Achieving High Efficiency Clean Combustion in Diesel Engines

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Objectives

- Explore potential of expanding HECC speed/load operation range in a light-duty diesel engine with only production-like controls.
- Demonstrate HECC operation under road-load type conditions.
- Characterize effect of transition approach from OEM to HECC operation on emissions and performance.

Approach

- Explore potential strategies for achieving HECC operation on a Mercedes 1.7-L diesel engine with only production-like controls.
- Explore effect of transition path from OEM to HECC operation on emissions and performance.
- Perform detailed emissions and combustion characterization to improve understanding of efficient advanced combustion modes.

Accomplishments

- Explored potential of achieving HECC over range of speed and loads. Based on these experiments, modifications will be made to the experimental setup in FY 2005 in an attempt to increase HECC operation window for this platform.
- Demonstrated efficient operation with a 90% reduction in NOx and a 50% reduction in PM emissions under road-load type conditions (20% load, 1500 rpm) without excessive HC emissions.
- Investigated transition from OEM to HECC operation. Experimental results indicate that the transition pathway has strong impact on achieving efficient operation.

Future Directions

- Upgrade engine control system for greater flexibility in injection timing and frequency as well as improved transient capability.
- Modify experimental setup to include a low-pressure EGR system and a diesel atomizer for partially premixed strategies to explore expanding the effective HECC speed/load range.
- Investigate techniques for entering and exiting HECC modes and consider potential diagnostic tools for feedback control when transitioning between these modes. Methods for transitioning between conventional diesel and HECC operation may have an important role in minimizing harmful emissions and maintaining efficiency.

<u>Introduction</u>

Researchers at ORNL have been exploring the potential of new combustion regimes that exhibit simultaneous low NOx and PM emissions. An improved understanding of these combustion modes is critical for lowering the performance requirements for post-combustion emissions controls and meeting future U.S. emissions and efficiency goals. Through proper combustion management, ORNL has achieved significant reductions in NOx and PM emissions without the decrease in efficiency typically associated with operating in these regimes. This type of operation is commonly referred to as high efficiency clean combustion (HECC) and was demonstrated at ORNL on a multi-cylinder engine using only production-like hardware. This achievement is dramatically different from other approaches to HECC which may require expensive hardware modifications or require the acceptance of significant fuel penalties.

Another important aspect of operating diesel engines in advanced combustion modes is the ability to transition in and out of these modes with minimal adverse effects on emissions or performance. ORNL researchers were able to demonstrate seamless transitions with no significant emissions excursions or effects on performance.

Approach

The overall objective of this activity is to improve the understanding and the ability to achieve and transition to HECC operation for a range of real-world speed/load conditions with only production-like parameters and controls. A combination of thermodynamic and detailed exhaust chemistry information will be used to dramatically improve the understanding of HECC regimes which is expected to result in even cleaner and more efficient operation of diesel engines. The thermodynamic and exhaust chemistry information will also be shared with industry and/or other national laboratories for the development and validation of improved combustion models and catalysts.

A Mercedes 1.7-L common rail diesel engine is the experimental platform for this study. This engine is equipped with a rapid-prototype, full-pass engine controller capable of actuating the EGR valve, intake throttle, and fuel injection parameters (timing, duration, fuel rail pressure, and number of injections). HECC operation was achieved on this engine under road-load conditions using a combination of high EGR and injection parameters. Specifically, EGR was used to achieve a low-NOx low-PM condition (aka low temperature combustion, LTC), and injection parameters were used to adjust combustion phasing to recover efficiency. The effect of transition path from the OEM condition to HECC operation using this approach was also investigated using the advanced controller.

Results

Extensive experiments have been performed to develop approaches for achieving HECC operation in a light-duty diesel engine. The results of an example road-load condition are summarized in Table 1. The OEM condition is 1500 rpm at 2.6 bar BMEP. Results are shown for the OEM condition, the low-NOx low-PM condition (LTC), and the HECC condition, which may also be referred to as an “efficient LTC” condition. Note that the phrase LTC as used in the literature typically refers to a low-NOx low-PM condition only and provides no information concerning efficiency. In this document, the LTC condition should be thought of as an intermediate condition which was explored during the search for HECC operation. Comparing the OEM and HECC conditions in Table 1 shows a 90% reduction in NOx and a 30% reduction in PM between the two cases with no degradation to engine efficiency or increase in HC emissions. Also note that this was achieved with conventional rail pressures and a single fuel injection event.

Table 1 Example of HECC operation at road-load conditions (1500 rpm, 2.6 bar BMEP)

	OEM	LTC	HECC
EGR (%)	21	49	48
BSFC (g/hp.hr)	211	240	209
NOx (g/hp.hr)	1.2	0.1	0.1
PM (g/hp.hr)	0.38	0.51	0.29
THC (g/hp.hr)	2.68	4.54	2.46
Intake Temp (C)	43	129	94
Exhaust Temp (C)	205	244	199
Main Timing (BTDC)	2	2	12
Pilot Timing (BTDC)	18	18	Off
Rail Pressure (bar)	320	320	328

The average heat release profiles for the conditions in Table 1 are shown in Figure 1. A significant shift in the heat release profile was observed with increasing EGR as seen in comparing Figures 1(a) and 1(b). The heat release profile is recovered (or improved) by re-phasing the combustion process with injection timing to achieve HECC operation as illustrated in Figure 1(c). Recall from Table 1 that the pilot injection was disabled during HECC operation. The 10-50% heat release interval was shorter for HECC operation as compared to OEM operation, indicating a higher fraction of premixed (or kinetically controlled) combustion. Conversely, the 50-90% heat release interval was longer for HECC operation indicating a slower mixing-controlled combustion phase, potentially due to the increased EGR level under the HECC condition.

