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Control Strategies for HCCI Mixed-Mode Combustion

CRADA Final Report

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By

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Abstract

Delphi Automotive Systems and ORNL established this CRADA to expand the operational range of Homogenous Charge Compression Ignition (HCCI) mixed-mode combustion for gasoline engines. ORNL has extensive experience in the analysis, interpretation, and control of dynamic engine phenomena, and Delphi has extensive knowledge and experience in powertrain components and subsystems. The partnership of these knowledge bases was important to address critical barriers associated with the realistic implementation of HCCI and enabling clean, efficient operation for the next generation of transportation engines.

The foundation of this CRADA was established through the analysis of spark-assisted HCCI data from a single-cylinder research engine. This data was used to (1) establish a conceptual kinetic model to better understand and predict the development of combustion instabilities, (2) develop a low-order model framework suitable for real-time controls, and (3) provide guidance in the initial definition of engine valve strategies for achieving HCCI operation. The next phase focused on the development of a new combustion metric for real-time characterization of the combustion process. Rapid feedback on the state of the combustion process is critical to high-speed decision making for predictive control. Simultaneous to the modeling/analysis studies, Delphi was focused on the development of engine hardware and the engine management system. This included custom Delphi hardware and control systems allowing for flexible control of the valvetrain system to enable HCCI operation. The final phase of this CRADA included the demonstration of conventional and spark assisted HCCI on the multi-cylinder engine as well as the characterization of combustion instabilities, which govern the operational boundaries of this mode of combustion.

ORNL and Delphi maintained strong collaboration throughout this project. Meetings were held on a bi-weekly basis with additional reports, presentation, and meetings as necessary to maintain progress. Delphi provided substantial support through modeling, hardware, data exchange, and technical consultation. This CRADA was also successful at establishing important next steps to further expanding the use of an HCCI engine for improved fuel efficiency and emissions. These topics will be address in a follow-on CRADA.

1. Statement of Objectives

- Improve fundamental understanding of the development of combustion instabilities with HCCI operation through modeling and experiments.
- Develop low-order model and feedback combustion metrics which are well suited to real-time predictive controls.
- Construct multi-cylinder engine system with advanced Delphi technologies and characterize HCCI behavior to better understand limitations and opportunities for expanded high-efficiency operation.

2. Benefits to the Funding DOE Office's Mission

An improvement in the fuel efficiency of gasoline engines is necessary to realize a significant reduction in U.S. energy usage. Homogeneous charge compression ignition (HCCI) in internal combustion engines is of considerable interest because of the potential reductions in flame temperature and nitrogen oxide (NOx) emissions as well as potential fuel-economy improvements resulting from un-throttled operation, faster heat release, and reduced heat-transfer losses. The successful widespread implementation of HCCI operation is expected to result in improved vehicle efficiency and therefore a reduction in the United States dependence on foreign oil. This is in direct support of the highest priorities of the Office of Energy Efficiency and Renewal Energy.

3. Technical Discussion of Work Performed by All Parties

Substantial progress in expanding the use of advanced combustion modes such as HCCI will require an improved understanding of the combustion process as well as new insight into control methods for real-time predictive control. Of particular importance is to improve combustion stability during transitions between conventional SI and HCCI combustion modes as well as for intermediate combustion modes which exhibit characteristics and benefits of both modes. This CRADA addressed these issues through a combination of simulation and experiments over the course of three years. The following discussion highlights the progress and accomplishments on a year-by-year basis.

<u>Year 1</u>

One of the most widely used methods for achieving the preheat conditions required to initiate HCCI is retention of high levels of exhaust gas in the cylinder from one cycle to the next through manipulation of the intake and exhaust valve events. While effective, this internal exhaust gas recirculation (EGR) creates a strong coupling between successive cycles, and small variations in the thermal and chemical composition of the retained exhaust gas can lead to large variations in the combustion process. Results from previous ORNL research showed that, due to this highly variable combustion, the SI-HCCI mode transition is very unstable with high torque variations, high unburned hydrocarbon emissions, and potential engine stall. Interest in the transition region was motivated by the recognition that it may be possible to limit variability here by applying the appropriate feedback control. The potential benefits would be to smooth the SI-HCCI transition and extend the window of steady-state operation with HCCI-like NOx emission levels.

A conceptual model of the SI-HCCI transition and intermediate mixed-mode combustion events was developed based on experimental observations. Spark ignition combustion is dominant for low levels of EGR. As EGR is increased further, the inlet fuel-air mixture is diluted with exhaust and the SI flame speed decreases. In the transition region, combustion typically begins when the spark creates a reaction front that expands and propagates through the premixed charge. Energy is transferred from the reaction front to the unburned mixture which results in an instantaneous, volumetric reaction over all (or some portion) of the remaining unburned charge. Thus, in the transition region, combustion occurs as a hybrid or mixed-mode event consisting of both propagating-flame and HCCI combustion during the same cycle.

Analysis of experimental data from a single-cylinder research engine showed that the large combustion instabilities typical of the transition region arise from variations in the timing and relative strength of the secondary HCCI combustion process. These observations were used to develop a data-based combustion model for estimating global kinetic rate constants and ultimately a low-order empirical model of the combustion process. The global kinetic rate constants estimated from experimental data suggested that the HCCI combustion is actually switching between two different modes (or mechanisms) with different propensities to auto ignite. This led to the hypothesis that the mode of combustion that occurs on a given cycle is determined by the presence or absence of sufficient concentration of partially oxidized fuel species that act as an enabler for HCCI combustion and accumulate in the cylinder through exhaust recirculation. As EGR is increased further, EGR heat becomes sufficient to stimulate HCCI, which preempts flame initiation (transition to HCCI is complete).

