Law, D 2010, CAI/HCCI Combustion Modeling and the Effects of SI-CAI-SI Switching on Engine Performance and Emissions

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CAI/HCCI Combustion Modelling and the Effects of SI-CAI-SI Switching on Engine Performance and Emissions

1. ABSTRACT

The operation of two engines, both with mechanical variable valve timing, was simulated under the controlled auto ignition (CAI) or homogeneous charge compression ignition (HCCI) mode of combustion.

The two engines were a 1.6L direct injection and 2.0L port injection engine. These are production engines (using conventional spark ignition), currently available in Europe.

Both engines investigated the effect of valve timing on combustion performance and engine exhaust emissions. Valve timing was varied while the fuel flow was held constant.

It was shown that varying valve timing and the overlap of intake and exhaust valve timing affected power, torque, in-cylinder temperature and exhaust emissions.

The anticipated advantage of CAI for reduction of NO_X and CO emissions could be shown.

During the research, the dependence between internal exhaust gas recirculation (EGR) values and the engine key values shown by the simulations were observed. Increasing the EGR value resulted in a decrease of power, torque and emissions of NO_X and CO.

With the exhaust gas trapping method (CAI/HCCI), varying the valve opening timing affects engine idle stability and confirms engine researchers' observations that CAI/HCCI engines can only be operated successfully in the part-load regimes.

The modeling and simulation data is thus validated by numerous real single and multi cylinder engine studies. This study successfully simulated evidence of the spark ignition-controlled auto ignition-spark ignition (SI-CAI-SI) combustion mode switch and *vice versa*.

It was possible to simulate the combustion mode switch in both the direct injected (DI) and in the port fuel injected (PFI) combustion engines.

2. KEY WORDS

DI	-	Direct Injection
PI	-	Port Injection
SI	-	Spark Ignition
CAI	-	Controlled Auto Ignition
HCCI	-	Homogeneous Charge Compression Ignition
EMOP	-	Exhaust Maximum Opening Point
EVDUR	-	Exhaust Valve Opening Duration
IMOP	-	Inlet Maximum Opening Point
IVDUR	-	Intake Valve Opening Duration
EGR	-	Exhaust Gas Recirculation

3 INTRODUCTION

Controlled Auto Ignition promises low particulate and low NO_X emissions, combined with relatively high engine thermodynamic efficiency. The principle is a combination of classical Otto and Diesel engines in that a premixed charge is ignited by residual-gas activated compression heat. The enabling technology to combine these two forms of combustion is flexible valve trains (electro-hydraulic and electro-magnetic controls).

Today's automobile industry is focused on faster development time and legislative-driven improvement in engines. These foci affect all the events and ideas in research, development prototyping and mass production.

In the past, considerable time was spent on the development of engines, despite the fact that feed-back loop between engine prototype construction and experiment was difficult and time-consuming. To solve these problems engine computer simulations were established to model the mechanics, physics and chemical aspects. The models have been well –tested by experimenters and nowadays most industry based models require only engine specific information to produce reliable results. During the last ten years, computer software has *come of age* and provides engine development teams with result that reliably predict the function of working engines, without the need for elaborate and costly experimental facilities. Detailed simulation work and results can be evaluated or validated on prototype engines, minimizing the extent of changes required before commitment to the production engine design.

One of the best-recognised simulation software packages is called WAVE [11], developed by the British company Ricardo. This program represents leading engine performance and 1D-2D gas dynamics, which is able to simulate all the processes during all operations of an engine.

In the last few years significant technical progress in improving the efficiency of combustion engines has taken place and much of this research has involved the progressing CAI or HCCI t towards maturity.

In August 2007, the first publicly drivable vehicle powered by a CAI or HCCI gasoline engine was unveiled by General Motors (GM). The base engine was the 2.2L Ecotec four-cylinder engine, modified using cam profile switching (CPS) to combination of CAI and SI operating modes.

This work follows on from data published by the Ford Motor Company in 2003, but in that case the engine data was test cell based [10]. This paper represents published data from an SI-HCCI-SI fully production orientated multi cylinder engine.

This paper is focused on the crucial engine combustion switch between SI mode and the CAI mode and vice versa, and on changes in combustion key data such as NOx, CO, HC emissions, cylinder temperature and power as related to the valve opening durations.

The research work here is believed to be the first such use of the WAVE engine simulation to strategic operation of the engine. Numerous simulation studies prior to this work have focused on the detailed chemical kinetics of CAI/HCCI combustion.

