will start at a location that has local inhomogeneous variations. This means that cycle to cycle the start timing maybe very similar but the location can be any point with in the cylinder (28). The rate of ion current signal is measured from the spark plug and represents only a local region close to and around the spark plug probe. If start of ignition location varies cycle to cycle then the distance from start of ignition and the sensor will vary. This variation in distance will cause a variation in delay between start of combustion and sensing of ions at the spark plug. From figure(7) it is therefore possible to see that start of combustion advances with leaner AFR and that this is shown through change in Peak Pressure Position and start of rate of ionisation. Peak Pressure Position also shows that combustion timing has some variability, and start of ionisation shows that start location of combustion is variable, typical of HCCI.

Figure(8) shows correlation between averaged peak pressure and averaged start location of ionisation for three different AFRs. The timing of start location of ionisation can be seen to have larger variation of 2.04 then the start of rate of ionisation. When considering peak finding methods of establishing the presence of a peak, most use the comparison of some signal attribute. For example, rate of change (first differential) against a user adjustable threshold, this method discriminates peaks from background signal noise (29).The rate of ionisation is the first differential of the ionisation, the start of the rate is therefore the point that ionisation starts to increase. The interpretation of where the start location appears to be more accurate with the rate then from determining a rise with in the noise on the ionisation signal.

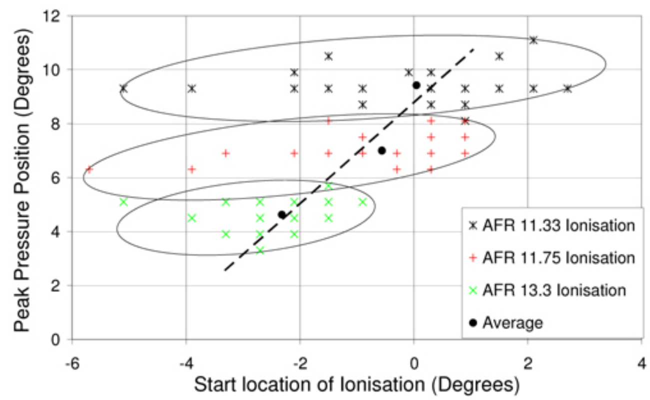

Figure 8. Correlation between Averaged Peak Pressure and Averaged Start Location of Ionisation

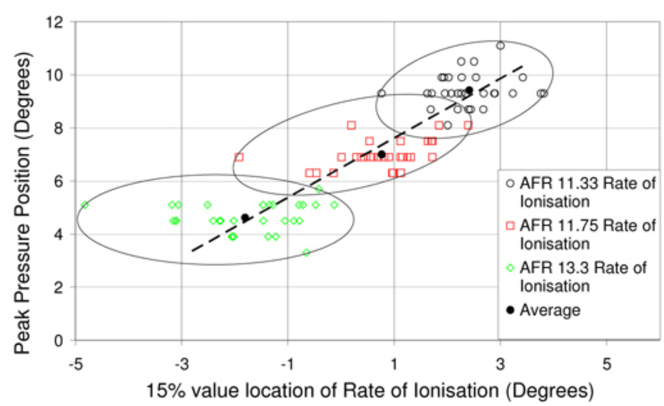

Figure 9. Correlation between Averaged Peak Pressure Position and Averaged 15% value location of Rate of Ionisation

Figure(9) shows the correlation between Averaged Peak Pressure Position and averaged 15% value location of rate of ionisation for three different AFRs. The variation in 15% value location of ionisation is reduced to 0.74 compared to start of rate of ionisation that had variation of 1.12. The base-line noise will decrease the accuracy of finding the start location. By taking a point at 15% value of rate of ionisation

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it is close to the start of combustion but will decrease the effect of the baseline noise.

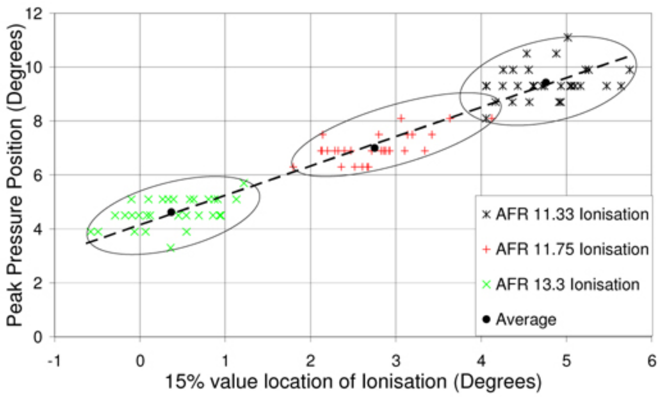

Figure 10. correlation between Averaged Peak Pressure and Averaged 15% value location of Ionisation

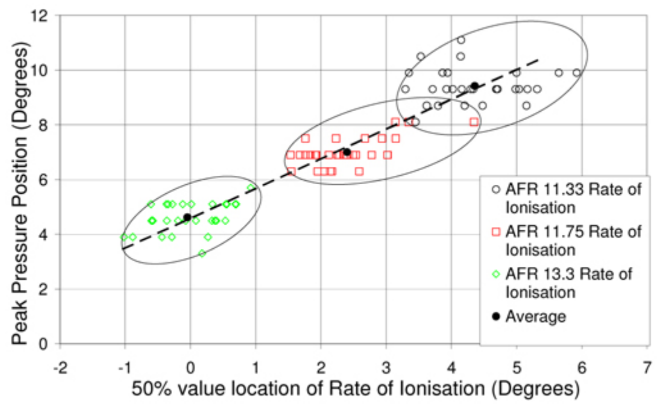

Figure 11. Correlation between Averaged Peak Pressure Position and Averaged 50% value location of Rate of Ionisation

Figure(10) shows the correlation between averaged peak pressure and averaged 15% value location of ionisation for three different AFRs. The variation for 15% value location for ionisation is 0.23 a significant reduction from the start location and lower than the 15% location for rate of ionisation. The 15% value location of rate of ionisation has a larger variation because it is referenced to the maximum rate of change of ionisation, and the signal has smaller signal-to-noise ratio than ionisation. Therefore the data from ionisation signal 15% location has less variation due to its larger magnitude of signal compared with the noise.