A method was also developed that uses multiple Wiebe relations to estimate the timing and relative strengths of the two portions of the hybrid combustion event from experimental data. This information will be useful in further refining our model and potentially as a combustion metric for feedback control.

Simultaneous to the above activities, Delphi initiated the modeling and development of the multi-cylinder engine platform to be used in subsequent years. This also included a modeling portion focused on development and execution of a full engine simulation to provide guidance in piston and valvetrain development. The multi-cylinder engine was based on an Ecotec 2.2-L engine with gasoline direction injection. In addition, Delphi initiated the process of acquiring a flexible engine controller and training ORNL staff on their Cylinder Pressure Development Controller.

Year 2

The low-order model was further developed based on an improved conceptual understanding of the combustion to better predict cycle-resolved combustion dynamics during the SI-HCCI transition. The model combines a diluent-limited laminar flame speed model for SI combustion and an HCCI model which accounts for temperature and residual-gas composition with a set of rules governing the competition between the two modes.

The propagating-flame model is based on empirical correlations for laminar flame speed limited by diluent concentrations (i.e., burned gases in the residual). In the literature, flame-speed correlations have been developed by fitting data to a form dependent on temperature, pressure, and diluent fraction. The HCCI model is governed by residual-gas composition and temperature. During the compression stroke, the temperature rise from compression and from residual gases may achieve some combustion under certain conditions. During the power stroke, combustion occurs following a Wiebe form using empirically derived ignition timings.

The mixed-mode model is a combination of the two separate models. During the compression stroke, both modes are viable depending on conditions (residual-gas composition). At a defined critical point (e.g., at or near the beginning the power stroke), conditions are evaluated. If HCCI dominates, then the propagating flame is quelled by the rapid global combustion; if conditions are not conducive to HCCI, then the flame propagates as conditions permit.

Development of the multi-cylinder platform continued at the Delphi Technical Center in Rochester, New York. Initial experiments included an evaluation using stock cam profiles to determine the optimal cam phasing for SI operation over the speed/load range. This included using a merit-function based method to appropriately weigh and compare several experimentally measured performance indicators (including BSFC, COV of BMEP, etc.) and determine optimal intake and exhaust cam timings at each speed and load. Full engine simulations with GT-Power were then used to identify a low-lift cam designs which would allow HCCI operation. These cam designs were manufactured and installed on-engine to explore the HCCI operating regime.

Year 3

After initial development and evaluation at the Delphi Technical Center in Rochester, New York, the multi-cylinder engine was relocated to a new facility in Auburn Hills, Michigan. Final modifications to the engine included the addition of new fuel injectors with improved injection control, cam phasers with 80 crank angle degrees of authority, and a two-step valve-lift mechanism developed by Delphi. The two-step mechanism has two cam profiles including a high-lift profile for SI operation and a low-lift profile for HCCI operation. As mentioned previously, a GT-Power model of the engine was used to define the valvetrain.

SI, HCCI, and spark-assisted HCCI operation was successfully demonstrated on the multi-cylinder engine. HCCI operation (with and without spark assist) was limited by a number of factors including combustion instability and high pressure rise rates at low speed and load. The low-lift intake cams were found to substantially restrict air flow at high engine speeds resulting in insufficient time to complete gas exchange. For higher load operation, the initial cam design was successful for establishing HCCI operation but did not achieve the anticipated benefit in NOx emissions and efficiency. New cam designs are being considered for future experiments. More specifically, a different lower-lift design is under consideration which is expected to increase the level of trapped exhaust gases and further expand the range of HCCI operation.

Analysis of data collected during SA-HCCI operation along the unstable boundary showed that the behavior of the multi-cylinder engine has a strong deterministic component, implying appropriate control strategies could possibly reduce combustion variability and expand the HCCI operating window. The behavior observed on this engine is very similar to that observed in previous ORNL studies of lean and high-EGR SI combustion. This observation in combination with past experiences on similar systems indicates that appropriate control strategies would likely be successful and reducing combustion variability and extending the HCCI operational range.

The models and multi-cylinder engine platform developed for this activity have provided substantial new information toward the expansion of HCCI operation in transportations engines as well as new insight into advanced engine control technologies and approaches. A discussion is underway to establish a new CRADA to further build upon these results and experimental setups.

4. Subject Inventions

No inventions were filed under this CRADA.

5. Commercialization Possibilities

This CRADA was important in establishing a strong foundation for further refinement and the eventual improved commercialization of HCCI engine operation for improvements in engine efficiency with lowest possible emissions. Delphi will continue to pursue these technologies in combination with Oak Ridge National Laboratory and others through a recent award from the DOE in support of the development advanced powertrain technologies for demonstrating technologies for improving vehicle efficiency.

6. Plans for Future Collaborations

ORNL and Delphi plan on continuing collaborations through the establishment of a new CRADA on “Expanding Robust HCCI Operation with Advanced Valve and Fuel Control Technologies” as well as with an existing CRADA on expanding high-efficiency ethanol operation.

7. Conclusions

Substantial progress was made toward an improved understanding of the physical mechanisms which drive unstable combustion phenomena in HCCI engines. This knowledge was used to form the basis of low-order models and in defining combustion metrics which will form the framework for real-time predictive control of HCCI engines. This information in combination with experimental results from a multi-cylinder engine with advanced Delphi powertrain components is expected to provide a foundation for expanding the operational range of HCCI engines for the eventual penetration in the transportation sector.

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