HECC operation using high levels of EGR results in a reduction in volumetric efficiency due to the increase in the temperature of the inducted intake charge. For the case summarized in Table 1, the temperature of the intake charge increased from 43 °C for the OEM condition to 94 °C for the HECC condition, but the thermal efficiency remained unchanged at approximately 30% for the two conditions. Therefore, some form of a reduction in losses occurred during the engine cycle. Further analysis is necessary to determine whether the reduction in losses is due to heat transfer effects or the combustion process. A more detailed first and second law thermodynamic analysis will be applied to this and other HECC data during the next phase of this activity. Not shown in the average heat release profiles is the effect of these different operating modes on engine stability. The COV in IMEP increased with EGR level but returned to a comparable OEM level during HECC operation.

Exhaust constituents were analyzed in detail to characterize the production of aldehyde emissions for the OEM, LTC, and HECC cases summarized in Table 1. The results of this analysis are shown in Figure 2 and indicate a sharp increase in aldehyde emissions as EGR is increased to achieve LTC operation. The increase in aldehyde emissions is believed to be the result of slower or delayed combustion and not necessarily due to increased locally rich combustion. Re-phasing of the combustion process and removal of the pilot injection to achieve HECC operation resulted in a reduction in aldehyde emissions to levels similar to those observed for the OEM condition.

Controlled transition experiments were performed to investigate potential emissions and performance problems which may be associated with transitioning in and out of HECC operation. The results shown in Figure 3 are for conditions similar to those summarized in Table 1. The most significant differences are the base condition for the transition experiments is 0% EGR and a different engine (same model, MB 1.7-L) was used for these experiments. No significant PM or NOx spikes were observed during transitions in and out of HECC operation. In addition, BSFC was the same for both modes with no significant excursions in performance.

Summary and Conclusions

- HECC operation under road-load conditions is possible in light-duty diesel engine applications and was achieved with a reduction of engine-out NOx (90%) and PM (30-50%) without excessive HC emissions and no efficiency penalty.
- HECC operation is characterized by an increased fraction of premixed combustion.
- Engine-out aldehyde emissions do not increase with HECC operation but are of levels similar to those observed for the OEM condition.
- Transitioning between OEM and HECC conditions does not result in significant PM or performance excursions under road-load conditions.

FY 2004 Publications/Presentations

1. C. S. Sluder, R. M. Wagner, S. A. Lewis, and J. M. Storey, “A Thermal Conductivity Approach for Measuring Hydrogen in Diesel Exhaust”, SAE Paper No. 2004-01-2908 and SAE Transactions (Tampa, FL USA; Octo-ber 2004).

2. C. S. Sluder, R. M. Wagner, S. A. Lewis, and J. M. Storey, “High Efficiency Clean Combustion in a Direct Injection Diesel Engine,” 2004 AFRC/JFRC Joint International Combustion Symposium (Maui, HI USA; October 2004).

3. R. M. Wagner, C. S. Sluder, S. A. Lewis, and J. M. Storey, “Achieving High Efficiency Clean Combustion in Diesel Engines”, 10th Diesel Engine Emissions Reduction Conference (San Diego, CA USA; August 2004).

4. R. M. Wagner, C. S. Sluder, S. A. Lewis, and J. M. Storey, “Chemical Composition of the Exhaust from Low-NOx Low-PM Diesel Combustion”, 2004 Internal Combustion Division of ASME and the CIMAC World Congress (Kyoto, Japan; June 2004).

5. C. S. Sluder, R. M. Wagner, S. A. Lewis, and J. M. Storey, “Exhaust Chemistry of Low NOx Low PM Diesel Combustion”, SAE Paper No. 2004-01-0114 and SAE Transactions (Detroit, MI USA; March 2004).

Acronyms

BSFC	Brake Specific Fuel Consumption
COV	Coefficient of Variation (standard deviation / mean)
EGR	Exhaust Gas Recirculation
IMEP	Indicated Mean Effective Pressure
HECC	High Efficiency Clean Combustion
LTC	Low Temperature Combustion
NOx	Oxides of Nitrogen (NO, NO_2)
PM	Particulate Matter

Figure Captions

Figure 1. Heat release profiles for OEM, LTC, and HECC engine operation under road-load conditions. The darker shaded region corresponds to the 10-50% heat release interval and the lighter shaded region corresponds to the 50-90% heat release interval.

Figure 2. Aldehyde emissions for OEM, LTC, and HECC engine operation under road-load conditions.

Figure 3. Controlled transition between OEM and HECC operation under road-load conditions.