Figure(11) shows correlation between average peak pressure position and averaged 50% value location of rate of ionisation for three different AFRs. The variation has reduced to 0.36 and is lower than that at 15% value location. The rate at 50% of the signal is less variable as once the combustion has become established the rate will be determined by the dilution of the mixture through residuals. The residuals were set by a constant valve position for testing, but will still have variation in quantity. So it could be seen that as combustion first initiates due to the local inhomogeneous conditions the rate will be variable but once combustion becomes more established the rate will become less variable, and depend upon ratio of dilution and EGR.

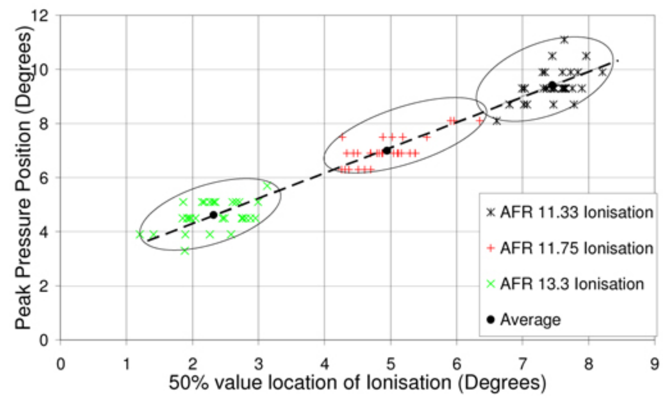

Figure 12. Correlation between Averaged Peak Pressure Position and 50% value location of Ionisation

Figure(12) shows correlation between averaged peak pressure position and 50% value location of ionisation for three different AFRs. The variation is 0.2 which is smaller than that at 15% value location. Once combustion has begun, it will take a certain time to complete. In HCCI combustion this is a fast process and happens throughout the cylinder with little or no flame front. As the combustion establishes, the effect from start of combustion location inside the cylinder on the local ionisation reading is reduced. The variations are mainly due to the dilution through EGR, AFR and the start of combustion. The 50% location of ionisation offers a more repeatable accuracy of feedback them at the 15% position and start of ionisation.

Figure(13) shows the correlation between averaged peak pressure position and 75% value of rate of ionisation for three different AFRs. The variation has reduced marginally to 0.35 showing a small reduction at 50% value location. The change in variation is small if the combustion has become established by 50% then by 75% there will be little difference in variation as the nature of the combustion means that once it is established it is burning over the entire cylinder(3).

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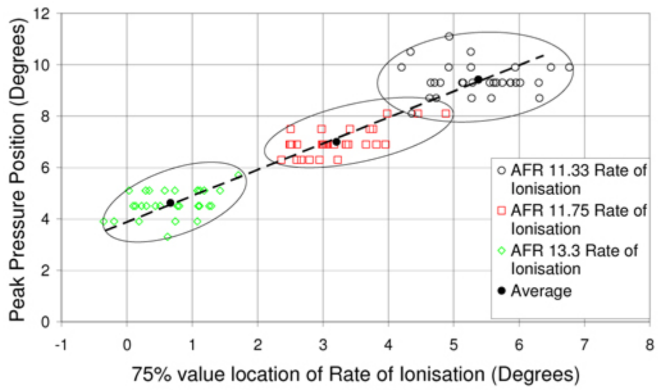

Figure 13. Correlation between Averaged Peak Pressure Position and 75% value of rate of ionisation

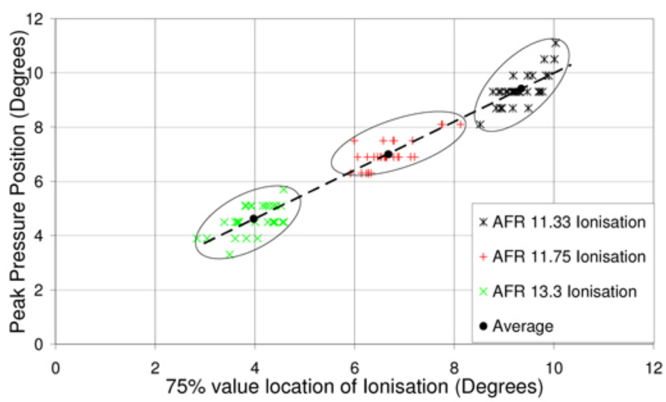

Figure 14. Correlation between Averaged Peak Pressure Position and Averaged 75% value location of ionisation

Figure(14) shows the correlation between average peak pressure position and 75% value of ionisation for three different AFR. The variation has marginally increased to 0.207 from that of 50% value location. The change in 75% for ionisation can be considered due to small effects as the value is very close to that of 50% ionisation.

