HCCI Combustion Research using Liquid-Phase Fuels

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Homogeneous charge, compression ignition (HCCI) engines have advantages in terms of efficiency and reduced emissions over conventional internal combustion engines. However research is required to overcome the technical barriers to the implementation of HCCI, such as controlling ignition timing, slowing of the heat-release rate, and limiting emissions of hydrocarbons and carbon monoxide (HC and CO). To address this need, an HCCI research project has been established, including both an HCCI engine laboratory and chemical-kinetic modeling of HCCI ignition/combustion. The laboratory will include both an all-metal engine to establish HCCI operating points and combustion-control techniques, and an optically accessible engine for the application of advanced laser diagnostics to investigations of the in-cylinder processes. Some of the features of these engines include: speeds up to 3600 rpm, an open combustion chamber to minimize crevices and surface area, a compression ratio variable from 13:1 to 21:1 by interchangeable pistons, and modifications to provide variable swirl. In addition the engine is being equipped with three fueling systems: fully premixed fueling with an electrically heated fuel vaporizer, port fuel injection, and direct injection (DI) with a gasoline-type fuel injector (optionally, a DI diesel injector can also be installed). The all-metal engine and supporting laboratory subsystems are in place, and shakedown testing is under way. The basic design of the optically accessible engine has been completed, and its features are discussed.

Computational investigations of HCCI combustion have also been conducted using the CHEMKIN kinetics-rate code with the full chemistry for iso-octane. Iso-octane was used because it is a reasonable surrogate for gasoline and its kinetic mechanisms are known. Low-load HCCI operation was investigated to determine the role that chemical kinetics play in smoothing the HCCI heat release rate at these conditions, and to determine whether bulk-gas reactions (gases in the central part of the combustion chamber) are a significant source of HC and CO emissions for fully homogeneous HCCI at light loads (in addition to the cooler gases near walls and in crevices). The results show that as fueling is reduced below an equivalence ratio in the range of 0.25-0.20, the chemical kinetics slow considerably causing significant smoothing of the heat release rate, which is beneficial. However, when the fueling rate is further reduced to equivalence ratios of 0.15 and lower (very light load and idle), combustion temperatures become so low that the CO-to-CO_2 reactions no longer go to completion, even in the bulk gases. This leads to inefficient combustion and emissions of CO and HC from these bulk gases. This understanding has significant implications for the design of HCCI combustion strategies for light loads. In addition, a computational investigation has been initiated into the effects of exhaust gas recirculation (EGR) on the heat release rate and ignition timing. In order to separate these two effects, intake temperatures were adjusted to compensate for the reduced compression heating with EGR. Results are presented showing that EGR does increase the heat release duration, but that when ignition timing is maintained, the improvement is substantially reduced.

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7th Diesel Engine Emissions Reduction Workshop
August 5-9, 2001

Sponsor: U.S. Dept. of Energy, OTT, OAAT and OHVT
Program Managers: Kathi Epping and Gurpreet Singh

Motivation

- Homogeneous charge compression ignition (HCCI) engines are a low-emissions alternative to diesel engines. Potential to:
  - Provide diesel-like or higher efficiencies.
  - Very low engine-out NO_X and PM emissions.
  - Applicable to automotive (light-), medium-, and heavy-duty engines.
- Recent research has greatly expanded our understanding of HCCI, but additional research will be required to resolve the technical barriers, including:
  - Control of combustion timing across the load-speed map.
  - Controlling the rate of heat release for high-load operation.
  - Unburned hydrocarbon emissions.
  - Cold-start and control during rapid transients.