4. COMBUSTION MODE CHANGE IN GENERAL

Combustion mode changes from SI to CAI/HCCI can be accomplished within a single engine cycle provided valve timing and fuel injection quantities can also be adjusted within one engine cycle. In addition, when the engine is operated un-throttled in SI mode, there is little difficulty in effecting the transient combustion response. In the SI mode pre-combustion switch (from conventional SI), the engine is operated with slightly modified valve timing to allow the engine to be temporarily operated un-throttled: specifically, the intake valves are closed earlier to limit the captured mixture mass.

As Koopmans *et al* [1] mention, a CAI mode change from SI engine operation (and vice versa) is required at low to mid range engine speeds. At higher engine speeds, the need to retain the required fraction of residuals needed for combustion ignition results in shorter valve opening periods and consequently lowers the engine volumetric efficiency.

If the flexibility of the valve motion is constrained, the resulting loss in airflow restricts the power attainable in CAI operation and the engine has to switch to SI operation.

5 THE SIMULATION MODEL

In creating the WAVE models, WAVE-Build is used. WAVE-Build is the primary pre-processor used for any WAVE analysis and is the starting point for the simulations using WAVE programs. The user defines the system by laying a series of unit elements that represent the engine system components on a "canvas". Boundary conditions (inlet pressures and temperature, wall temperatures, and operating conditions for complex machinery such as engine cylinders, turbines/compressors, and pumps) are defined as well as initial conditions for each duct/element.. The next step is to run the *solver* within the simulation model. WAVE simply reads input data, processes it, and creates the final output data from the simulation.

The results of the simulation are viewed with a post-processing program called WAVE Post. This views and interprets the results provided by the solver for the simulation, enabling visualisation and report-generation. Within WAVE Post, the user can view plots requested from the analysis during setup in WAVE Build, or create new plots of results generated by the simulation.

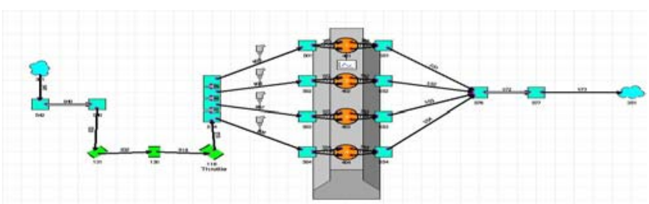

Figure 1: Model of the 2.0L Port Injection Engine

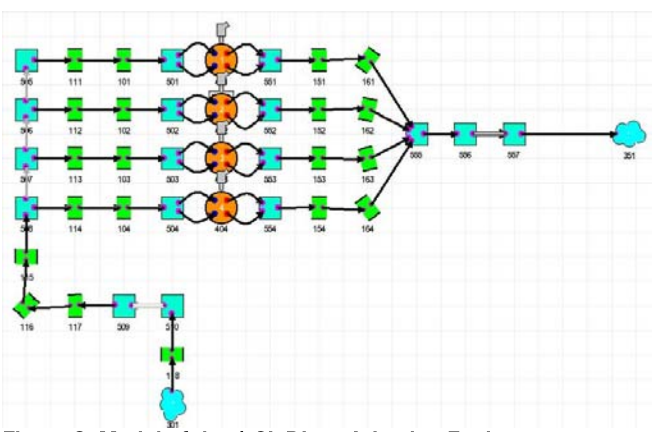

Figure 2: Model of the 1.6L Direct Injection Engine

6 EXPERIMENTAL

2.0 L PORT INJECTION ENGINE

The engine modeled for this part of the investigation was a port injection engine with four cylinders, four valves per cylinder (figure 1) and a total displacement of 2.0 liters. Operation was simulated over a typical range of speed-load conditions (between 1000 and 5000 revolutions per minute (RPM). Engine parameters were set as shown in Table 1.

Table 1: PI Engine Data

	Unit	Value
No. of Cylinders	[-]	4
Valves per Cylinder	[-]	4
Valve Lift	[mm]	6.0
Bore	[mm]	85.0
Stroke	[mm]	88.0
Compression Ratio	[-]	10.5
Inlet Valve Diameter	[mm]	31.0
Outlet Valve Diameter	[mm]	27.0

<u>Baseline</u>

For analysis of the subsequent CAI investigations, combustion mode SI baseline plots have been experimentally created. The key data pressure (Fig. 3), power (Fig. 4), torque (Fig. 5) and emissions (Fig. 6) were plotted. These plots can be viewed below:

