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Direct Injection Assisted HCCI Combustion of Pre-mixed Natural Gas

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ABSTRACT - Homogeneous Charge Compression Ignition (HCCI) is an internal combustion process that is difficult to implement in a production setting due to the lack of direct control over combustion timing. A direct injector has been adapted to a single cylinder research engine to initiate and control the combustion of a pre-mixed natural gas charge by introducing a stratified charge near top dead center. N-heptane is used as the direct injected fuel as its low autoignition temperature allows for a predictable ignition delay of the main charge. The effect of the pilot charge on combustion timing, stability, and severity is investigated, as well as the extension of the load range of the engine.

INTRODUCTION

HCCI is a combustion process that combines the advantages of Diesel and Otto cycle engines by using compression ignition with a dilute, homogeneous mixture to produce low-temperature combustion. The benefits of HCCI are higher compression ratio and efficiency than Otto engines with lower NOx and particulate emissions than Diesel engines.

There is no direct control over the combustion timing in an HCCI engine, unlike the Diesel and Otto engines which use injection timing and spark timing respectively to control the start of combustion. The autoignition timing in an HCCI engine is dependent on many parameters including equivalence ratio, fuel composition and properties, compression ratio, intake pressure and temperature, and external and internal EGR. The overall efficiency of the engine depends strongly on the combustion timing and duration.

Natural gas (nominally CH_4) HCCI is inherently difficult to control efficiently as the methane autoignition temperature is relatively high at around 1100K (depending on mixture properties). Combustion tends to occur before top dead centre and proceeds very rapidly, often leading to severe combustion and unacceptable rates of pressure rise or knock. Mixture dilution is used to delay and reduce the rate of combustion. However excessive dilution leads to unstable combustion, unacceptably high variation in IMEP and eventually misfiring.

Direct Injection Control Solution

It is proposed that a small (<20% of fuel energy) pilot injection of a fuel with high volatility and low autoignition temperature will act to initiate combustion of a premixed natural gas charge in an HCCI engine. The fuel is injected shortly before TDC (within 30 degrees) to burn as a stratified charge or a diffusion jet, and not as a homogeneous mixture. As such, it will cause a relatively slow rise in the cylinder pressure and temperature and cause the homogeneous natural gas charge to autoignite at an appropriate timing. The pilot injection is used to lower the variation in IMEP at the lean limit, as well as prevent misfiring of the engine at marginal conditions. It can also be used to control the combustion timing in an

HCCI engine and increase the efficiency of fuels like natural gas that have very high reaction rates.

EXPERIMENTAL APPARATUS

A single cylinder Waukesha Co-operative Fuel Research (CFR) engine has been adapted for natural gas port injection and n-heptane direct injection. The engine retains its factory spark plug to ease startup and mode switching and has been outfitted with an intake heater and closed loop temperature controller. To increase the temperature at the end of compression and aid autoignition, the engine is also supercharged. This engine is the same one described by Hosseini in (1,2). The compression ratio of the engine is variable but has been set at 16 for all experiments in this study. It is worth noting that all compression ratios discussed in this paper have been measured using motoring pressure traces, and are not geometric compression ratios but effective compression ratios.

The engine has been run under both pure natural gas HCCI conditions and direct injection assisted HCCI conditions, and for this study HCCI will refer to the pure natural gas conditions while DI-HCCI will refer to direct injection assisted conditions.

A schematic of the engine and measurement locations is shown in Figure 1.