Project Objective and Approach

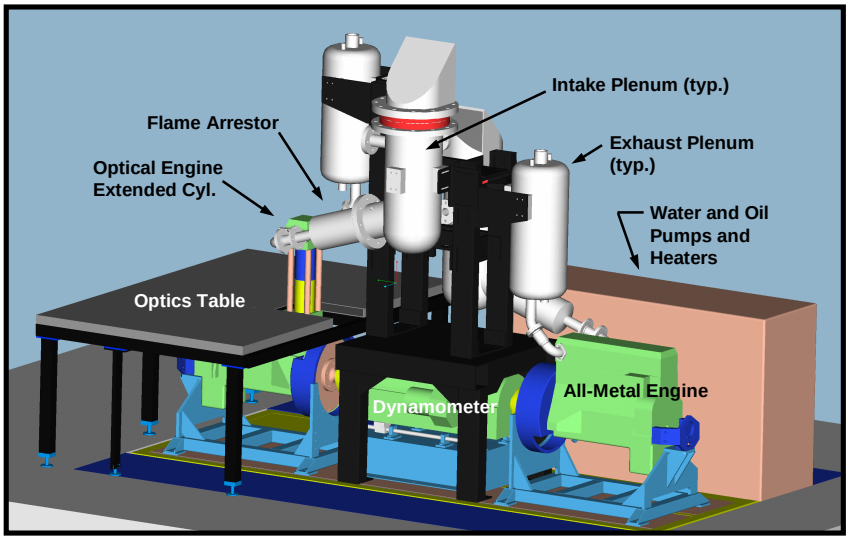
- **Project objective** is to provide the fundamental understanding required to overcome the technical barriers to the development a practical HCCI engines by industry.
- Establish a laboratory to investigate HCCI combustion fundamentals.
  - All-metal engine
    - > Establish operating points, develop combustion-control methods, emissions measurements, and validate kinetic-rate computations.
  - Optically accessible engine
    - > Apply optical diagnostics to develop an understanding of: the nature of HCCI combustion, the effects of fuel/air/residual mixture, the effects of partial stratification of charge mixture and temperature, wall quench, etc.
- CHEMKIN kinetic-rate computations
  - Guide for: engine design, operating points, fuel type, & expected trends.
  - Fundamental understanding of selected processes.
    - > Role of Kinetics: 1) Low Loads; and 2) EGR.

Approach: Laboratory

- Build a versatile facility to allow investigations of various fuel, mixing, and control strategies. All-metal and optical engines.
  - Compression ratio variable through interchangeable pistons (13 to 21:1).
  - Variable swirl to alter mixing and heat transfer rates.
  - Three fueling systems: premixed, PFI, & DI-gasoline (optional DI diesel).
  - Intake charge conditioning: air, simulated or real EGR, inert charge, temperature and pressure control up to 200° C & 3 atms., respectively.
  - Balanced single-cylinder operation to 3600 rpm.
  - Displacement 0.98 liters/cylinder; Variable valve timing - FY02.
- Design matching optical engine, additional features include:
  - Full optical access of chamber near TDC - high combustion pressures.
  - Optional full quartz cylinder to investigate mixture preparation - low loads or inerted charge.
  - Hydraulically operated drop-down cylinder – rapid cleaning & switch cyls.

Schematic of HCCI Engine Laboratory

Installation as per this schematic is underway.