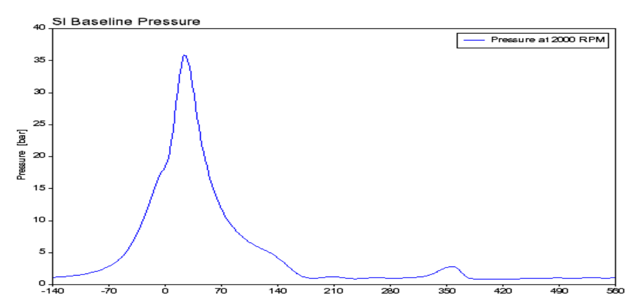

Figure 3: Pressure Baseline of 2.0 L PI Engine

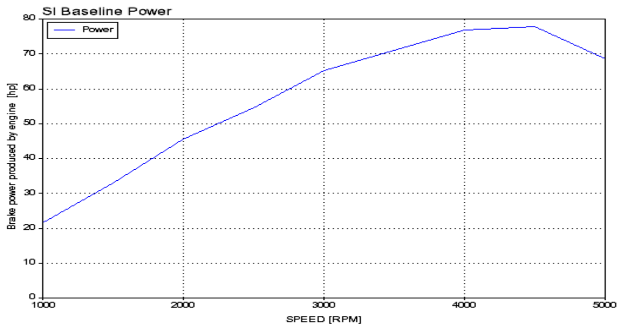

Figure 4: Power of 2.0 L PI Engine

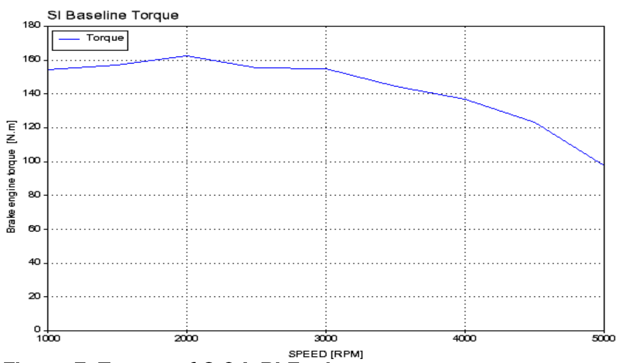

Figure 5: Torque of 2.0 L PI Engine

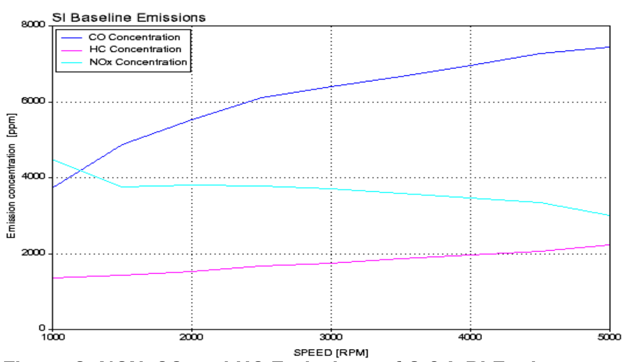

Figure 6: NOX, CO and HC Emissions of 2.0 L PI Engine

Varying Valve Timing

Running the engine model in CAI mode, the change from standard positive overlap valve timing to negative overlap valve timing is necessary. Figure 7 shows the difference between both valve timings. The negative overlap valve timing allows the engine to trap exhaust gas during the engine cycle.

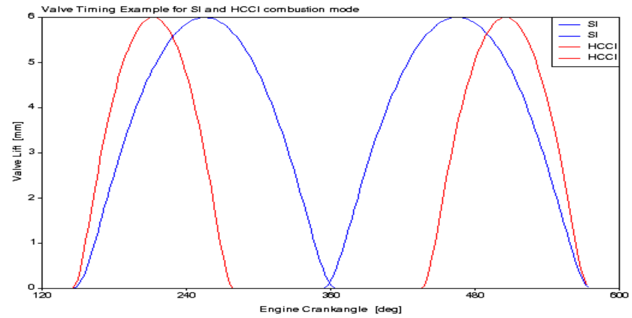

Figure 7: Typical Valve Timing during SI (blue) and CAI (red) Mode

The standard valve opening durations IVDUR and EVDUR as well as EMOP and IMOP can be found in table 2. These are typical positive overlap valve opening time data.

Table 2: Valve Timing of the Baseline Setup

	Unit	Standar Value
EVDUR	[deg]	220
EMOP	[deg]	255
IVDUR	[deg]	225
IMOP	[deg]	440

Effect of Varying Valve Timing

During this research, the influence of varying valve timing on engine key values was investigated. Therefore four different valve timing values for negative overlap valve timing were introduced. They were determined during earlier investigations on real engines [2-4]. The valve timings which have been used during this research are illustrated in Table 3 below.

Table 3: Valve Timings for the different EGR (%) Values

	Unit	23.0 %	31.7 %	40.9 %	50.1 %
EVDU	[deg]	165	155	145	135
EMOP	[deg]	227	222	217	212
IVDUR	[deg]	165	154	144	141
IMOP	[deg]	493	498	503	505

Pressure

The pressure chart for CAI mode is shown in Figure 8. The EGR was set to be 23.0% EGR by trapped volume. It shows that the maximum pressures in the first peak are reached between 1000 and 3000 RPM. The maximum of the second peak is reached at 4000 RPM.