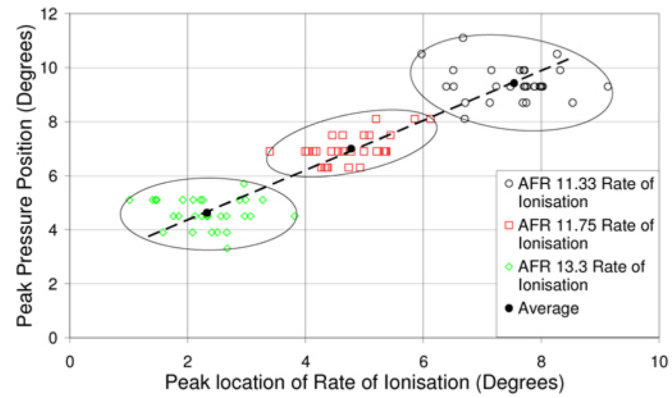

Figure 15. Correlation between Average Peak Pressure Position and Average Peak location of rate of Ionisation

Figure(15) shows the correlation between average Peak Pressure Position and average peak location of rate of ionisation. The variation has increased to 0.401. This increase potentially could be due to the effect of averaging the multiple peaks of the unprocessed signals as shown in Figure(4). Also, rate of ionisation is not an accumulated reading like pressure. Any variations in charge mixture will affect the rate of combustion, which will further affect the magnitude and location of peak value of rate of ionization.

The other figures have been suggesting there is a variation in rate of combustion from cycle to cycle. As the same amount of fuel is being delivered each cycle, the increase in variance seen in fig(16) could be due to the effect of rate of combustion. For instance if there is a slower rate it will take longer to burn all the fuel and therefore longer to get to peak value of ionisation.

Conversely if there is a faster rate then the fuel will ignite faster and the peak value of ionisation will be sooner. Figure(17) shows a comparison of peak pressure position and peak value of rate of ionisation signal for AFR 11.33. The plot shows that if the peak rate of ionisation is lower than the timing of the peak pressure position tends to be later. Conversely if higher then the peak pressure position becomes Advanced towards TDC.

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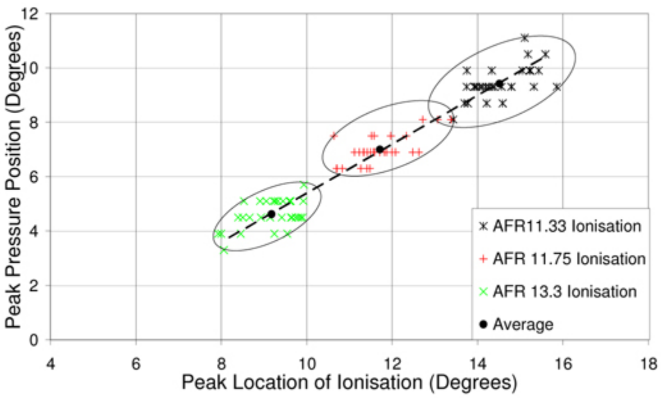

Figure 16. Correlation between Average Peak Pressure Position and Average Peak location of Ionisation

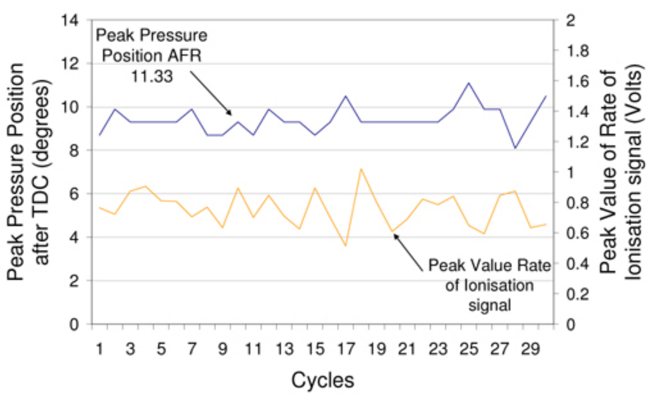

Figure 17. Comparison of Peak value of rate of Ionisation signal and Peak Pressure Position

Figure(16) shows the correlation between average Peak Pressure Position and average peak location of ionisation. The variation has increased to 0.4001.

The peak locations of pressure is effected by start of combustion and rate of combustion. Therefore this comparison is not faultless as there will be some effect from variation of start of combustion. However there is a trend for peak pressure to vary inversely with the change in peak rate of ionisation. This potentially providing information on rate of combustion, that is also demonstrated in variation of peak ion current position.

Figure(18) shows the average error for all three AFRs of predictions of peak pressure position against the average line of the AFRs. It shows that overall the start location has the largest error then this error reduces as you move along the signal to the 15%,50% and the 75% locations. The 75% locations tending to offer the lowest error. Peak positions then have an increase in error. It is also possible to see that points taken from the ionisation signal tend to give less error than the equivalent point on the rate of ionisation signal. Apart from the start position where there are improvements on error for AFR 11.33 and 13.3 for start of rate of ionisation. These results are what would be expected from the different levels of variation that have been discussed at each point. It therefore illustrates that the more reliable locations for timing relationships are between the locations of 50% and 75% ionisation. At these points combustion is established and less effected by the start location of combustion. The level of ions is high enough to be reliably sensed, repeatable and relate to the timing of combustion.