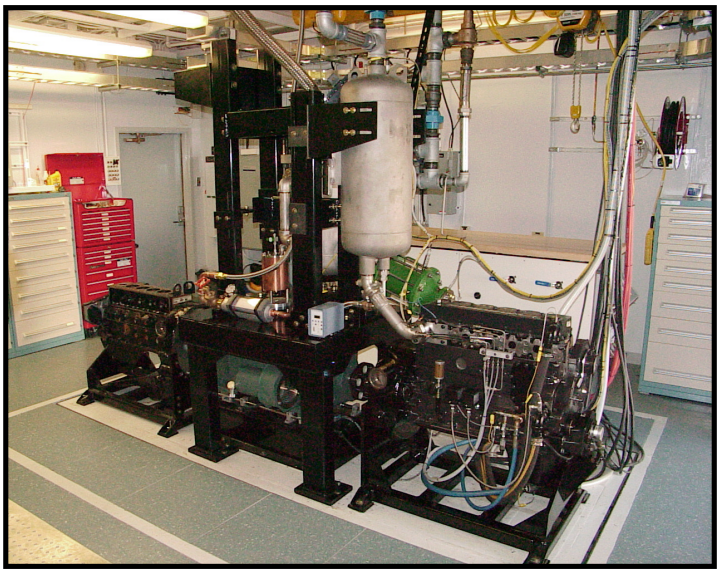


Design of Optically Accessible Engine

- Extended cylinder and piston with full piston-crown window.
- Outer post-supports - wide view angles.
- Upper cylinder interchangeable:
  - Metal with with three large windows in spacer ring.
    - View of processes near TDC.
    - Can be fired at all loads.
  - Full quartz cylinder:
    - View of mixing during entire intake and compression strokes.
    - Motored or fired at light loads.
- Drop-down cylinder with hydraulic lift.
  - Rapid cleaning.
  - Rapid interchange of cylinders.

HCCI Laboratory - May 2001

Metal Engine is complete. Initial testing and debugging have begun.



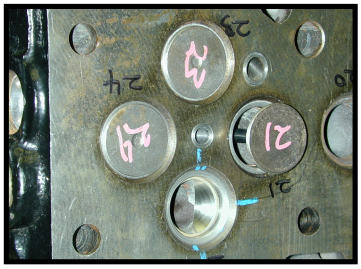
Pict. 21

Metal-Engine: Pistons

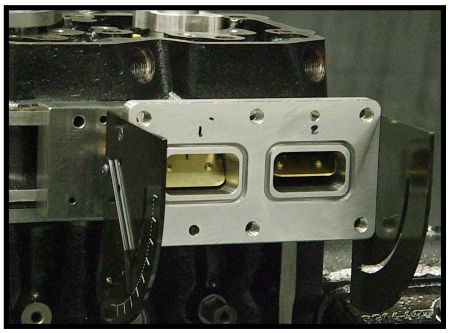
CR = 21:1	CR = 18:1	CR = 13:1	Balance Piston Cylinders 1 – 5

- Interchangeable pistons allow the compression ratio (CR) to be varied from 21:1 to 13:1 in increments of 1 or 2.
- Open chamber design minimizes crevices & maximizes average gas temperature (to minimize HC emissions).
- Balancing pistons match weight, with no compression.

Metal-Engine: Variable Swirl

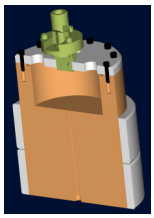


- Intake ports modified to provide variable swirl.
  - Intake port on right is directed to give CCW swirl.
  - Custom swirl plate in lower port directs flow opposite direction, CW.

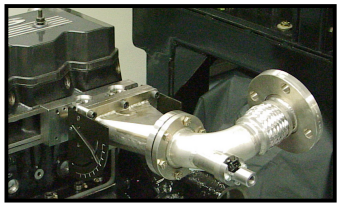


- Butterfly valves adjust relative flow between the ports to vary swirl.
  - Both ports give S.R. = 0.9.
  - Directed port (left butterfly) give S.R.= 3.2.

Fuel Systems

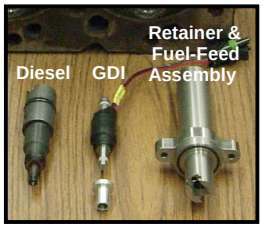


- Fully premixed.
  - Fuel injector or metering pump to supply fuel to heated vaporization chamber.
  - Vaporized liquid fuel mixed with intake air (or gaseous fuel).



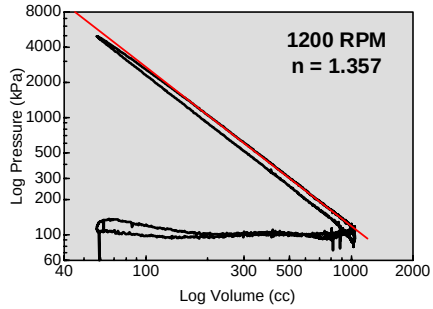
- Port Fuel Injection (PFI).
  - Standard automotive PFI (Delphi or Bosch).

