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Characterizing the Effect of Combustion Chamber Deposits on a Gasoline HCCI Engine

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ABSTRACT

Homogenous Charge Compression Ignition (HCCI) engines offer a good potential for achieving high fuel efficiency while virtually eliminating NOx and soot emissions from the exhaust. However, realizing the full fuel economy potential at the vehicle level depends on the size of the HCCI operating range. The usable HCCI range is determined by the *knock limit* on the upper end and the *misfire limit* at the lower end. Previously proven high sensitivity of the HCCI process to thermal conditions leads to a hypothesis that combustion chamber deposits (CCD) could directly affect HCCI combustion, and that insight about this effect can be helpful in expanding the low-load limit. A combustion chamber conditioning process was carried out in a single-cylinder gasoline-fueled engine with exhaust re-breathing to study CCD formation rates and their effect on combustion. Burn rates accelerated significantly over the forty hours of running under typical HCCI operating conditions. Variations of burn rates diminished after approximately 36 hours, thus indicating equilibrium conditions. Observed trends suggest that deposits change dynamic thermal boundary conditions at the wall and this in turn strongly affects chemical kinetics and bulk burning. In addition, this work presents a methodology for investigating the thermal diffusivity of deposits without their removal. The experimental technique relies on a combination of instantaneous surface temperature and CCD thickness measurements. Results demonstrate a strong correlation between deposit thickness and the diffusivity of the CCD layer.

INTRODUCTION

The main principle behind HCCI is the compression of a homogenous mixture of air and fuel until chamber conditions are favorable for auto-ignition. The diesel-like efficiency is achieved thanks to un-throttled lean operation with high compression ratio, while premixed lean combustion leads to low temperatures in the combustion chamber and very low NOx and soot formation. The main challenge is the absence of a direct trigger for combustion and limited range of HCCI operation. For a quick primer on HCCI, refer to Stanglmaier and Roberts [1]. A likely technology roadmap for passenger car applications will be development of dual mode engines, i.e. engines that will operate in the HCCI mode at part load, and then switch to spark-ignition (SI) mode at high load beyond the HCCI *knock* limit, or at very low load, below the *misfire limit*. Advanced engine subsystems, such as direct injection of gasoline, variable valve actuation and/or variable compression ratio are required for practical implementation of this concept. Control challenges stem in part from HCCI engine's extreme sensitivity to thermal conditions, e.g. charge temperature or combustion chamber wall temperature. The latter is significantly affected by deposits and hence the motivation for this work.

Combustion chamber deposits (CCD) in internal combustion engines have been extensively studied in the past, e.g. CCDs were noted for increasing the risk of knock or the *octane requirement* in SI engines. Since HCCI combustion is sometimes referred to as "controlled knock", it is expected that, in the case of an HCCI engine, deposits will affect the main combustion event. The main goal of this investigation is to quantify the effect of CCD on HCCI combustion, provide insight into the properties of deposits in an HCCI engine and assess mechanism behind their effect on combustion.

There is a substantial body of work on deposits in conventional SI or CI engines [2,3,4,5,6], but there is no previously published work addressing deposits in the HCCI engine. The approach in this study will be to relate deposit formation to features of HCCI combustion by making connections through other common threads. For instance, since HCCI is driven by thermo-kinetics, the thermal conditions existing in the combustion chamber have a tremendous influence on combustion rates and the nature of final products. Combustion chamber deposits are mostly known to have an effect on fuel octane requirements in an SI engine because of their inclination to increase the effective compression ratio and raise the temperature of the chamber surfaces. The change of autoigntion timing would indicate the dominant effect of the latter, while dynamic surface temperature and near-wall temperature gradients might affect bulk burning only. In addition, measurements of deposit thickness and instantaneous wall temperature allow calculation of CCD diffusivity and correlation with thickness. Consequently, the results complement combustion studies and offer valuable guidance for further development of CCD related diagnostic techniques. Greater understanding of the mechanisms behind the influence of deposits can further our ability to indirectly control HCCI ignition/combustion and offer solutions beneficial for future practical applications.

The paper is organized as follows. The background related to HCCI sensitivity to thermal boundary conditions is followed by an overview of previous findings regarding general properties of deposits and their effects on conventional SI or CI engines. The experimental setup is described next, including the instrumentation for instantaneous wall temperature measurement and non-destructive deposit thickness measurement. Subsequently, the effect of naturally formed HCCI deposits on combustion is tracked in time, and complemented with observations regarding the wall temperature and heat flux measurements. The insight into dynamics of CCD thickness build-up enables application of one-dimensional diffusivity analysis and provides basic information about the thermal diffusivity of deposits. The paper ends with conclusions.

BACKGROUND – HCCI SENSITIVITY TO THERMAL CONDITIONS

As mentioned earlier, one of the primary issues with HCCI is its range of operability. Because of thermo-kinetic requirements in the low load regime and excessive heat release rates in the high load regime, there is only a relatively narrow range of HCCI operability. These limits are outlined in detail by Thring [7]. It would be a significant step towards expanding practical use if methods could be devised to expand these limits, and one direction to pursue is through precise understanding and quantification of thermal effects.

<u>HCCI combustion and thermal conditions</u>

There have been several experimental as well as numerical studies focused at understanding the sensitivity of HCCI to thermal conditions [8,9,10,11]. Sensitivity of HCCI combustion parameters and local heat flux to variations in both coolant and intake temperature investigated by Chang et al. [12] is of particular interest for the present study. Specifically, the nature of changes in near wall thermal conditions versus core gas temperatures was compared. Just five degree changes in each have a significant influence on both ignition and phasing. However, the nature of the impact of intake charge temperature vs. coolant (wall) temperature is very different. As seen in Figure 1, examining individual cycles shows a very close correlation between burn duration and ignition timing, when intake temperature is varied. The high coefficient of correlation (R=0.92) confirms that all cycles follow the trend closely throughout the range of intake temperatures. The same was reported by Sjöberg et al. [13]. In contrast, Figure 2 shows stratified layering of data points corresponding to different coolant temperatures, i.e. the increasing coolant temperature causes burn duration to decrease more than what would be expected strictly from changes in ignition phasing. The resulting coefficient of correlation for all points is much lower (R=0.722). These differences illustrate a special nature of the wall temperature effect on heat release. While intake temperature has direct impact on core gas temperature and thus ignition, the coolant temperature variations affect near-wall regions and bulk

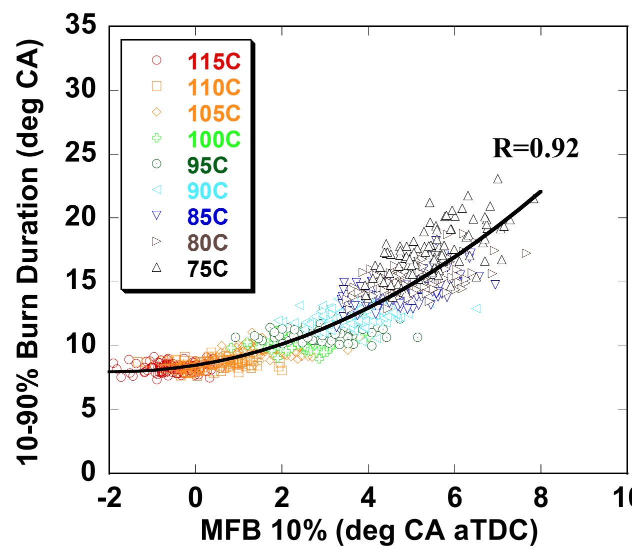

Figure 1: Burn duration versus ignition timing at varying intake charge temperatures, individual cycles [11]