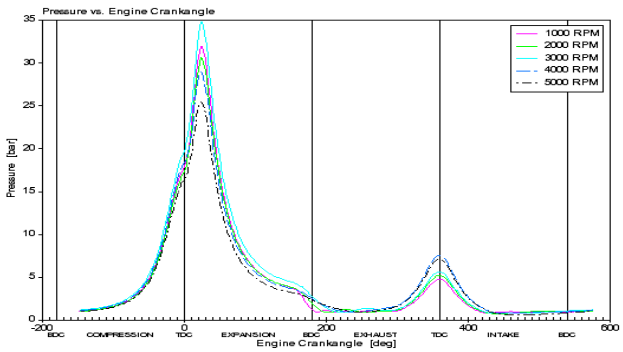

Figure 8: Significant CAI pressure chart at 23.0 % EGR

Power

The model predicts some difficulty in achieving optimum power output, Figure 9. The results of the first test series show the differences between the engine power output in SI mode and CAI mode. It was found that the differences at lower engine speeds were not significant. This result confirms earlier research projects on running CAI engines conducted by Koopmans *et al* [1].

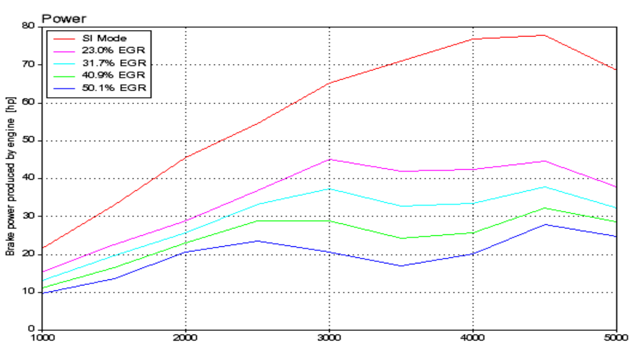

Figure 9: Comparison of Power with different EGR values

Torque

The influence of the amount of trapped exhaust gas in CAI mode is shown in Figure 10. Torque output decreases after reaching an engine speeds of ~3000 RPM quickly. This was not observed in standard SI mode. The maximum torque output is also dependent on the amount of trapped exhaust gas. A higher percentage of trapped exhaust gas produces a reduced torque output.

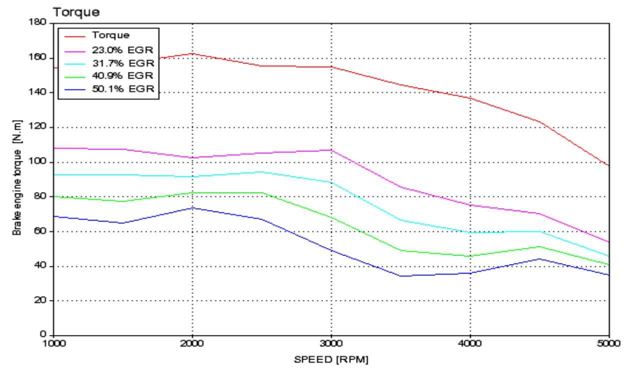

Figure 10: Comparison of Torque versus Engine Speed recorded during different EGR Values

In-Cylinder Temperature

During combustion, the temperature is both increasing (compression) and decreasing (combustion expansion) quickly. In SI mode, the air/fuel mixture ignites and the highest temperatures are reached producing peak in-cylinder temperatures of around 2530K. Lower peak temperatures can be observed in CAI mode (20% reduction) and due to this, the engine emissions generated in CAI are decreased especially for NO_X.

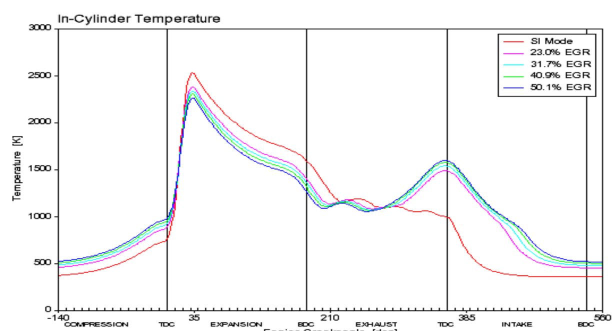

Figure 11: In-Cylinder Temperature

Emissions

Demand for fuel efficient and low emissions engines is higher than any time before. Thus, the effect of varying valve timing on emissions is one of the most considered parts of this research. The influence of NO_X, CO and hydrocarbons (CO) was also investigated.