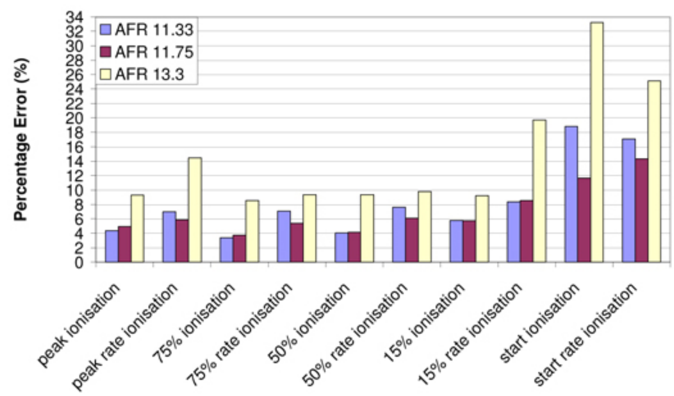

Figure 18. Comparison of average error of prediction of Peak Pressure Position from points of Interest on Ionisation signal and rate of ionisation signal

Figure(19) shows change in averaged prediction error of the three AFRs at different locations along the ion current signal rising edge. 73.5% location is estimated to give the best results with a estimated average error of 5.23% in peak pressure position.

DURATION

In determining a comparison for combustion duration it would be difficult taking points directly from the pressure trace that could be reliably stated as combustion and not pressure due to volume change. Therefore, for investigating duration the MFB was calculated using the equation 4,5,6 that were developed by Rassweiler and Withrow(26). Using the MFB allowed the theoretical separation of the pressure change due to volume change and combustion.

Figure(20) shows a typical calculated MFB curve for the HCCI combustion. The duration that has been taken for the MFB is between 10% of the curve and 90% of the curve as these points are out of any noise and should provide a repeatable measurement. For ionisation the duration will be taken from the 15% of the rising edge of the signal and the location peak. This point is more distinguishable than attempting to find the end of the rate of ionisation as discussed above. The duration for rate of ionisation is the same as the duration of ionisation so only one comparison is produced.

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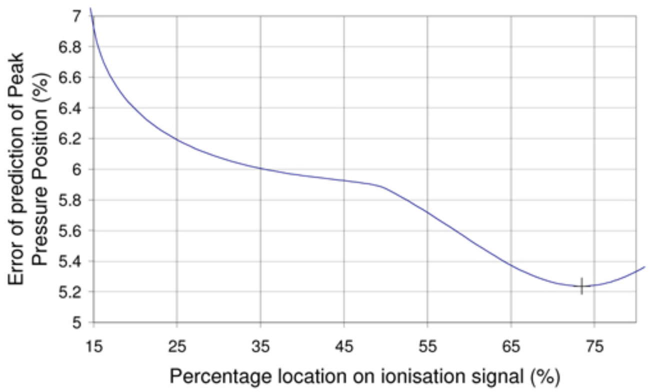

Figure 19. The change in averaged prediction error of pressure position with the change in comparison location of ionisation signal.

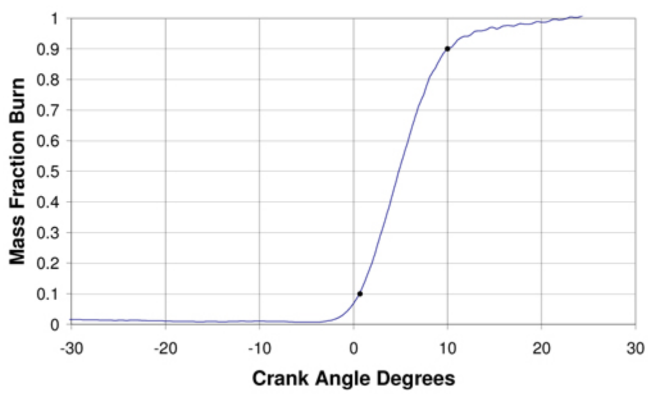

Figure 20. Typical calculated Mass Fraction Burnt from Cylinder Pressure.

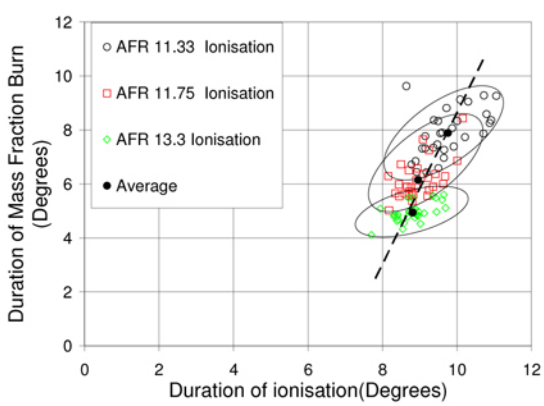

Figure 21. Correlation between duration of MFB and Duration of Ionisation

Figure (21) shows the correlation between the duration of MFB and duration of ionisation for three different AFRs. It can be seen that as the AFR becomes leaner the duration of MFB decreases and the duration of ionisation follows this trend. As the mixture becomes leaner there is less fuel to burn, this will lead to a shorter duration as it will take less time to burn all of the fuel unless the rate of combustion is changed.