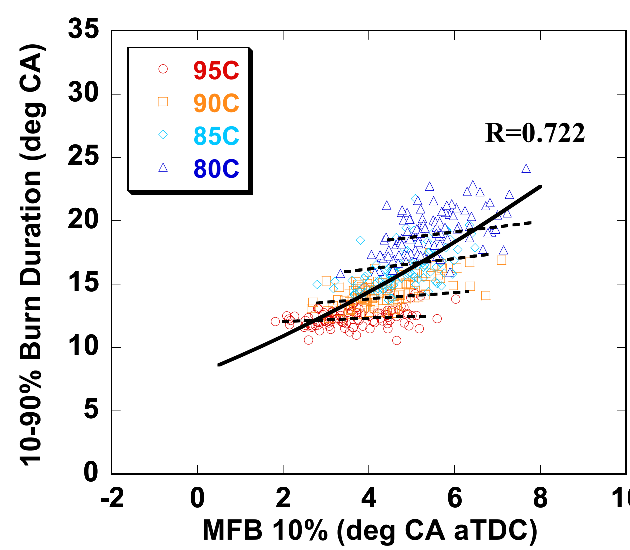

Figure 2: Burn duration versus ignition timing at varying coolant temperatures, individual cycles [11]

burning. In this light, it seems that CCD could potentially have high impact on bulk burning as well, due to their effect on dynamic variations of surface thermal conditions.

BACKGROUND - COMBUSTION CHAMBER DEPOSITS

'Deposits' can include any number of materials, excess, or residue that is gradually grown or accumulated on critical parts of an internal combustion engine. There are a number of varieties of engine deposits, categorized according to their location in the engine [2]. But the focus of this work is on combustion chamber deposits because these have the most direct influence on combustion and emission formation and they are also the most likely to have a unique effect on HCCI operation.

<u>CCD Formation Factors</u>

Generally speaking, combustion chamber deposits are formed from the condensation of fuel (or oil) on a metal surface. Gas and surface temperature and fuel composition are very influential in dictating the rate and type of CCD formation. The sources of condensed fuel can be leftover unburned fuel from incomplete combustion, extra fuel mass escaping from chamber crevice volumes, or fuel accumulated from direct injection spray impingement, as in a diesel CI or gasoline DISI engine.

Nakic et al. [4] confirmed the strong dependence on surface temperature as well as the critical temperature above which no further CCD formation occurs. Secondarily, the effect of different types of fuels on CCD formation was studied. It was found that, regarding the type of hydrocarbon molecules, the boiling point of the fuel was a good indicator for its tendency to result in deposit formation. Because of a greater chance of condensation, higher boiling point fuels, like aromatics (toluene and xylene) led to greater rates of formation than lower boiling point fuels like iso-octane, which is a saturated paraffin. Cheng [5] performed a study on CCD formation tendencies as a function of different operating parameters for a direct injection SI engine. While surface temperature is still the main parameter, it is shown how factors such as spark timing, equivalence ratio, and fuel type are important. Nevertheless, the most important thing to consider for these factors is how they in turn also affect chamber surface temperatures.

<u>Effects of CCD on SI and CI</u>

Deposits can have a significant effect on in-cylinder heat transfer. However understanding the details of how this effect varies under different modes of combustion, for example SI versus CI versus HCCI, and how it varies further at different operating conditions, has proven to be a challenge. This is primarily because in addition to the thermal effect of CCD on combustion, in many instances there is a not yet understood potential for additional physical influence due to absorption of fuel or gases in layer porosities.

Ishii et al. [6] confirmed through the use of fast response chamber surface heat flux probes that heat flux to the metal below a layer of deposit material decreases. The net heat transfer out of the chamber decreases for the cycle. This is the primary cause of octane requirement increases in an SI engine with deposit layers. However Woschni [14] shows the opposite is true for a CI engine. He suggests that the thermal storage capacity of soot and deposit on the wall of the chamber will cause the flame to burn closer to the present thermal boundary layer and actually increase the heat transfer to the wall.

Anderson and Prakash [15] show that it is oversimplified to look at CCD as a homogenous layer of insulating quality. They claim that the effective porosity of the material is a dominant characteristic which controls the rates of heat transfer at the surface, suggesting that conduction is indeed the major mode of heat transfer related to deposits. Tree et al. [16] extended this line of reasoning by claiming that the porous characteristics of the CCD layer actually interacted with fuel spray in a diesel engine, causing an increase in the duration of heat release.

EXPERIMENTAL SETUP

HCCI ENGINE HARDWARE

The engine used for this work is a single-cylinder intended for a 4-stroke gasoline cycle. The engine features a prototype pent-roof shaped aluminum head with belt-driven double overhead cams and dual intake and exhaust valves. The aluminum piston has a shallow bowl. Table 1 provides engine specifications.

The engine utilizes exhaust re-breathing strategy. The exhaust valves open a second time during the intake stroke with reduced duration and lift in order to re-induct a hot residual charge back into the chamber. This is crucial for promoting HCCI auto-ignition in an engine with low (for HCCI) compression ratio, without having to use extra intake charge heating. The amount of residual brought back into the chamber is controlled by the pressure ratio across the engine. No external EGR is used in the following tests. Figure 3 shows the schematic of the laboratory single-cylinder engine setup.

Table 1: Engine Hardware Specifics

Engine Type	4 valves, single cylinder
Bore / Stroke	86.0 / 94.6mm
Displacement	0.549 liter
Connecting Rod Length	152.2 mm
Compression Ratio	12.5
IVO / IVC	346^o ATDC / 128^o BTDC
Main EVO / EVC	130^o ATDC / 352^o BTDC
2^{nd} EVO / EVC	326^o BTDC / 189^o BTDC

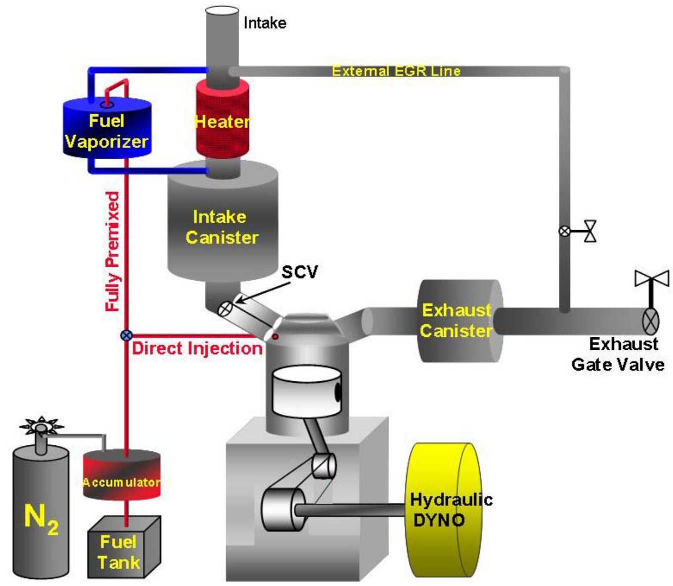

Figure 3: HCCI experimental engine setup

The engine dynamometer is a computer controlled hydrostatic dynamometer. Exhaust gas is sampled at the exhaust plenum for emissions measurement with gaseous analyzers measuring concentrations of HC, NO_x, CO, CO_2 and O_2. Additionally the exhaust gas is sampled by an AVL Smokemeter for quantitative smoke level measurements. A Kistler 6125A piezo-electric pressure transducer measures cylinder pressure with 0.5^o crank-angle resolution.