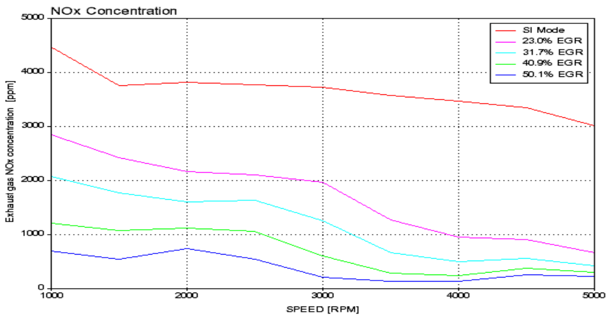

Figure 12: NOX Emissions

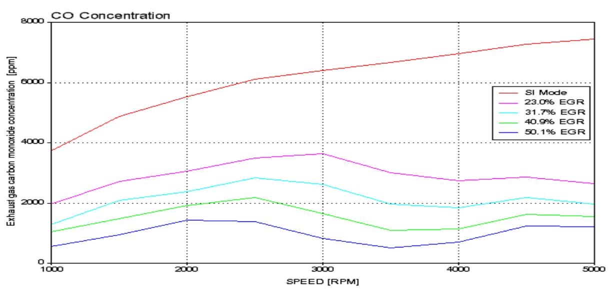

Figure 13: CO Emissions

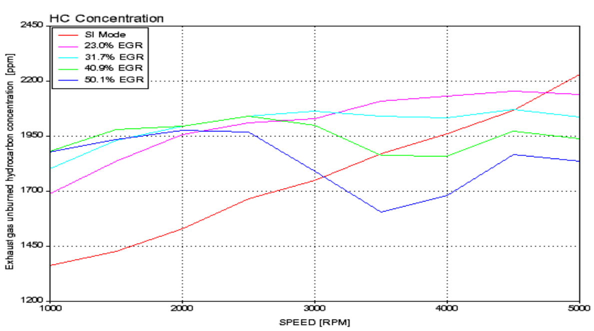

Figure 14: HC Emissions

It is shown that the CAI combustion mode has a significant positive influence on NO_X and CO (Figure 13) emissions. With an EGR value of 23.0 %, the emissions at engine speeds of 2000-3000 RPM can be reduced by about 40 % for NO_X and 45 % for CO (Figure 14 and 15), when compared to a standard SI engine. The disadvantage of CAI with hydrocarbon (HC) emissions is illustrated in Figure 14. The reasoning for this will be addressed in detail in a subsequent paper.

1.6 L DIRECT INJECTION ENGINE

The engine, shown in Figure 2, is a port injection engine with four cylinders, 4-valves per cylinder and a the total displacement of 1.6 liters. Engine operation was simulated over a typical range of speed (1000 to 5000 RPM) Engine parameters were set as shown in Table 4.

Table 4: Engine Data

	Unit	Value
No. Of Cylinders	[-]	4
Valves per Cylinder	[-]	4
Valve Lift	[mm]	6
Bore	[mm]	78.1
Stroke	[mm]	82.0
Compression Ratio	[-]	10.0
Inlet Valve Diameter	[mm]	28.0
Outlet Valve Diameter	[mm]	23.5

The simulated operation of this engine was initially plotted for a conventional engine SI mode, to establish a clear reference point. Key SI derived values of the engine will be compared with the CAI engine combustion modes.