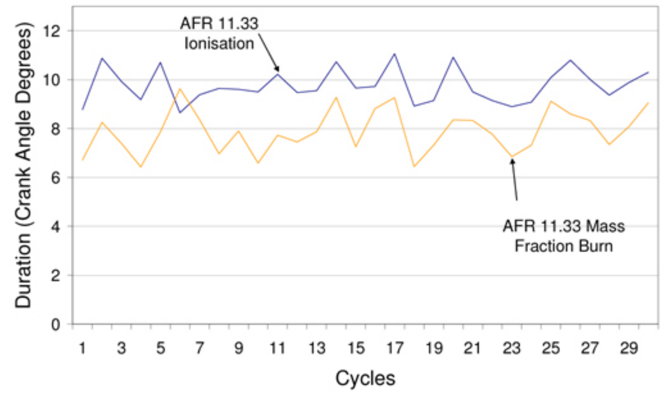

Figure 22. Comparison of Variation in Duration for MFB and Rate of Ionisation at 11.33 AFR

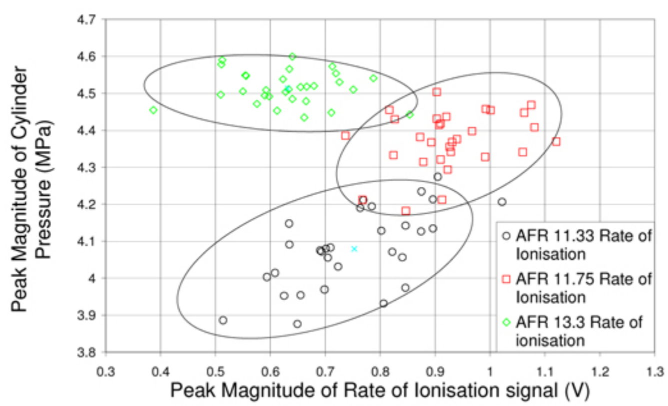

Figure 23. Correlation of Peak Pressure Magnitude and Peak Ionisation rate signal Magnitude

Figure (22) shows the comparison between the variation in duration for MFB and rate of ionisation for 11.33 AFR. It can be noticed that as the MFB duration varies in length the duration of ionisation also tends to follows this variation.

PEAK PRESSURE MAGNITUDE

The peak pressure magnitude gives information on combustion performance, it would be interesting to see if there is a correlation between the peak pressure and the peak values of ionisation and rate of ionisation.

Figure(23) shows the correlation between Peak Pressure Magnitude and Peak ionisation rate magnitude. As the AFR becomes leaner the cylinder pressure is seen to rise for this range of AFRs; however this is not followed by the peak magnitude of ionisation. For the leanest AFR the Peak magnitude of rate of ionisation decreases. At each of the AFRs there appears to be correlation showing that there are

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relationships but without further evidence this is difficult to clarify.

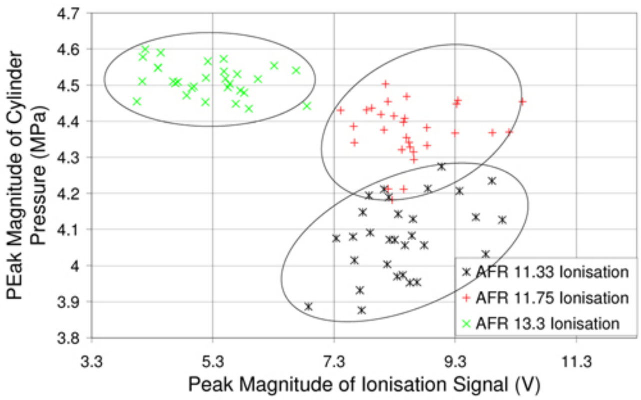

Figure 24. Correlation of Peak Pressure Magnitude and Peak Ionisation signal Magnitude

Figure(24) shows the correlation of Peak Pressure Magnitude and Peak Ionisation signal for three different AFR. Again it can be seen that the peak of ionisation does not follow the same trend as the Peak Pressure Magnitude and at the leanest AFR 13.3 the Magnitude decreases.

Ionisation is a measurement of the ions from combustion and the peak magnitude represents the maximum ions at the location of the spark plug. The peak cylinder pressure is an accumulation of pressure due to volume change and pressure due to compression of a gas. As the AFR becomes leaner there is less fuel within the cylinder. The mixture compresses to a higher temperature as less energy is used to heat the fuel to point of ignition, as there is less fuel. This extra heat causes a increase in pressure and will give a small increase to peak pressure for this range of AFRs. As there is less fuel in the cylinder there will be fewer ions to be picked up by the sensor causing the magnitude of the signal to be less. Therefore, due to the nature of the two readings they will not show the same relationships between peak magnitudes.

AFR EFFECTS ON IONISATION SIGNALS

The AFR has been altered to gain the three different operating points of HCCI for this investigation. It has been seen in investigation so far that as the AFR changes it has produced a change in ionisation. Currently this has only been compared to changes in pressure signal. Some of these points maybe clarified by looking at the change in the ionisation signals with change in AFR.

The ionisation signal can be seen to decrease in magnitude as the AFR becomes leaner this has been reported in other publications(17). If the concentration of fuel in the cylinder decreases then the products through combustion of this fuel will also decrease. Ion signal is a reading of the ions from combustion, if there is less fuel combusted there will be fewer ions to be sensed. Although fig(24) shows for a number of cycles the magnitude of the AFR 11.75 is very close if not higher then AFR 11.33 magnitudes. This is not explained by the above theory. It is apparent from fig(21) and fig(25) the duration of ionisation does decrease with AFR.