The high-pressure fuel delivery system is based on a hydraulic bladder-type accumulator. A bladder containing fuel is in a vessel pressurized by nitrogen. Regulating the pressure of N_2 allows control of the fuel injection pressure. The injector is a commercially available DI-type injector. For this work, all tests were performed with direct injection operation. Table 2 below lists specifics of the control fuel used in this investigation.

Table 2: Fuel Specification

Specific Gravity	0.737
Carbon [wt%]	85.56
Hydrogen [wt%]	13.64
Oxygen [wt%]	0.0
Hydrocarbon Types [Vol %]	73.4 % Saturates 22.5 % Aromatics 4.1 % Olefins
RON	90.8
MON	83.4
Pump Octane Number	87.1
Lower Heating Value	44.37 MJ/kg
Higher Heating Value	47.26 MJ/kg
Stoichiometric A/F	14.64

INSTANTANEOUS SURFACE TEMPERATURE AND HEAT FLUX MEASUREMENTS

The ability to measure instantaneous combustion chamber surface temperature adds a valuable new dimension to this investigation. This is accomplished through the use of removable custom made heat flux probes mounted at two locations in the head, as depicted in Figure 4. In previous investigations, these probes combined with seven additional ones mounted flush with the top surface of the piston were used to characterize the heat transfer characteristics and thermal sensitivity of the engine [11,12]. In this investigation, they allow measuring the changes of instantaneous surface temperature profiles on the metal surface due to the deposits being accumulated on top of them. Removable probes will also serve as coupons for measuring deposit thickness at regular intervals during combustion chamber conditioning.

The probe is coaxial type and it was selected for this work because of the demonstrated accuracy and reliability from the previous heat transfer studies performed on the same engine [11]. A coaxial thermocouple (TC) probe consists of a thin wire of one TC material (Iron) coated with ceramic insulation of high dielectric strength, swaged securely in a tube of a second TC material (Constantan). The TC junction is formed by a vacuum-deposited metallic plate with 1~2 microns thickness over the sensing end of the probe, forming a metallurgical bond with the two TC elements. The probes are custom manufactured to fit our cylinder head [17] and their response time is on the order of a micro-second. The sensing area is mounted flush with the combustion chamber surface. Each probe, Figure 5, has an additional back-side junction located 4 mm behind the surface junction so that one dimensional heat flux can be measured.

A short review of the methods required to calculate heat flux through the wall of the combustion chamber based on measurements taken with our heat flux probes is included in the Appendix.

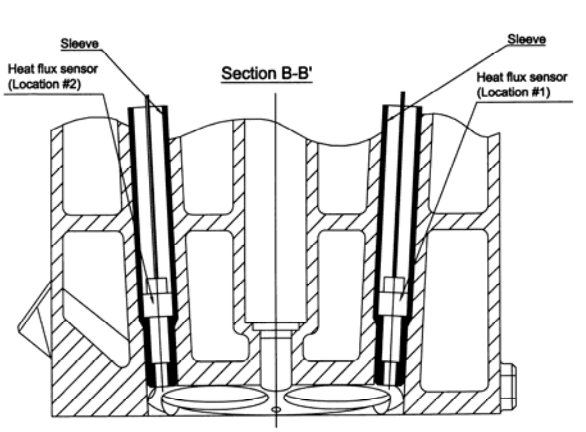

Figure 4: Heat Flux Probe mounting locations in the cylinder head

Figure 5: Fast-response coaxial heat flux probe with surface junction shown

DEPOSIT THICKNESS MEASUREMENT

Measuring the thickness of a deposit layer on a metal surface is a prerequisite for correlating CCD formation with change in combustion. Based on the work of Hopwood et al. [3], a special hand-held device that is capable of measuring the thickness of various types of coatings on different substrate materials was utilized for this investigation. The principle of operation is based on measuring the strength of an induced magnetic field on the substrate material of the sample. The strength depends on the distance from the substrate, which happens to be the thickness of the coating. For this investigation two different probes were obtained. One for measurements on the aluminum combustion chamber surfaces (non-ferrous) and one for measurements directly on the face of the steel heat flux probes (ferrous).

PASSIVE CONDITIONING – THE EFFECT OF NATURALLY FORMED DEPOSITS

A carefully controlled test procedure is established in order to methodically track changes in combustion parameters and quantify the sensitivity of HCCI combustion to varying levels of deposit growth. Determining when CCD formation rates in the chamber will reach an equilibrium point, i.e. after how many hours of HCCI operation will the chamber become *fully conditioned*, is of high interest as well. In addition, we strive to understand the spatial variations of CCD growth in the chamber and what effect this may have on combustion. Finally, we want to use our instantaneous heat flux measurements to gain detailed insight into the effects of CCD on chamber heat transfer in this engine. This includes using documented correlations for calculating thermal diffusivity of the deposit material based on surface temperature measurements. In case the obtained data show strong correlation between properties and CCD thickness, the results will confirm the expectation that instantaneous temperature measurements could be used in the future to track local CCD formation rates 'in-situ'.

EXPERIMENTAL APPROACH

Combustion chamber deposit formation is affected by a range of factors, i.e. mixture preparation, fuel properties, combustion chamber design, wall temperatures, etc. Various ways of creating favorable conditions for ignition in the HCCI engine, e.g. high CR, retention or reinduction of residual, can be additional influencing factors. There is no previously published work involving both HCCI and CCD and hence no base for hypothesizing about the magnitude of CCD effects on combustion. However, initial work hinted at a strong influence of deposits on combustion in this specific engine [18], and that was utilized to develop a procedure for systematic evaluation reported here.

The test starts with a completely clean 'unconditioned' combustion chamber. The engine operates at a standard representative operating point, listed in Table 3, accumulating CCD over time. Changes in combustion and heat flux are tracked at regular intervals by way of in-cylinder pressure measurements and heat flux measurements, respectively. This is continued until there is no longer any appreciable change with further engine operation. At this point the chamber is considered 'conditioned' and the test is concluded.

The engine did not necessarily run continuously for the whole duration of the test, since the size of the fuel accumulator limits operation to 2 hours at a time. However, test procedure ensured that restarts did not significantly affect the CCD formation rates. At the beginning of every new test cycle the combustion parameters were compared to those measured right before the end of the previous cycle to verify consistency. In addition, successive probe thickness measurements confirmed that deposit levels were not affected by the restarts.