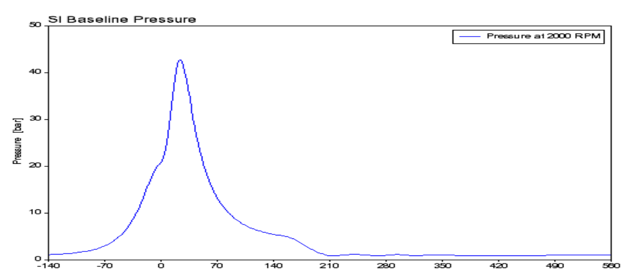

Figure 15: Pressure Baseline of 1.6 L DI Engine

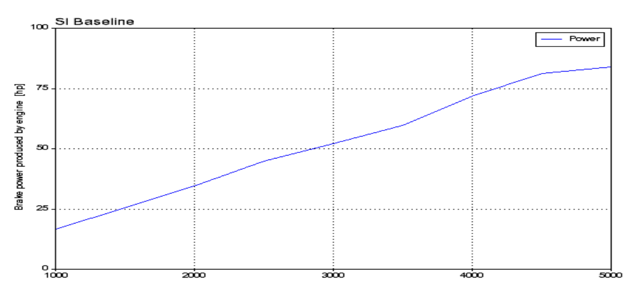

Figure 16: Power of the Engine in SI Mode

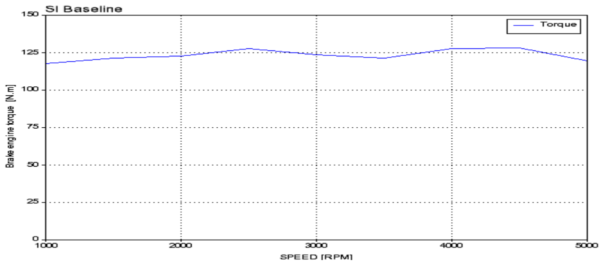

Figure 17: Torque of the Engine in SI Mode

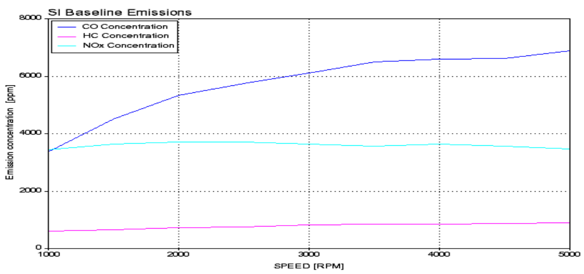

Figure 18: Emissions of the Engine during SI Mode

<u>Varying Valve Timing</u>

Pressure

The pressure chart of homogeneous charged compressed ignition combustion has a very distinctive shape. The second peak occurs due to the negative overlap of the cam profile. The exhaust gas will be trapped and because of this, the in-cylinder pressure increases.

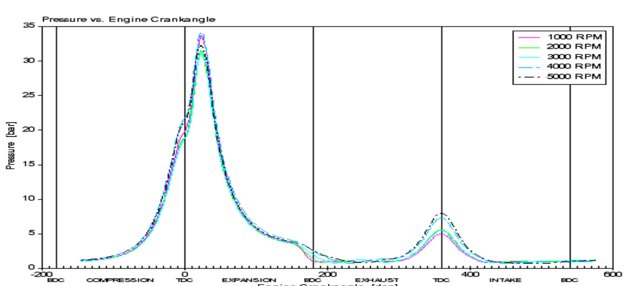

Figure 19: Significant CAI Pressure chart (23.0 % EGR)

Power

As mentioned in the chapter of the port injected engine, similar results are obtained for the direct Injection (DI) were power output is observed to be decreasing while increasing the quantity of trapped exhaust in the combustion chamber. The results of this test series reveal differences between the engine power output in SI mode and CAI mode of the DI engine. It was also observed that differences in performance at slower engine speeds were not as apparent as observed with the PI engine. This again validates and confirms earlier research in CAI combustion [1].

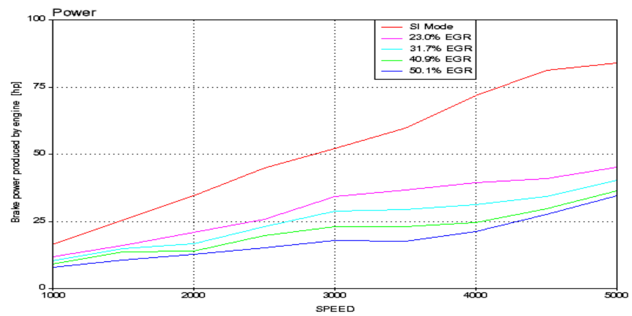

Figure 20: Comparison of Power Charts with CAI combustion Mode Levels

Torque

Compared with the PI engine, torque outputs of the DI model in SI mode is as well as in CAI mode more stable.

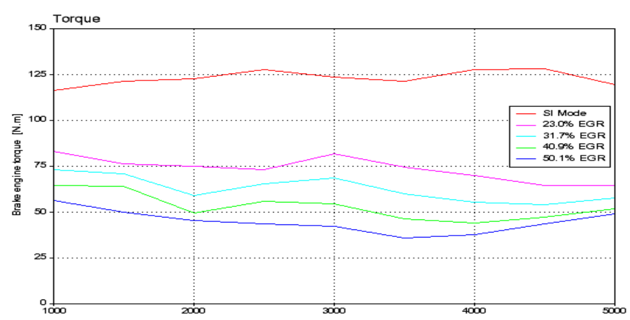

Figure 21: Comparison of Torque

In-Cylinder Temperature

Figure 22 shows the in-cylinder temperature during the combustion cycle. It was observed that the peak temperature of SI combustion is generally higher than in CAI mode. Again as with the PI engine, this has a direct effect on NOx/CO and HC emissions.