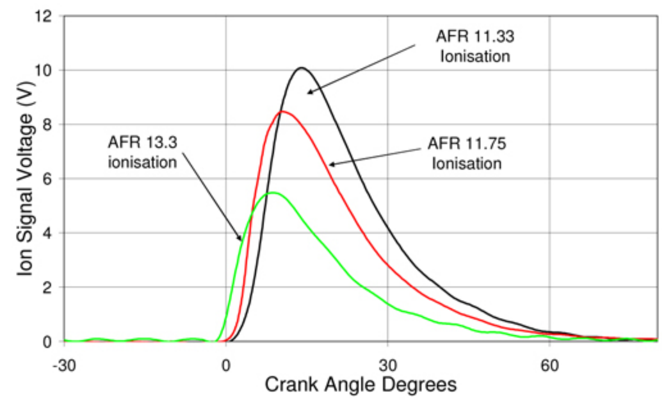

Figure 25. Comparison of typical ionisation signals

As the rate of ionisation appears to be faster for the AFR 11.75 the peak value of ionisation will be located closer to TDC. The closer to TDC the smaller the cylinder volume is where the reactants and products are located. The decrease in fueling between AFR 11.33 to 11.75 has decreased the width of the ionisation giving less ionisation overall. However the peak may have risen as the timing of peak ionisation may have fallen in a smaller volume. This would have an effect of giving an increase in density around the sensor momentarily. So although peak ionisation of AFR 11.33 maybe larger, it appears less due to the local reading of the ion sensor and the change in density at the sensor due to expansion. The peak of the ionisation may not necessarily be only due to changes in AFR but could potentially also depend on the density change due to volume change when looking at small changes in AFR. Because the change from 11.33 to 11.75 AFR is small this maybe why this is seen. Larger changes in AFR will decrease the magnitude of ionisation sufficiently to make this effect of density at volume negligible as seen between AFR 13.3 and 11.33.

Figure(26) shows a comparison of typical rate of ionisation signals for the three different AFRs ionisation signals in figure(25). The rate of ionisation does not follow this same trend as the magnitude of the signal for AFR 11.75 is larger then AFR 11.33. This shows that the peak of ion rate does not depend on the AFR alone but is also effected by other factors such as rate of combustion.

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ARTIFICAL NEURAL NETWORK PROCESSING

From the above investigation it has been seen that the ionisation and rate of ionisation signals have relationships with duration of combustion, timing of combustion and to a certain extent may show information on rate of combustion and knock. However for peak pressure magnitude it was difficult to see a relationship as the AFR changes, although there did seem to be correlation with peak cylinder pressure at each of the AFRs. Currently the investigation has only considered point to point relationships and linear relationships between them. By using a neural network it will be possible to train the network to find the relationships between ionisation signal, rate of ionisation signal and the pressure trace. By using the neural network it may be possible to find relationships between all the points of the signals and relationships that may not be linear that are not clear through visual inspection of the signals.

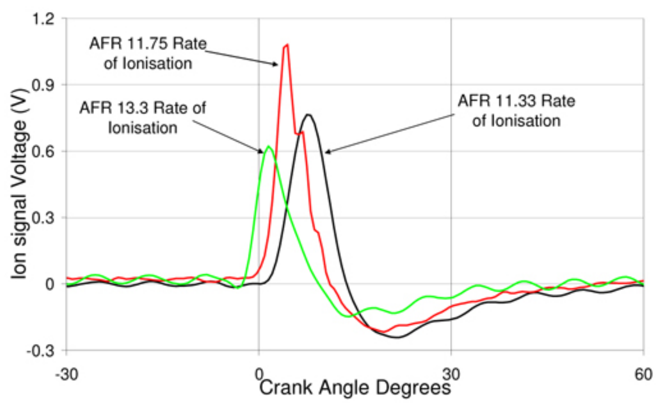

Figure 26. comparison of typical rate of ionisation signals

The "nftool" in MATLAB has been used to produce the neural networks. The settings used in this work are 20 hidden neurons, 70% data training, 15% data validation, and 15% data testing. Two networks were created, one for ionisation and the other for rate of ionisation. For each neural network only the ion signals for AFR tests at 11.33 and 13.3 were used as inputs and the corresponding pressure signals were used as the desired outputs. These sets were then split up randomly by the program so that 70% of the traces were used for training, then 15% for validation, and the reminding 15% for testing. This makes a total of 42 combustion cycles for training then 9 for validation and 9 for testing.

At the beginning of the training there will be large error between the network output and the desired pressure trace. This error is back-propagated through the neural network layers and used to update weights at each neuron. Through this process of weight adaption, the relationships between the inputs and the outputs are generalized and stored with in the combination of weights through out the network. When the neural network has an input not with in its training knowledge, it can approximate the output from the generalized relationships held within its knowledge. If the unknown input differs significantly from the inputs that the network has been trained upon; the generalized relationships will be less applicable and the output error will increase. As the neural networks have been trained from data taken at AFR of 11.33 and 13.3, obtained knowledge will give an approximation of the outputs for the unknown inputs at an AFR of 11.75. Once the two networks where created the appropriate ion signals for test condition AFR 11.75 where used as inputs to give predictions of cylinder pressure. The predicted pressure traces are compared against the real pressure traces for this operating condition.

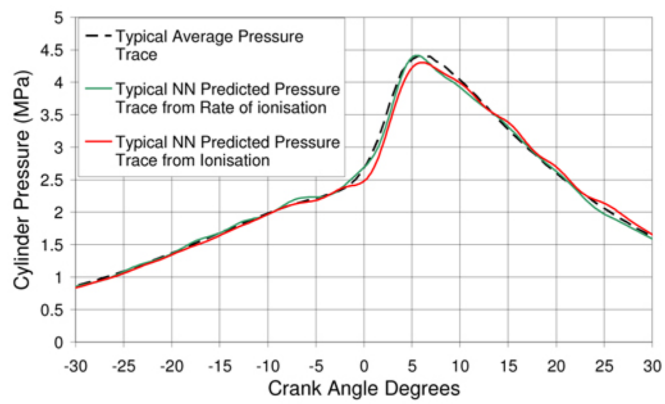

Figure 27. Comparison of Typical Average Pressure Trace and Neural Network prediction of Pressure trace

Figure(27) shows a comparison between typical pressure trace and predicted pressure trace from neural networks trained from rate of ionisation and ionisation signals for test condition AFR 11.75. It is possible to see that even with a limited data set it can predict the basic shape of the pressure trace although there are errors around peak position and magnitude and around the point of inversion. From the predicted pressure trace it will be possible to estimate peak pressure position, peak pressure magnitude and maybe combustion duration.