Table 3: Operating Parameters

Engine Speed	2000 rpm
Load	11 mg of fuel/cycle
Air to Fuel Ratio	20:1
Injection Timing (DI operation)	EOI 315 deg bTDC
Swirl Control Valve	Fully open (no swirl)
Intake Air Temperature	95 deg Celsius
Coolant and Oil Temperature	90 deg Celsius

<u>Growth Stabilization</u>

As mentioned above, changing in-cylinder thermal conditions, specifically wall temperatures, in combination with fuel component boiling points, will eventually lead to the stabilization of deposit growth rates. As outlined by Kalghatgi et al. [19], when the chamber is clean CCD formation is the fastest and directly dictated by combustion parameters and their effect on surface thermal conditions. As deposits grow they act as a thermal insulator, dampening and decreasing the rate of local heat flux. This in turn increases chamber surface temperatures and reduces deposit growth rates. Eventually, an equilibrium corresponding with the previously mentioned critical surface temperature is reached, and deposits no longer grow.

COMBUSTION RESULTS

The duration of the deposit growth mapping testing on the single-cylinder HCCI engine was 40 hours. After approximately 36 hours there were no more changes in combustion and heat flux and it was concluded that the deposits reached equilibrium. Additionally, by the end of 40 hours, the speed of combustion had increased enough to be close to the knock limit.

Figures 6 through 8 show the evolution of several key combustion performance parameters as a function of engine operation time. Figure 9 shows heat release results for every ten hours of engine operation.

Figures 6 and 7 show the evolution of 10-90% burn duration, ignition timing, represented by 10% mass fraction burned (CA10), and peak pressure (Pmax). There is a significant change in combustion from simply running the engine for several hours. In general, combustion occurs faster and closer to TDC as chamber conditioning progresses. Burn duration decreases by about 5 crank angle (CA) degrees, and 10% MFB advances by about 2.5 deg CA. Changes slow down and tail off in the last 10 hours. Cylinder peak pressure ultimately increases from 35 bar for the clean chamber to 43 bar for the conditioned.

Figure 7 also shows combustion stability through coefficient of variance of mean effective pressure (CoV). The cycle to cycle variability decreases significantly throughout the duration of the testing. This is important when considering load operability limits and is thought to be primarily related to the advancing combustion phasing. Figure 8 shows the changes in NOx and HC emissions throughout the testing. As expected from the increase in peak burn rates, nitrous oxide emissions increase significantly while unburned hydrocarbon emissions decrease. It is speculated that the deposits on the chamber walls raise instantaneous wall temperatures enough to reduce the 'flame' quenching near the wall and in the crevices. There were essentially no smoke emissions throughout the test.

Figure 9 shows the results of cycle heat release analysis performed on the pressure data taken throughout the 40 hours. They are very consistent with combustion performance results. Starting from the slowest burn rate, heat release rates increase in a gradual manner during the first 30 hours of operation. The ignition timing is advancing, although not very rapidly, and duration of heat release is shortening. In summary, peak heat release rates increase from about 18 joules per crank angle to about 27, a roughly 50% increase!

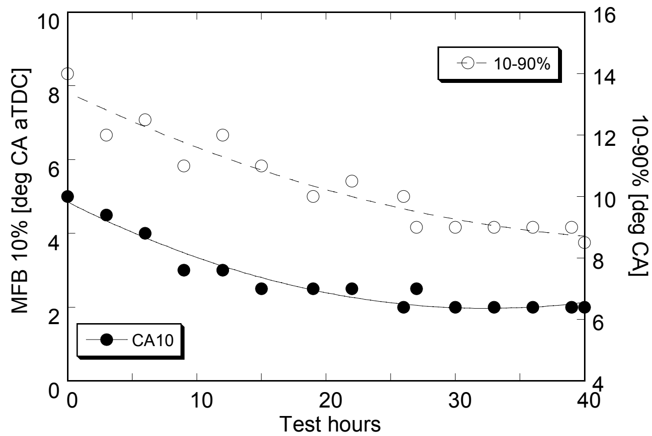

Figure 6: 10-90% Burn Duration and Ignition Timing

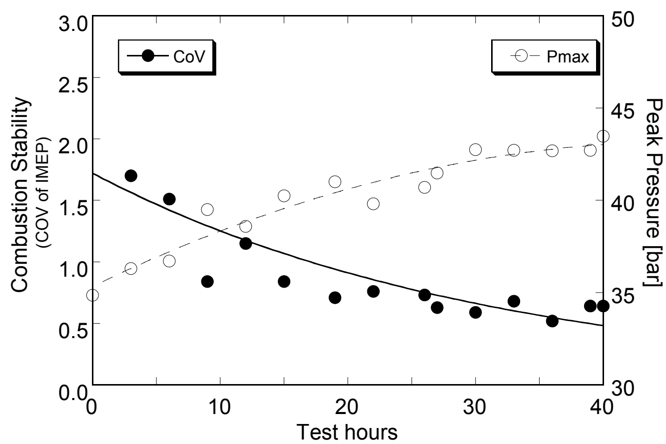

Figure 7: Combustion Stability and Peak Cycle Cylinder Pressure

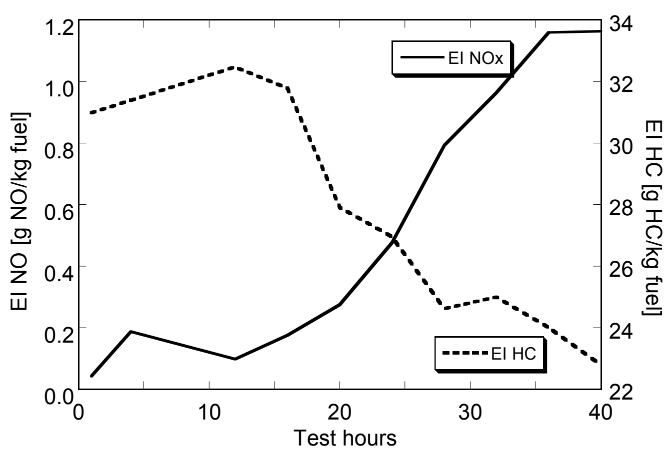

Figure 8: NOx and HC Emissions indexes

It is worth pointing out that while the formation of a CCD layer on the surfaces of the combustion chamber will reduce the clearance volume and thus increase the effective compression ratio, this is not nearly enough to account for the changes in burn rates observed during these tests. Based on sample measurements in this engine, calculations indicate that even the most extensive degree of deposit coverage in the chamber would only increase the compression ratio a negligible amount.

Cyclic Distribution of Combustion Parameters

A unique way of extracting insight about the nature of CCD effects on combustion is to examine the spread of individual cycles throughout the chamber conditioning process. When measurements are taken at a particular operating point, 200 successive cycles are typically recorded. As has been done in the previous sections, it is common to only look at the average of all cycles. However, assessing the spread of individual cycles reveals trends that are otherwise lost after averaging.