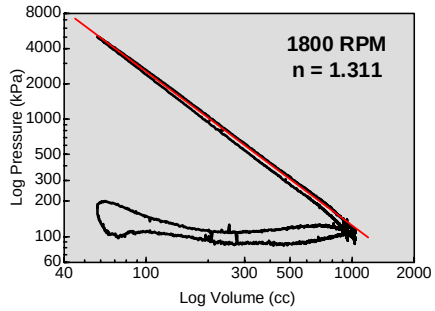
- Gasoline Direct Injection (GDI).
  - Production Siemens injector
  - Conventional DI diesel injector could also be used.



Motored Pressure Data

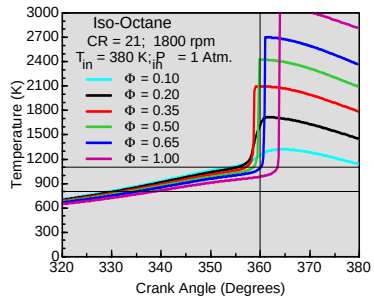
- Motored metal engine up to 3000 rpm.
  - 18:1 Compression ratio piston
  - Non-boosted – P_{in} = 108 kPa
- IMEPg after ~1 hour of "break-in"
  - 1200 rpm -75 kPa
  - 1800 rpm -61 kPa
  - 2400 rpm -52 kPa
  - Expect to improve with additional "break-in" time.
- Polytropic Coefficients (n)
  - 1200 rpm 1.357
  - 1800 rpm 1.311
- Pressure oscillations in intake and exhaust runners
  - Minimal below 1800 rpm
  - 3000 rpm ±8 kPa on intake.





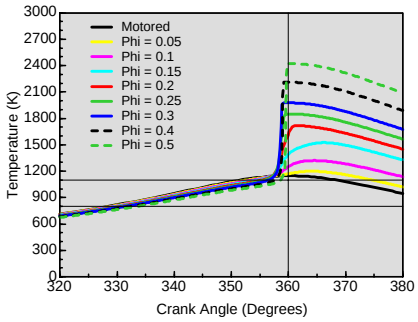
Investigate kinetic limits of low-load operation using CHEMKIN with the full chemistry for iso-octane.

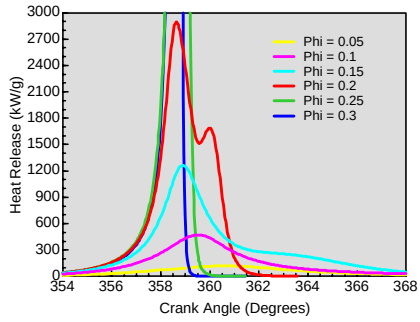
- Motivation:
  - Our previous results indicated a longer heat release at low loads.
  - Experiments indicate higher fuel-specific HC and CO at low loads.
    - > Generally assumed to arise from colder gases near walls and in crevices.
    - > Slower heat release suggests possible kinetic contribution.



- Objectives/Approach:
  - Investigate changes in combustion duration with fuel loading to better understand the effect of kinetics on smoothing heat release.
  - Investigate potential bulk-gas contributions to HC and CO emissions at low loads.

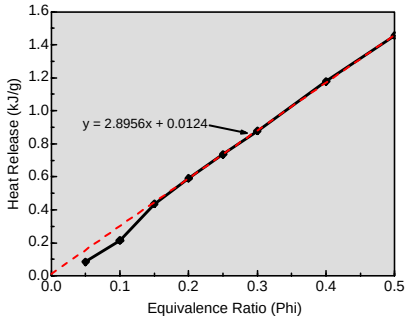
Kinetics Affect Heat Release Rates Significantly

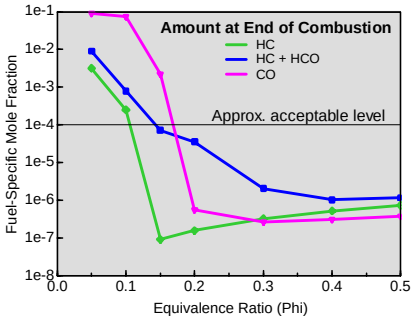




- Temperature and pressure rise is noticeably slower for equivalence ratios (ϕ) less than 0.25.
- Heat-release-rate duration increases progressively with decreasing ϕ.
  - Duration increases from 90 µs for ϕ = 0.3 to 270 µs for ϕ = 0.2.
    - For ϕ = 0.1 duration is 680 µs (10 – 90% burn).
- Kinetics can play a significant role in smooth operation at lower loads.