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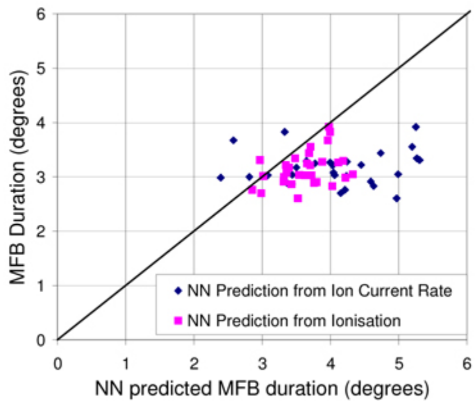

Figure 28. Correlation of Peak Pressure Position And Neural Network Predicted Peak Pressure Position For AFR 11.75

Figure(28) shows the correlation between peak pressure position and the neural networks predictions of peak pressure position for networks trained on rate of ionisation and ionisation signals. The error for prediction from rate of ionisation is 17.71% and 13.7% for ionisation.

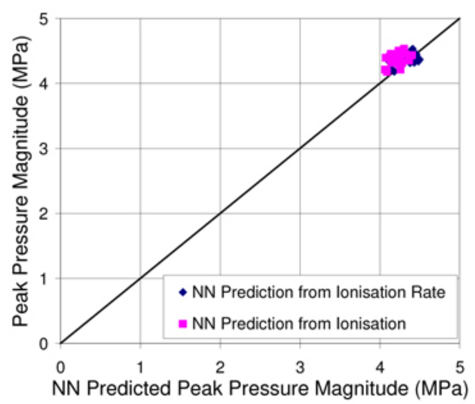

Figure 29. Correlation of Peak Pressure Magnitude and Neural Network Predicted Peak Pressure Magnitude for AFR 11.75

Figure(29) shows the correlation of peak pressure magnitude and predictions of peak pressure magnitude from neural networks trained from the rate of ionisation and ionisation signals. The error for the network prediction trained from rate of ionisation is 2.38 % and for ionisation trained 3.72%. This level of accuracy is surprising considering the relationship between both peak ion rate/peak ionisation, and pressure magnitude did not show the same behavior. For purpose of comparison a prediction of the AFR 11.75 Peak Pressure Magnitude was calculated from the results of AFR11.33 and AFR13.3 peak rate of ionisation magnitude, the average error was 16%.

Therefore training of neural networks to find relationships between ionisation and pressure trace is capable of finding relationships that at this time, is not clear from visual inspection of the signals alone. The neural networks may well be finding relationships between several points on the input and output to makes these predictions where as with the visual inspection we only consider a single point to point comparison. This finding is a good demonstration of the use of neural networks for their capability of pattern recognition.

Figure(30) shows the correlation between MFB duration and predicted MFB duration calculated from pressure traces predicted from Neural Networks trained from rate of ionisation signal and ionisation signal. The error for the network trained on rate of ionisation is 34.66% and the error for the network trained ionisation is 16.25%.

SINGLE INPUT OUTPUT NEURAL NETWORK

The neural networks so far have been constructed to accept the entire ionisation or rate of ionisation signals as inputs, to give an entire cylinder pressure trace output. A simplification to make feedback more efficient could be a reduced neural network architecture that only accepts singular values for the point to point relationships. From the point to point relationships for combustion timing, the results of 75% ionisation offered the smallest error as shown in Figure(18). To train a neural network to predict peak pressure position from the timing values of the 75% ionisation, input-output data pairs need to be presented to the architecture. The architecture is smaller then the previous. As the number of hidden neurons have been reduced from 20 hidden neurons to 8 to get better representation of the data.

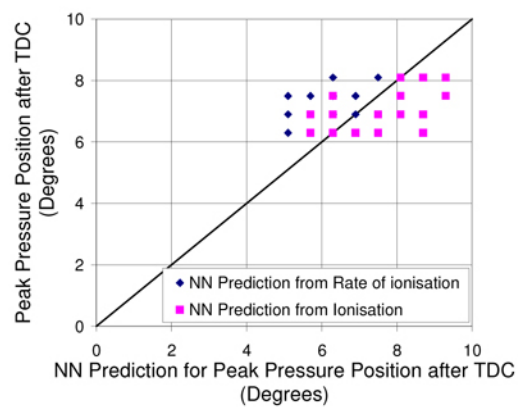

Figure 30. Correlation Between MFB duration and MFB duration Calculated from NN prediction for AFR 11.75

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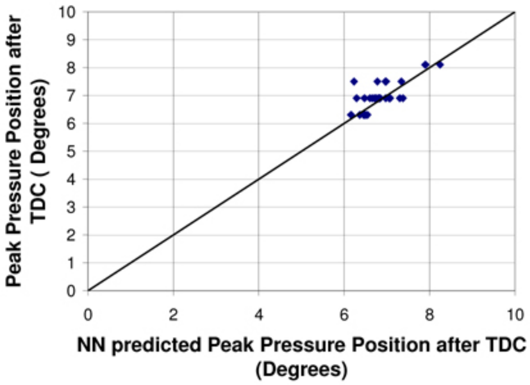

Figure 31. Correlation between Peak Pressure Position and Neural Network prediction Peak Pressure Position from 75% ionisation location.