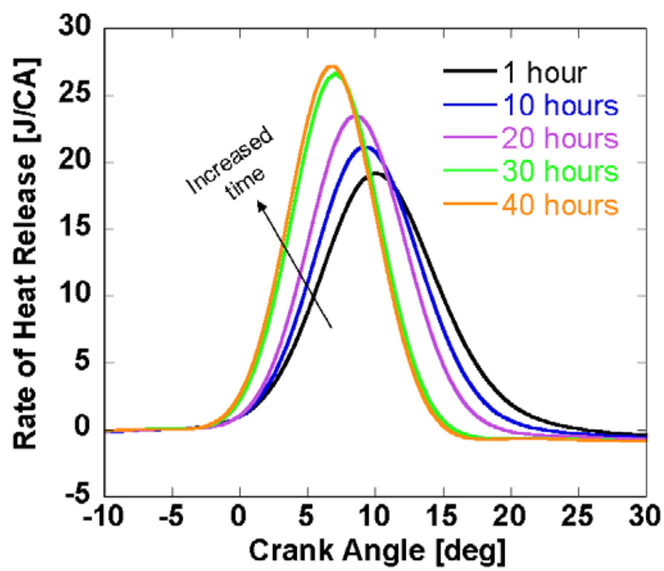

Figure 9: Evolutions of Heat Release Rates during the 40 hour 'conditioning' test at 10 hour intervals.

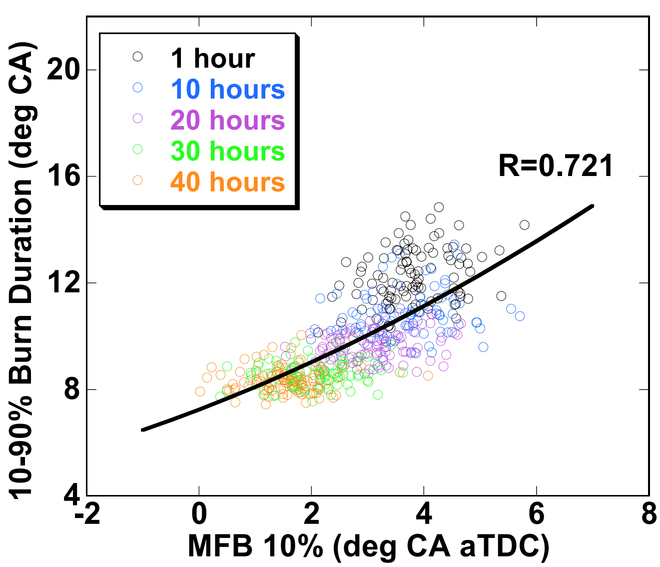

Figure 10: Correlation between 10-90% Burn Duration and Ignition (MFB10%) measurements obtained at 10 hour intervals. Every set of points contains 100 cycles.

Figure 10 shows scatter plots of 10-90% burn duration versus 10% MFB, respectively. It can be seen that each set of points obtained at ten hour intervals moves to the left and down, thus indicating an advance in ignition timing and an increase in the rate of burning. However, the correlation between the ignition timing and burn duration is relatively weak, just as it was in the case of varying wall temperature (see Fig. 2). The distribution of points around the regression line and the calculated coefficient of correlation resemble results in Fig. 2. The implication of this is that reduction of burn duration is not just a function of advancing ignition. In summary, CCD affect ignition due to the variations in heat transfer during intake/compression, but also produce an additional strong effect on bulk burning due to altered near-wall boundary conditions.

SURFACE TEMPERATURE AND HEAT FLUX RESULTS

Understanding the mechanisms responsible for the strong impact of deposits on HCCI combustion requires additional information about the in-cylinder processes. This section provides insight into the effect that chamber deposits have on surface heat transfer. It is important to note that the heat flux probes are mounted on the metal surface. As deposits grow, they form a thermal barrier on top of the probe. Therefore, measurements do not reflect conditions at the gas-surface interface; rather they characterize the effect of CCD on heat transfer and enable evaluation of deposit properties.

Surface Heat Flux Evolution

Two probes were used to track instantaneous temperature and heat flux throughout the test. The results from one probe are shown in Figure 11 and they indicate significant changes over the 40 hours of operation. As deposit material grows over the probe

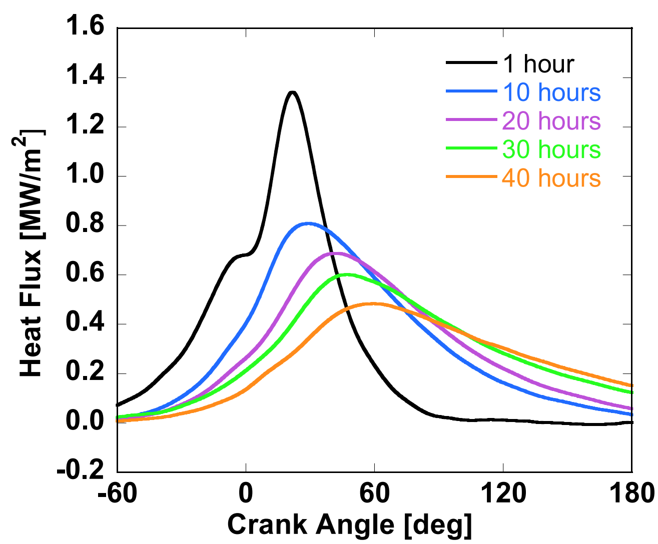

Figure 11: Measured local heat flux at 10 hour intervals, cylinder head location #1.

surface, the heat flux signal measured at the junction location becomes dampened. During the first hour, it is easy to see the heat flux shape mimicking heat release in the chamber. But as hours accumulate and deposit material thickens, the peak levels decrease and the phasing becomes more and more retarded. Essentially, the fast response surface thermocouple is being insulated from the high temperatures of combustion. Since burn rates increase as deposits grow (see Fig. 9), the variations of heat release produce a secondary effect that slightly offsets the effect of deposits. Compensating for the secondary effect will be discussed in a following section.

<u>Mapping deposit thicknesses after full conditioning</u>:

Detailed measurements of CCD thicknesses were taken at multiple locations on the piston and head surfaces after completion of passive conditioning. The measured values in *micrometers* are indicated on photographs of the piston top and the cylinder head shown in Figures 12 and 13, respectively. Photos allow detection of spray direction, since impinging fuel cleans the piston bowl and leaves a mark on one of the intake valves. The highest thicknesses are seen around the periphery, since this is where average temperatures are lower, promoting accelerated CCD formation. In particular, the thickest deposit layer is found on the edge of the piston bowl. As the fuel film forms and moves towards bowl's edge it cools the surfaces and provides plenty of fuel in liquid form. The surfaces of all four valves are virtually clean. The temperatures on these surfaces appear to be higher than the maximum for any CCD layer to form.

Another significant point is that the piston bowl remained almost completely clean. This is obviously due to washing from the fuel spray. These types of qualitative findings are confirmed by Cheng [5], where some interesting points are made regarding direct injection gasoline engines and mixture formation peculiarities as a result of injector spray patterns.

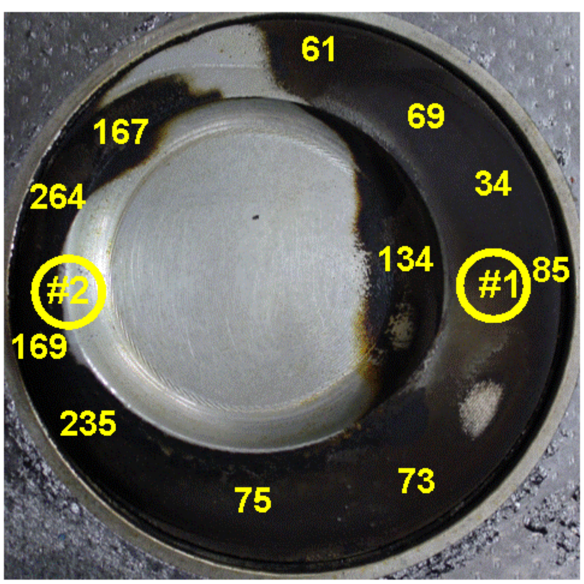

Figure 12: Deposit layer thicknesses [μm] at various locations on piston after 40 hours of testing.

