Abstracts

Session 9 – Combustion and HCCI Development

A MIXED-MODE HCCI/DI ENGINE BASED ON A NOVEL DIESEL FUEL ATOMIZER

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The homogeneous charge compression ignition (HCCI) mode has long been touted as the next engine combustion system to combine the high efficiency of diesel engines with very low tail-pipe emissions; however, it has been demonstrated only in the laboratory under very controlled conditions. It is clear that achieving a robust and controllable HCCI combustion system capable of handling heavy fuels in engines under a realistic and wide range of operating conditions and transients is not feasible today.

Our approach is aimed at developing a compression engine capable of operating with heavy fuels over a wide range of operating (speed, load, temperatures) conditions in a robust and controllable fashion to achieve both high thermal efficiency and low emissions. Furthermore, our approach builds upon the technological recent advances and successes in advanced CIDI engines, married with a novel enabling technology in ultra-fine heavy fuel atomization and advances in modern, model-based engine control systems.

The novel atomizer is a low-pressure system capable of atomizing heavy liquid fuels in a "fog-like" suspension of sub-micron liquid droplets over a very wide range of temperature conditions. The air/fuel mixture so formed has many positive attributes: it behaves in a gas-like manner; is highly resistant to settling and segregation, subsequent film condensation, and wall wetting; and is highly homogeneous and capable of achieving a well-mixed air/fuel vapor mixture very fast due to the extremely high surface-to-volume ratio of the fuel droplets.

Our engine concept is also a mixed-mode, HCCI/CIDI combustion system:
part of the fuel is introduced in the engine to achieve a lean and very homogeneous, premixed phase capable of combusting in an HCCI mode, while part of the fuel is introduced directly by a common rail direct injection (DI) system. The non-condensing, highly mixed nature of the fuel/oxidizer mixture achieved with the novel atomizer enables port injection for the preparation of a very lean and highly homogeneous phase capable of supporting the HCCI combustion mode at low-to-medium loads. The CR-CIDI conventional injection system enables the medium-to-high load operation, which is not feasible with a pure HCCI combustion system. However, both systems are intended to operate *simultaneously* with the emphasis between the two systems shifting as load/speed varies. We foresee that the DI injection at high loads into a lean and homogenous air/oxidizer mixture phase will further extend the PM/NO_x trade-offs and limits facing conventional CIDI engines. At low-to-medium loads, a relatively smaller DI part can act as a "combustion" trigger for the otherwise homogeneous (and possibly lean) phase, hence capable of achieving much greater controllability of the combustion system. This mixed-mode fueling strategy is combined with advanced, model-based control for the VGT/EGR loop to achieve at each cycle a reliable estimate and control of

the thermochemical oxidizer charge, hence achieving the narrow range of intake conditions required for proper HCCI operation.

Finally, the system is to be used with an active, thermochemically managed exhaust aftertreatment system. Again, the novel atomizer plays a significant enabling role to achieve the thermochemical management of a bifurcated lean-NO_x trap system, which does not require an engine-based reductant addition to achieve NO_x trap regeneration.

DIESEL HCCI DEVELOPMENT AT CATERPILLAR

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Implementation of a practical homogeneous charge compression ignition (HCCI) engine has numerous technical challenges. Among these are proper mixture preparation, controlling combustion phasing and cylinder pressure rise rates, and expanding the operating range to higher loads. Methods to control combustion phasing include managing inlet manifold temperature and pressure, exhaust gas recirculation rate, and injection timing. Recent progress on part-load HCCI operation using diesel fuel will be given.

HCCI COMBUSTION: DETAILED ANALYSIS AND PERFORMANCE EXPERIMENTS

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and

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Homogeneous charge compression ignition (HCCI) is a new engine technology that allows both high efficiency and low emissions for cars, trucks, and sport utility vehicles (SUV's). The high efficiency of diesel engines is highly desirable for improving the fuel economy of light-duty trucks and SUV's. However, diesel engines are well known as significant sources of NO_x and particulate matter emissions. The use of HCCI combustion systems represents a promising approach that needs further research and development.

Our research work on HCCI is divided into two major tasks: analysis and experimental work. On analysis, we have developed two powerful HCCI analysis tools: a single-zone HCT model and a multi-zone HCT model. The single-zone model has proven very successful in predicting the start of combustion and providing reasonable estimates for peak cylinder pressure, indicated efficiency, and NO_x emissions, with very little computational cost (5 minutes on an engineering workstation). The multi-zone model is capable of very accurate predictions of the combustion process, including HC and CO emissions, at the cost of substantially longer running times (8 hours on an engineering workstation). The two models complement each other very nicely. Most of the work can be done with the single-zone model, and the multi-zone model can be used for a detailed analysis of important operating points and to learn more about the fundamentals of HCCI combustion.

We are currently conducting detailed analysis of experiments at other institutions, such as University of California at Berkeley, Sandia National Laboratories in Livermore, California, and Lund Institute of Technology. The purpose of the detailed analysis is to determine the fundamentals of HCCI combustion, study the effect of mixing on HCCI combustion, and develop methodologies for controlling the engine. We are also working in collaboration with the chemical kinetics group at Lawrence Livermore National Laboratory (LLNL) to develop surrogate mechanisms for practical HCCI fuels, mainly gasoline.

On experimental work, we are working on validating the application of the modified HCT code and implementing strategies for HCCI engine startability and control. We currently have a 4-cylinder Volkswagen TDI engine and a Caterpillar 3401 engine operating in HCCI mode in the University of California at Berkeley Engine Laboratory. Experiments on the TDI engine are focused on balancing combustion between the cylinders and on

obtaining combustion at the appropriate timing. The experiments on the Caterpillar engine are dedicated to performing fundamental experiments on HCCI combustion in collaboration with the LLNL Accelerated Mass Spectroscopy team.