Figure (31) shows the correlation between measured peak pressure position and predicted peak pressure position for AFR 11.75 from the reduced neural network architecture trained on 75% ionisation location. The average error of the prediction is 4%. This is a improvment over the prediction seen in figure (30) with an error of 16.25%. By reducing the input data and output data to the key components of the signal that hold the relationship, the reduced architecture prediction can have better accuracy. By reducing the input output size the network is no longer trying to generalize relationships for the entire trace but for a single point. This allows the network to represent that point more clearly.

Overall the results from all the neural networks are promising. They have shown the capability of predicting the shape of the pressure trace, and show that there may be further relationships between ion current signals and pressure signals that are not initially obvious from inspection. The accuracy of the prediction of peak pressure magnitude is one instance where the neural networks have been able to find relationships that have been unclear. Where relationships are more clearly seen, like combustion timing, the reduction of the input output data for the network has improved the networks performance. By limiting the data it allows just the key information about the relationships to be mapped in the networks weights.

The drawback of neural networks is that the accuracy is directly related to the spread of data used for training. To develop an applicable feedback system, full range engine data would be needed. The neural network can generalize its knowledge to predict outputs for unknown inputs between the training data sets. However, the further the unknown inputs are away from the training knowledge, the accuracy would decrease.

COMPARISON OF FEEDBACK

This study has shown several methods for gaining feedback information from ionization. The ionisation signals can be used as a whole or in part with neural networks. This allows prediction of pressure trace or its parameters. The ionisation signal could also be used directly. Ionisation has show relationships with pressure trace proving it to be related to combustion.

The purpose of a feedback signal is for supplying a control architecture with information. A feedback control architecture's performance will be effected by the efficiency and accuracy of the feedback signal. It can be seen already that the neural networks performance can be improved by carefully selecting the appropriate input and output data.

Table 2. Comparison of variance for feedback of combustion timing with peak pressure position.

	Real peak pressure position	NN using entire ion trace predicted peak pressure position	NN 75% value ion trace predicted peak pressure position	Direct ion trace 75% value
Variance	0.275	1.275	0.248	0.275

Table 2 shows the comparison of the variance for the three feedback methods compared to peak pressure position variance. The direct ion trace 75% value offers a feedback with the closest variance match to that of real peak pressure position. The neural network prediction using the entire ionisation trace offers the worst. However the reduced input, 75% ionisation location neural network, shows substantial improvements. Nevertheless the predictions have lower variance than the real peak pressure position showing inaccuracy.

Ionisation is a direct feedback of the combustion. It offers the closest match to combustion timing variation than any predictions made from it. Using the ionisation signal itself can therefore offer a more efficient feedback for combustion timing then converting to cylinder pressure for information.

CONCLUSION

Ionisation and rate of ionisation signals both show a relationship of timing with combustion. This has been demonstrated to varying accuracy at points along the signals in comparison to Peak Pressure Position. Overall the ionisation signal was seen to have better accuracy for information on combustion timing compared to the rate of ionisation signal. Ion current has shown the ability to predict location of peak pressure position to an average error of the

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three operating conditions of 5.24%. this shows that ion current has a relationship with combustion timing and could be used for timing feedback.

Further conclusions from the comparison of the locations compared are:

- Start of ionisation has a larger variability than peak pressure position. The start of ionisation is effected not only by the timing of the combustion but also the location of the combustion.
- Taking points further up the rising edge of the signals offers more accurate timing results as it reduces the effects of base line noise. Points between 50 and 75 % have offered the smallest error on timing predictions.
- Peak position of rate of ionisation and ionisation tended to have slightly larger variation than results from locations of 50% and 75%.

The ionisation signals have also shown a relationship between the duration of ionisation and the duration of the MFB for the three different AFRs. As the MFB increases and decreases cycle to cycle, the ionisation follows the trend. This shows that there is a potential relationship between ionisation duration and combustion duration.

The rate of ionisation signal has shown strong spikes within the peak of the signal, this represents rapid changes in the rate of ionisation. This characteristic maybe linked with combustion occurring at multiple sites of the cylinder. This relationship could give the ability to detect knock, and auto ignition combustion.

The peak value of the rate of ionisation tends to show an inverse relationship with timing location of peak pressure. This shows a potential relationship for combustion duration.

Leaner AFR was seen to have an effect of reducing the magnitude of ionisation and a decrease in duration.

At small changes in AFR the peak magnitude of ionisation can be misleading if combustion timing changes. The peak magnitude is effected by timing of peak ionisation. As ionisation is a local reading it is effected by the density of the gas due to volume change.

Neural networks can be trained to predict pressure trace from ionisation signals and rate of ionisation signals. From these predicted pressure traces it is possible to estimate combustion duration, peak pressure position and peak pressure magnitude.

The neural network prediction of peak pressure magnitude had a much smaller error or 2.38% compared to prediction from point to point relationships 16% error. This shows Neural Networks capability of pattern recognition and capturing relationships that may not be clear through inspection of the signals.

Neural network performance was seen to improve if input-output data can be reduced to the key parameters of interest with a particular relationship.

Overall pressure trace can offer visual feedback for peak pressure position, peak pressure magnitude, knock and combustion timing. Through calculation combustion duration and start of combustion can be estimated.

Feedback parameters directly obtained from ionisation match variance of combustion timing with better accuracy than predictions of peak pressure position from ionisation through neural networks. It is potentially an efficient feedback signal for two stroke HCCI combustion.

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