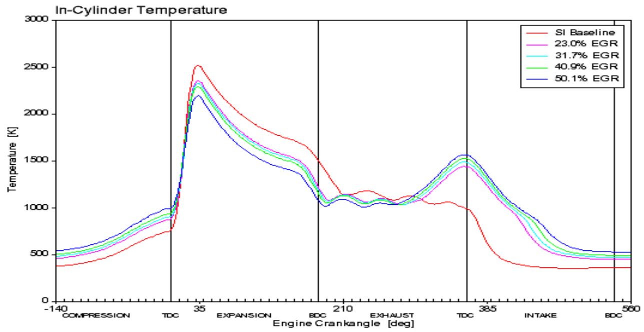

Figure 22: In-Cylinder Temperature during Combustion Cycle

Emissions

The influence of the EGR trapped mass percentage was investigated. Thus first a measurement in standard SI mode was made. With the experiments of the engines in EGR trapped mode, a comparison of the emissions was possible.

As expected, the advantage of the CAI combustion is a less NO_X emission then in regular spark ignited combustion engines. This advantage is considerable with an EGR trapping volume of 23.0%. The low emissions of NO_X result directly from both dilution homogeneous air and fuel mixture with trapped exhaust gas in addition to lower combustion temperatures [6]. Internal EGR settings from 31.7 % to 50.1 % decrease CO emissions. It should keep clearly in mind that with these settings the amount of power and torque are low level. In this case HC emissions are on a similar level to the PI engine. The emissions are illustrated in Figures 23, 24 and 25.

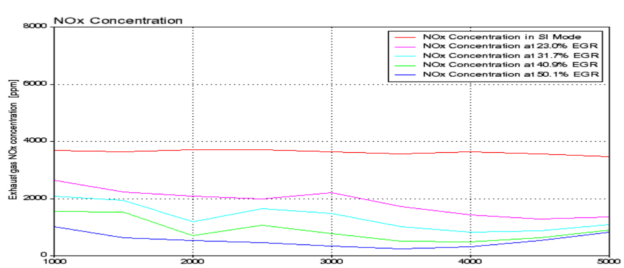

Figure 23: NOX Emission at different EGR Values versus Engine Speed

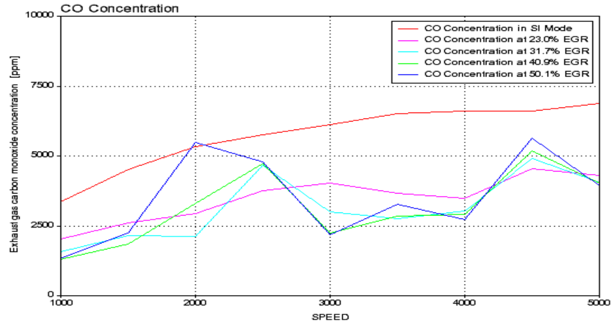

Figure 24: CO Emissions at different EGR Values versus Engine Speed

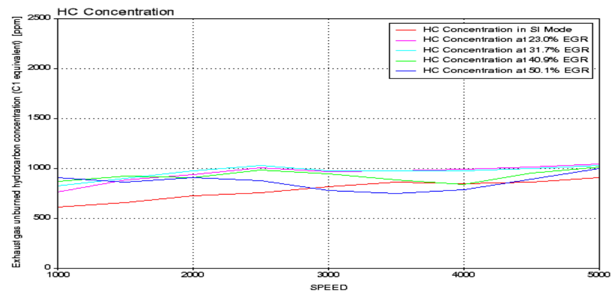

Figure 25: HC Emissions at different EGR Values versus Engine Speed

7. SWITCHING BETWEEN SI AND CAI COMBUSITON

The experiments show that CAI can reduce exhaust gas emissions significantly. NO_X and CO concentrations in particular were decreased dramatically.

CAI usefulness appears to be limited to a small range of engine speeds, generally between 2000 RPM and 3000 RPM as Koopmans *et al* confirm [1]. At lower speeds the engine operation is unstable in CAI combustion mode. Therefore it is necessary to simulate the switch between SI combustion and CAI combustion and vice versa, as the engine speed traverses normal operational ranges.

Conventional formulations of petrol were chosen as fuel type.

To prepare for the simulation of the switch between SI and CAI, real engine data files were used to provide cam profile, heat release data and cam phasing events. A software based sensor was installed on one of the simulated cylinders to record simulated cylinder pressures. Then the engine speed was set to 2000 RPM, this being the point where stable CAI combustion is easily achieved. For the first experiments, the engine speed was stabilized at the low value (1000rpm), and then progressively increased (1000-5000rpm) to observe the effects of the switching phenomenon.

MODE SWITCH IN THE 1.6 L DI ENGINE

Figure 26 shows the sensor data plot taken from the SI-CAI-SI combustion switching engine. The data clearly shows the single-peak, characteristic of SI combustion having been substituted by the dual-peak (now containing the internal exhaust gas trapping) of the CAI combustion. This simulation data researched and presented here is an accurate simulation of recent work on a real (2.0L) 4-cylinder cam profile switching (CPS) engine [10]. The data also shows the success of the simulation research in returning back to conventional SI combustion.