HCCI Combustion: the Sources of Emissions at Low Loads and the Effects of GDI Fuel Injection

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Abstract

Homogeneous Charge Compression Ignition (HCCI) engines have been shown to provide both high efficiency and low emissions of NO_X and particulate. However, hydrocarbon (HC) and carbon monoxide (CO) emissions are often high, with amounts depending on operating conditions. To gain a better understanding of the reasons for these emissions and their relative importance over the operating range, a study of HCCI combustion and emissions has been conducted, with particular emphasis on understanding the sources of HC and CO emissions and the associated combustion inefficiencies during low-load operation. This investigation included both experimental measurements and computations for a variety of fuel loads and engine speeds.

The experiments were conducted in a single-cylinder engine (0.98 liters/cyl.) fitted with a custom HCCI piston that minimizes crevice volume, using iso-octane as the fuel. For three engine speeds (600, 1200, and 1800 rpm) the fuel loading was varied from near the knocking limit to loads at or below idle (based on typical diesel-engine fueling). For each condition, cylinder pressure and exhaust-gas data (CO_2, O_2, CO, HC, NO_X, and smoke) were acquired. Comparative computations were made using the Senkin application of the CHEMKIN III kinetic rate code with the full chemistry mechanisms for iso-octane. This single-zone model provides results that are representative of the bulk-gas behavior for an idealized engine with no crevices.

The experimental data show that when the fueling rate is reduced below an equivalence ratio (ϕ) of 0.18, CO emissions begin to increase substantially, reaching levels corresponding to 60% of all fuel carbon at idle loads (ϕ = 0.1 to 0.12). As this occurs, the combustion efficiency falls from 95% to less than 60%. These high CO levels are found to be in very good agreement with those predicted by the model, indicating that the high CO emissions and the associated combustion inefficiencies are due to incomplete bulk-gas reactions. HC emissions also increase, but the effect is less pronounced than that of CO. In addition, the model indicates that high levels of oxygenated hydrocarbons (OHC) should occur as bulk-gas reactions become less complete. Since these emissions are not readily measured, a method of estimating the OHC level from the available data was developed, and is shown to compare well with the modeling results. Finally, partial charge stratification, obtained using a gasoline-type direct fuel injector has been investigated as a means of mitigating the problem of incomplete bulk gas reactions at lower loads, and the results are presented and discussed.

SIMULTANEOUS LOW ENGINE-OUT NOX AND PM WITH HIGHLY DILUTED DIESEL COMBUSTION

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We are investigating the simultaneous reduction of nitrogen oxides (NO_x) and particulate matter (PM) in a modern light-duty diesel engine under high exhaust gas recirculation (EGR) levels. This type of behavior was observed under lean conditions at several low-load conditions using two different approaches.

The first approach utilizes a throttle to increase EGR rate beyond the maximum rate possible with only the EGR valve for a particular engine condition. The second approach does not use a throttle but rather uses a combination of EGR and manipulating injection parameters.

A significant reduction in PM size and concentration was observed corresponding to the reduction in particulate mass. This was accompanied by a significant shift in the heat release profile. In addition, there were significant cylinder-to-cylinder variations in PM characteristics, gaseous emissions, and heat release.

A fuel penalty is associated with operating in the low NO_x and low PM regime. Preliminary experiments indicate that the penalty can be reduced to a few percent while still maintaining a significant reduction in NO_x and PM. An improved understanding of this combustion regime could lead to improved EGR utilization for lowering the performance requirements of post-combustion emissions controls.

OPTICAL DIAGNOSIS AND MODELING TOOLS APPLIED TO DIESEL HCCI

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Fundamental investigation of diesel homogeneous charge compression ignition (HCCI) has been performed through the use of optical diagnostic techniques and computational modeling tools. An optically accessible engine and a spray visualization rig have been used to characterize HCCI-type combustion and appropriate spray characteristics for charge homogeneity. In parallel, improvements to computational modeling of multidimensional sprays and combustion have been implemented in order to identify potential HCCI-enabling technologies.

HIGH-ENERGY, PULSED LASER DIAGNOSTICS FOR REAL-TIME MEASUREMENTS OF RECIPROCATING ENGINE PM EMISSIONS

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With stricter particulate matter (PM) emission regulations looming ahead in 2004 and 2007, there is a need for new instrumentation capable of real-time measurements with high sensitivity. We foresee applications for both extractive sampling and *in situ* measurements, where the former is the simplest approach to implement, and the latter is needed to characterize engine-out/aftertreatment in conditions for design optimization and life-cycle simulation. High-energy, pulsed-laser diagnostics are well suited for these tasks, and offer a wide range of measurement capabilities that include the following: (1) laser-induced incandescence (LII) for soot volume fraction and primary particle size; (2) elastic light scattering (ELS) for total volume fraction; (3) laser-induced desorption (LID) with ELS (LIDELS) for volatile fraction; (4) LII with ELS for aggregate size, number, and structure; and (5) laser-induced breakdown spectroscopy (LIBS) for metallic-ash species and concentration.

The principles behind these diagnostics will be briefly discussed, followed by a description of a compact, mobile instrument for "hands-off" implementation based on PC control. Three demonstrations of the instrument's use will be presented: (1) LII measurements during cold-start of a gasoline engine, comparing open- and closed-valve fuel injection; (2) LII measurements of transient diesel PM emissions for a cranking-start/idle/shutdown sequence and on/off cycling of exhaust gas recirculation (EGR); and (3) real-time LIDELS measurements of the volatile fraction during EGR and load sweeps.