Combustion Reactions are Incomplete at Low Loads.

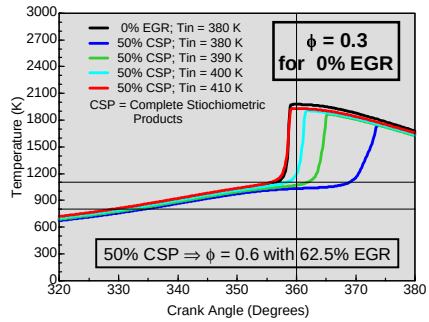




- Below ϕ = 0.15, combustion efficiency drops significantly.
  - High levels of unburned HC, HCO, and CO. (Note HCO is 3x HC).
- Temperatures are too low to complete reactions, esp. CO $\rightarrow$ CO_2.
  - Computations with increased intake temperature show complete reaction at low loads, but ignition timing is too early.
- Results for bulk-gas only, effects of walls and crevices make incomplete combustion and emissions worse.

Investigate the Effect of EGR/Residuals on HRR

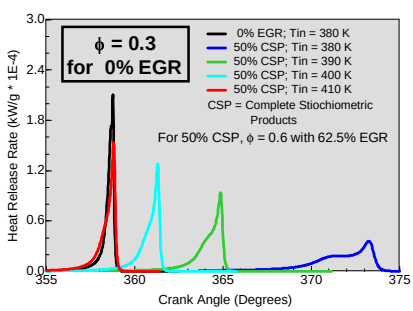
- Motivation:
  - Experiments at Lund University showed EGR addition slowed the heat release rate (HRR).
    - > Did not maintain ignition timing.
    - > Our past work has shown that lower γ (c_p/c_v) significantly affects ignition timing which can also affect HRR.

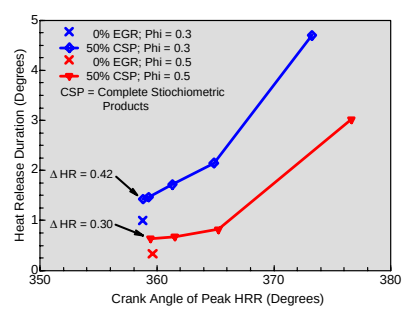


CHEMKIN Computations Iso-Octane

- Objectives/Approach:
  - Investigate chemical-kinetic effects of EGR addition on the heat release rate.
  - Compensate for the reduced compression heating to determine whether EGR gases directly affect combustion rates.

Kinetic Effect of EGR on Heat Release Rate





- In agreement with experiments, EGR slows the heat release rate.
  - Majority of increase is due to shift in ignition timing, due to reduced compression heating because of the reduced γ (c_p/c_v).
- When T_{in} is increased to compensate, effect is substantially reduced.
- At higher loads – bigger percentage increase, but less real time.
- EGR can help slow HRR allowing higher loads, but is probably not sufficient by itself.

Summary and Conclusions

- Metal engine and supporting subsystems have been completed.
  - Features: HCCI pistons, adjustable CR, variable swirl, intake-charge conditioning, and three fuel systems (fully premixed, PFI, GDI).
  - Testing and debugging are underway.
- Basic design of optical engine is complete. Expect complete fabrication of parts and begin assembly in early 2002.
- CHEMKIN results:
  - At low loads, bulk-gas reactions are important for combustion rates, and HC and CO emissions - wall effects would make it worse.
    - > Heat release slows significantly for $\phi \leq 0.2$ - 0.25 – advantage.
    - > For $\phi \leq 0.15$, low combustion efficiency and high HC and CO.
    - > Suggests charge stratification may be required for avg. $\phi \leq$ ~0.15.
  - EGR can help reduce the heat release rate, but most of the reduction observed in experiments appears due to shift in ignition timing.