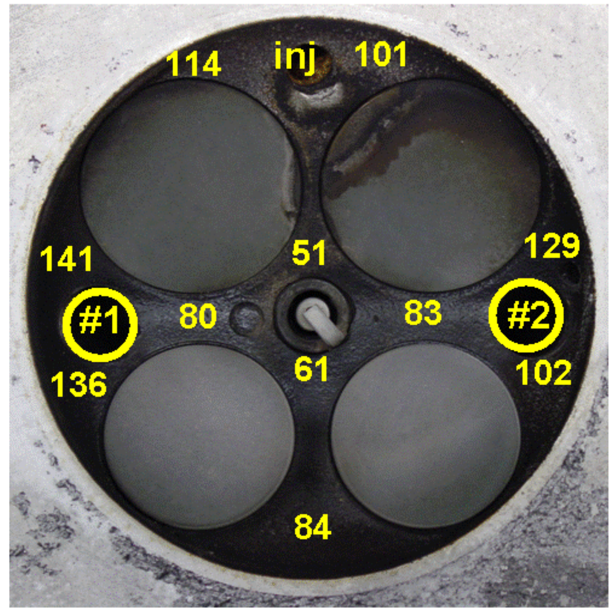

Figure 13: Deposit layer thicknesses [μm] at various locations on the head surface after 40 hours of testing.

CHARACTERIZATION OF CCD THERMAL PROPERTIES

In order to enable potential use of the insight gained so far for expanding the HCCI operating range and control, it is critical to fully understand the mechanisms behind deposits' influence on combustion. Is it strictly a thermal influence or is there perhaps a physical interaction between CCD and fuel spray? The answers require obtaining knowledge about CCD thermal properties. Furthermore, if a correlation can be developed between local deposit formation and changes in local measured surface heat flux, it will be possible to estimate the degree of in-cylinder conditioning in real time and develop in-situ methodology for future testing.

<u>Experimental Techniques for Determining Thermal and Physical Properties</u>

The objective of this part of the study is to determine properties of the deposit layer, since it is the CCD coating that affects heat transfer and HCCI combustion. Previous work reported in literature provides useful background. Anderson and Prakash [15] tried to indirectly determine quantitative values for conductivity, diffusivity, and heat capacity through temperature measurements below and on the surface of the deposit layer. They found that not only do the properties change as the thickness changes, but they change in a non-linear manner, such that their effect on unsteady heat transfer is quite significant. Additionally the porous volumes found in the material presented the potential for intra-material heat transfer through convection and radiation, which complicates the ability to fully understand the heat transfer mechanisms.

Nishiwaki and Hafnan [20] used infrared radiometry on probes with deposit material growth on them. The probes were removed from the engine. They calculated values of the relevant properties, but also tracked the changes in these properties as a function of different operating conditions, such as equivalence ratio, load, speed, and fuel oil content.

Hopwood et al. [3] devised one of the most practical methods for estimating the thermal properties of chamber deposits. Like others, they relied on instantaneous chamber surface temperature measurements. They tracked the changes in the signal phasing as deposit material formed on its surface. Combining this with thickness measurements of the deposits material, they were able to calculate the effective thermal diffusivity. This procedure is deemed most practical for our experimental setup. Measurements of deposits on the two heat flux probes confirmed a strong correlation between CCD thickness and surface temperature phasing – details are provided in the next subsection.

CORRELATING DEPOSIT THICKNESS AND INSTANTANEOUS TEMPERATURE PROFILES

Figure 14 illustrates how much the peak surface temperature shifted after 30 hours of running due to the accumulated deposit material on top of the fast response thermocouple junction. The phase-shifting of the peak temperature is determined at regular intervals during the conditioning test, and CCD thickness was measured at the same time on probes temporarily removed from the engine. In other words, the probes served as coupons, and were not cleaned after individual measurements.

Figure 15 shows the correlation between $\Delta\Theta_{Tmax}$ and CCD thickness and indicates consistent behavior at both locations. Hence, even though the deposits grow at different rates at two locations, their properties seem to be equally closely correlated with thickness. There is no loss of sensitivity as thickness increases. Consequently, the analytical methodology of Hopwood et al. [3] for determining the thermal diffusivity of deposit materials based on instantaneous surface temperature measurements can be applied to the HCCI engine.

THERMAL DIFFUSIVITY

Hopwood used in-cylinder temperature measurements and combined them with intermittent deposit thickness measurements over the tip of the probe. Applying unsteady heat conduction analysis, a formula can be derived for determining thermal diffusivity (α) in units of m^2/s. The formulation is based on the solution for the periodic temperature cycle at any depth in a surface. The constant t_o is calculated from the measurement

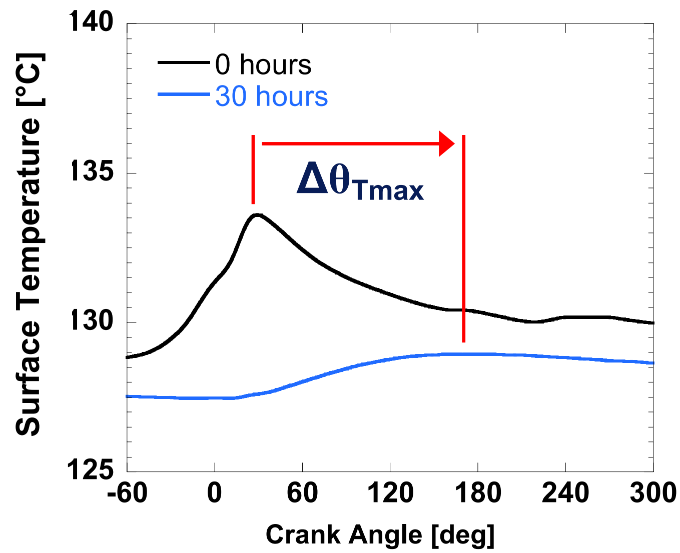

Figure 14: Depiction of characteristic change in measured surface temperature as deposits form on the probe surface.