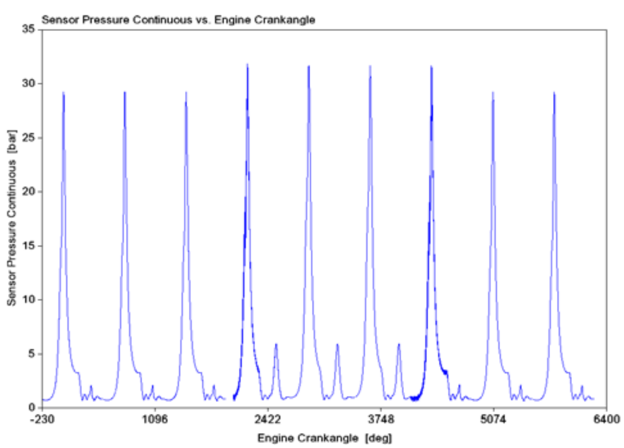

Figure 26: Switch between SI and CAI Mode and vice versa

Further validation of this research work and the accuracy of the simulation model can be seen in Figure 27, were a combustion mode switch between CAI and SI is shown in a 5-cylinder VOLVO engine. The comparison between the WAVE simulation and experiments with the real engine show that the simulation is very close to reality.

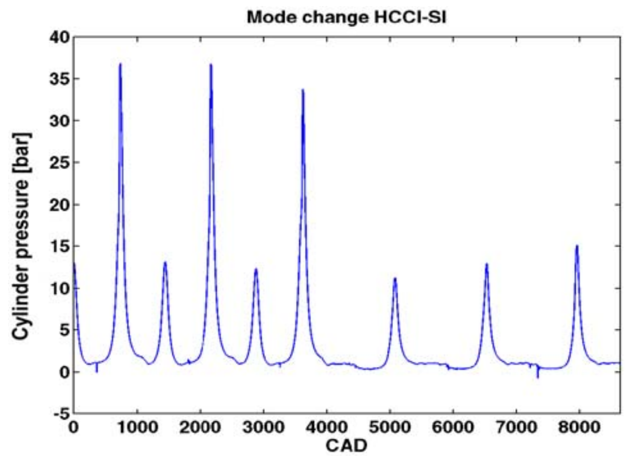

Figure 27: CAI-SI switch done in a 5- cylinder Volvo engine [1]

SWITCH IN THE 2.0 L PI ENGINE

The simulation of the switch between SI and CAI and vice versa was also done on the 2.0 L PI engine. The engine speed was also started at 2000 RPM. As shown with the DI model, the SI-CAI-SI switch has been successfully accomplished by changing valve timing events as seen in Figure 28.

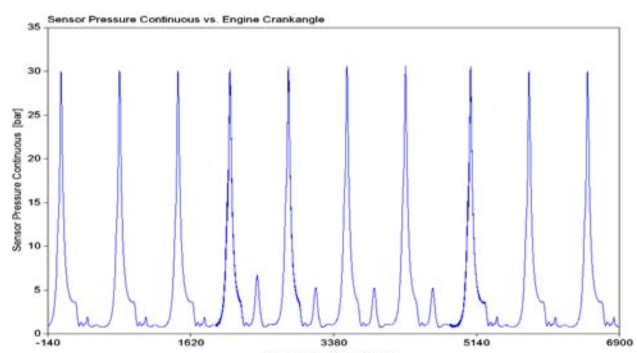

Figure 28: SI-CAI-SI Switch done with the 2.0 L PI Engine

8 CONCLUDING REMARKS

Traditional engine development approaches incur excessive development times and costs.

With multiple regulatory and economic design-criteria to be met, as well as the imperative to decrease development cycle times, there is a need for a software modeling approach that can adequately predict most aspects of engine performance prior to creation of a testbed engine. For this approach to be useful, the adequacy and validity of the model is clearly paramount.

Homogenous Charge Compression Ignition / Controlled Auto Ignition Charge describe a technology in which diluted fuel air mixture is ignited in multiple points within the cylinder. The technology promises major reduction in unburned carbon (particulate emissions) and in the production of NOx. The technology is only usable over certain load-ranges, and so working engines have to switch between HCCI/CAI mode and conventional ignition modes during the normal operation of the engine.

The paper demonstrates the application of a typical software modeling package, to modeling the performance of HCCI/CAI systems, and ignition changeover.

The modeled results for two typical engines are compared to actual results: As well as demonstrating some of the advantages and disadvantages of HCCI/CAI over conventional ignition technologies, the comparison between the modeled outputs and published actual engine data offer a good indication of the usefulness of the modeling approach

9. REFERENCES

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