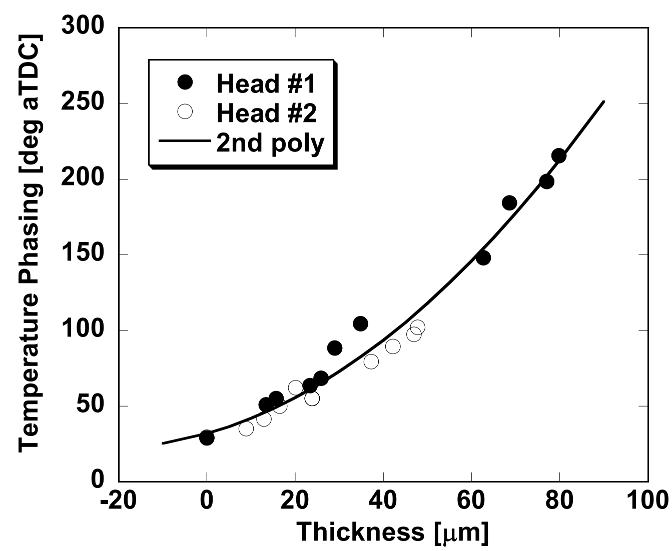

Figure 15: Relationship between local peak temperature phasing and combustion chamber deposit thickness.

period, which is a function of engine speed. For details please refer to the Appendix. The final formula is:

$$\alpha = \left(\frac{x}{\Delta t} \frac{\left(1+\sqrt{2}\right)}{6} \right)^2 \frac{t_0}{\pi}$$

where x is the thickness of the deposit layer (in micrometers), and Δt is the change in peak temperature phasing (in seconds).

Modified Procedure for HCCI investigations

Normally the procedure for using the above correlation requires a direct comparison of surface temperature measurements between the temperature profile of the clean probe and that covered with a deposit layer. For an SI engine, such as in Hopwood's work, a direct comparison was possible. But for the special case of an HCCI engine, it was realized that the procedure had to be modified. HCCI combustion advances significantly with deposits growth. As the phasing of combustion advances so does the surface temperature profile, thus distorting the calculations based on the assumption that thermocouple signal phasing depends only on the thermal diffusivity of the CCD layer covering the junction. Hence, it is necessary to remove the effect of higher combustion rates. This is accomplished by reducing intake temperature until the original phasing of combustion with a clean chamber is replicated. At that point, the measured surface temperatures are affected only by the deposit layer and proper analysis of diffusivity can be completed.

The intake temperature had to be varied by different amounts as the testing progressed, due to increased degree of chamber conditioning. By the end of the 40 hours, a T_{intake} decrease of 25 degrees from the original 95°C was required to match the combustion rates of a clean chamber. The engine ran with a lower intake temperature only for short intervals right before it was to be stopped for deposit probe thickness measurements. Otherwise T_{intake} was maintained at 95°C for the duration of the 40 hour test.

Thermal diffusivity values obtained with the technique described above are plotted in Figure 16. A 2nd order polynomial was first fitted to the data in Figure 15. Subsequently, the formula for thermal diffusivity was applied using the polynomial in order to reduce noise and obtain data shown in Figure 16. This was useful particularly in the lower end of the deposit thickness range, where the changes in peak temperature phasing are very small. Short intervals measured with half crank angle degree resolution make calculation of thermal diffusivity extremely sensitive to the time interval expressed in seconds, and using a curve fit proved to be very effective for removing the noise stemming from the limited resolution of measurements.

Calculated values of thermal diffusivity are a strong function of thickness. This confirms that properties of the deposits in each location on the cylinder head are very similar to each other. Thicker layers of material have a lower *effective* thermal diffusivity. This is due to the fact that as the deposit is forming, its morphology is constantly changing as well. The degree of porosity, the consistency, and the types of hydrocarbon molecules that make up different layers of the total material are constantly changing. The range of thermal diffusivity values throughout the testing falls between $0.8*10^{-7}$ – $2.3*10^{-7}$ m^2/s. This is a few orders of magnitude less than the diffusivity values for aluminum of about $1.0*10^{-4}$ m^2/s [21]. Interestingly, even though the HCCI combustion process is very different, the results in Figure 16 matched closely those published for an SI engine [3].

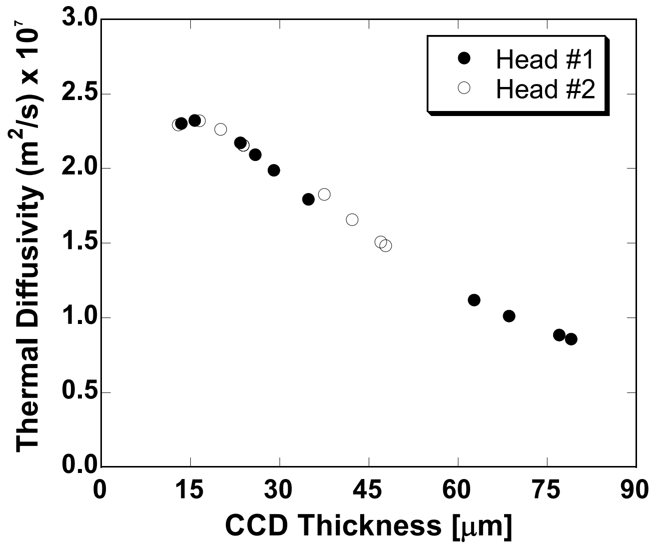

Figure 16: Plot of calculated effective thermal diffusivity as a function of CCD thickness at each head flux probe location

CONCLUSION

A single-cylinder, gasoline-fueled HCCI engine with reinduction of residual was tested over an extended period of time to allow build up of deposits and assessment of their effect on HCCI combustion. Burn rates became significantly faster as the test progressed. Thus, the main combustion event in the HCCI engine is very sensitive to the presence of a deposit layer on the combustion chamber surface. Full conditioning of combustion chamber walls was achieved in forty hours, as there were no further variations of combustion after that period of time. Peak heat release rates increased 50% after full conditioning.

The analysis of individual cycles recorded during the combustion chamber was used to explore the nature of the CCD effect on HCCI combustion. When a correlation between ignition timing and burn duration is examined for a large number of cycles, groups of points corresponding to different instants in the test are staggered, suggesting that burn rates change more than what would be expected based solely on ignition phasing. This is in contrast to the effect of increased intake temperatures, where the correlation between ignition timing and combustion duration is very strong. This leads to a conclusion that deposits affect bulk burning near the wall more than the core gas temperature at the end of compression. Consequently, thermal capacity of deposits and temperature swings at the surface are more relevant than global reduction of heat loss due to their insulating characteristics.

The engine was instrumented with two fast thermocouple probes on the cylinder head. They also served as coupons for tracking deposit thickness during the combustion chamber conditioning process. The results show very strong correlation between phasing of the peak instantaneous temperature measured at the metal surface and deposit thickness. This enables application of the technique suggested by Hopwood [3] for determining the diffusivity of the deposit layer. The original methodology was slightly modified to remove the effect of accelerated burn rates on phasing of wall temperature profiles. Thermal diffusivity values throughout the conditioning were between $0.8{*}10^{-7}$ – $2.3{*}10^{-7}$ m^2/s. They match relatively closely published properties of deposits determined in conventional SI engines.

The data base of deposit thermal properties provides valuable insight into near-wall phenomena, but also opens up the possibility of using the fast response thermocouples for in-situ evolution of deposit growth on the firing engine. Instrumenting the combustion chamber, including the piston, with more thermocouples will provide valuable insight about dynamics of the CCD formation process and its spatial variations.

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REFERENCES

1. Stanglmaier, R.H., Roberts, C.E., “Homogenous Charge Compression Ignition (HCCI): Benefits, Compromises, and Future Engine Applications,” SAE Paper 1999-01-3682
2. Kalghatgi, G. T., “Deposits in Gasoline Engine – A Literature Review”, SAE Paper 902105
3. Hopwood, A.B., Chynoweth, S., Kalghatgi, G.T., “A Technique to Measure Thermal Diffusivity and Thickness of Combustion Chamber Deposits In-Situ”, SAE Paper 982590
4. Nakic, D.J., Assanis, D.N., White, R.A., "Effect of Elevated Piston Temperature on Combustion Chamber Deposit Growth", SAE Paper 940948
5. Cheng, S., “ The Impacts of Engine Operating Conditions and Fuel Compositions on the Formation of Combustion Chamber Deposits”, SAE Paper 2000-01-2025
6. Ishii, H., Emi, M., Yamada, Y., Kimura, S., Shimano, K., Enomoto, Y., “Heat Loss to the Combustion Chamber Wall with Deposit Adhering to The Wall Surface in D.I. Diesel Engine”, SAE Paper 2001-01-1811
7. Thring, R.H., “Homogenous-Charge Compression-Ignition (HCCI) Engines,” SAE Paper 892068
8. Aceves, S.M., Flowers, D.L., Westbrook, C.K., Smith, J.R., Pitz, W., Dibble, R., Christensen, M., Johansson, B., “A Multi-Zone Model for Prediction of HCCI Combustion and Emissions”, SAE paper 2000-01-0327
9. Richter, M., Engström, J., Franke, A., Aldén, M., Hultqvist, A., Johansson, B., “The Influence of Charge Inhomogeneity on the HCCI Combustion Process”, SAE paper 2000-01-2868
10. Kakuho, A., Nagamine, M., Amenomori, Y., Urushihara, T., Itoh, T., “In-Cylinder Temperature Distribution Measurement and Its Application to HCCI Combustion”, SAE paper 2006-01-1202
11. Chang, J., Guralp, O., Filipi, Z., Assanis, D., Kuo, T.W., Najt, P., Rask,R., “New Heat Transfer Correlation for an HCCI Engine Derived from Measurements of Instantaneous Surface Heat Flux”, SAE Paper 2004-01-2996
12. Chang, J., Filipi, Z., Assanis, D., Kuo, T., Najt, P., Rask, R., “Characterizing the thermal sensitivity of a gasoline homogeneous charge compression ignition engine with measurements of instantaneous wall temperature and heat flux”, IMechE, Int. J. Engine Res. Vol. 6, 2005
13. Sjöberg, M., Dec, J.E., Babajimopoulos, A., Assanis, D., “Comparing Enhanced Natural Thermal Stratification Against Retarded Combustion Phasing for Smoothing of HCCI Heat-Release Rates”, SAE paper 2004-01-2994
14. Woschni, G., Huber, K., “The Influence of Soot Deposits on Combustion Chamber Walls on Heat Losses in Diesel Engines”, SAE Paper 910297
15. Anderson, C.L., Prakash, C., “The Effect of Variable Conductivity on Unsteady Heat Transfer in Deposits”, SAE Paper 850048
16. Tree, D.R., Wiczynski, P.D., Yonushonus, T.M., “Experimental Results on the Effect of Piston Surface Roughness and Porosity on Diesel Engine Combustion”, SAE Paper 960036
17. Product Information Coaxial Surface Thermocouple Probes, Medtherm Corporation, Huntsville, Alabama USA
18. Guralp, O.A., “Development and Application of a Telemetry System for Piston Surface Temperature Measurements in a Homogeneous Charge Compression Ignition Engine”, MS Thesis, 2004
19. Kalghatgi, G.T., McDonald, C.R., Hopwood, A.B., “An Experimental Study of Combustion Chamber Deposits and Their Effects in a Spark-Ignition Engine”, SAE Paper 950680
20. Nishiwaki, K., Hafnan, M., “The Determination of Thermal Properties of Engine Combustion Chamber Deposits”, SAE Paper 2000-01-1215

21. Incropera, F.P., DeWitt, D.P., Introduction to Heat Transfer, 3rd edition. 1996, John Wiley and Sons.

22. Alkidas, A.C., "Heat Transfer Characteristics of a Spark-Ignition Engine," ASME vol 102, May 1980

APPENDIX

1. ONE DIMENSIONAL HEAT FLUX CALCULATIONS

Heat flux calculations require a measurement from the surface junction as well as the one that is located 4 mm below the surface. For additional details consult Alkidas [22]. The basis of this method for formulating heat flux is provided by the following assumptions. The system is simplified as one-dimensional unsteady heat conduction. Heat transfer can is assumed to be one dimensional, perpendicular to the chamber surface because the front-side and back-side junctions are so close to each other. Also, each of the junctions makes up a boundary condition for the problem. The final formulation is simplified because the backside junction is located far enough from the surface that any fluctuations in temperature are masked so this junction provides a constant temperature reading for the entire cycle. The analysis starts with a one-dimensional heat conduction equation (1). A Fourier series representation of the surface temperature is shown in Equation (2). Applying Fourier's law to the heat conduction equation leads to the expression for heat flux given in Equation (3), i.e.:

(1) $$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

(2) $$T_w(t) = \overline{T}_w(0) + \sum_{n=1}^{N} \left(A_n \cos n\omega t + B_n \sin n\omega t \right)$$

(3) $$q_w(t) = -K \frac{\partial T}{\partial x}(0,t) = \frac{K}{\delta}\left[\overline{T}_w(0) - T(\delta)\right] +$$

$$K \sum_{n=1}^{N} \sqrt{\frac{n\omega}{2\alpha}} \left[A_n (\cos n\omega t - \sin n\omega t) + B_n (\sin n\omega t + \cos n\omega t) \right]$$

2. CALCULATION OF EFFECTIVE CCD THERMAL DIFFUSIVITY BASED ON INSTANTANEOUS IN-CYLINDER SURFACE TEMPERATURE MEASUREMENTS

The basic premise starts with one-dimensional unsteady heat transfer,

(4) $$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T(x,t)}{\partial t}$$

and by representing the surface temperature with a Fourier Series,

(5) $$T(0,t) = \sum_{n=1}^{\infty} \left\{ a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t) \right\}$$

a solution for the periodic temperature cycle at any depth in a surface can be derived, as shown in the following equation:

(6) $$T(x,t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} e^{-\left(x\sqrt{\frac{n\omega_0}{2\alpha}}\right)} \left[a_n \cos\left(n\omega_0 t - x\sqrt{\frac{n\omega_0}{2\alpha}} \right) \right] + \sum_{n=1}^{\infty} e^{-\left(x\sqrt{\frac{n\omega_0}{2\alpha}}\right)} \left[b_n \sin\left(n\omega_0 t - x\sqrt{\frac{n\omega_0}{2\alpha}} \right) \right]$$

Since absolute temperature levels are not relevant, only the phasing, the term with a_0 can be eliminated. Approximating the instantaneous surface temperature profile with a trigonometric function, then taking the time derivative, setting it equal to zero (for the peak temperature), and simplifying leads to:

(7) $$t_{peak} = \Delta t = x \frac{\left(1+\sqrt{2}\right)}{6} \sqrt{\frac{t_0}{\pi\alpha}} \quad \text{or,}$$

(8) $$\alpha = \left(\frac{x}{\Delta t} \frac{\left(1+\sqrt{2}\right)}{6} \right)^2 \frac{t_0}{\pi}$$

where, x is the thickness of the deposit layer, and Δt is the change in peak temperature phasing.