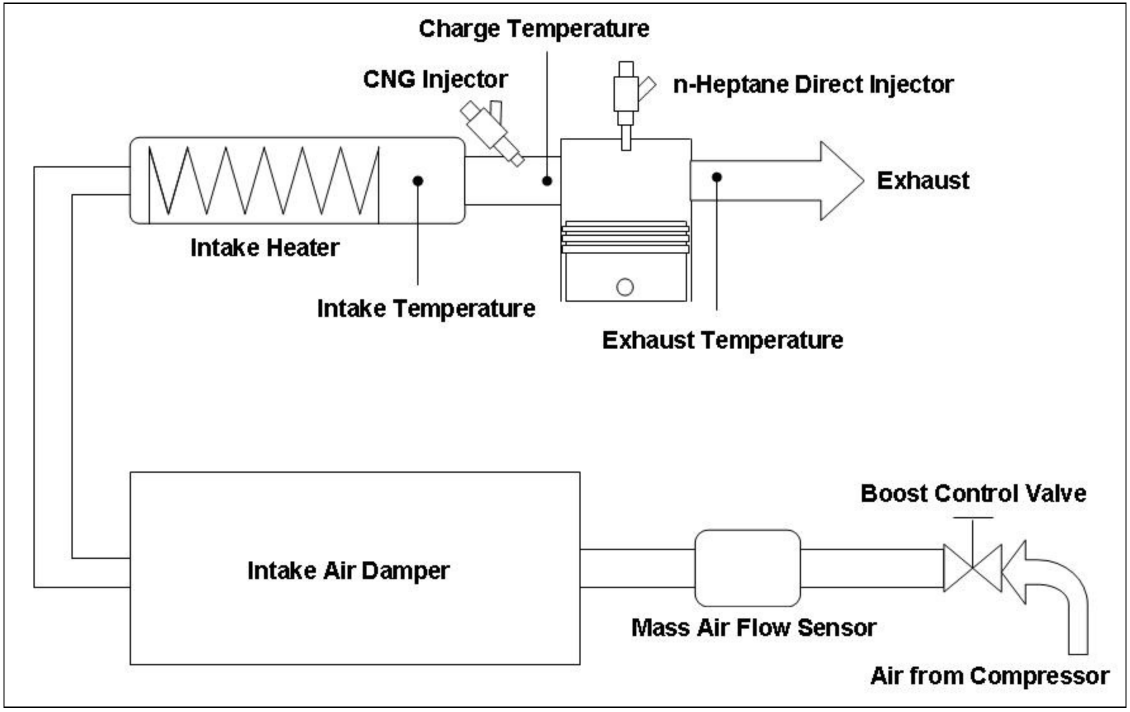

Figure 1: Engine Flow and Temperature Measurements Schematic

Direct Injection System

The injector, from an Audi FSI gasoline direct injection system, is pressurized up to 100 bar by applying pressurized nitrogen to a sealed sample cylinder containing n-Heptane.

A National Instruments PXI 6602 Timing I/O device is used to generate the injection pulse based on a 0.1 CAD BEI shaft encoder and a hall effect camshaft sensor. The 5V signal generated by the PXI system is passed to a custom injector driver based on the National Semiconductor LM19N chip which provides 6A peak current followed by 1.5A hold current. The PXI system is coupled with LabView software that allows deterministic updating of the pulse width and pulse timing.

Measurement Apparatus

The primary measurements for this study include the in-cylinder pressure, air mass flow rate, fuel mass flow rates, and intake and charge temperatures.

Cylinder pressure is measured using a Kistler 6043A pressure transducer and a National Instruments PCI system indexing the measurements to the 0.1 CAD signal generated by the BEI crankshaft encoder.

Air consumption is measured by a TSI 4235 mass air flow sensor. The natural gas mass flow rate is measured with an Omega FMA-A2117 transducer, while the n-Heptane mass flow is measured by a Max Machinery 213 series four-piston positive displacement flowmeter.

Intake system temperature (heated air +EGR) is measured using a type T thermocouple, and charge temperature is recorded as the setpoint of the temperature controller. The intake temperature is much higher than the charge temperature which is reduced by the high heat capacity of the port-injected CH4.

EXPERIMENTAL PROCEDURE

Data points were recorded at steady state operating conditions. Engine speed for the tests was held constant at 500 RPM with a charge temperature setpoint of 160 C. Data sets were taken at boost pressures of 10, 20, and 30 kPa. Each data set contained numerous points as equivalence ratio was adjusted from the lean (misfire) limit to the rich (knock) limit. The data sets were first taken without direct injection and then repeated with direct injection. All direct injection events began 20 degrees before TDC, which (for these conditions) provided good combustion stability with a reasonably low energy content provided by the n-heptane.

RESULTS AND DISCUSSION

Several combustion and engine output characteristics were investigated in this study. The ability to control combustion timing is of great importance when optimizing the efficiency of the combustion, and as such is the primary result. Engine and thermal efficiency, combustion stability, combustion severity, and the implications of the direct injection event on the load range of the engine are also of importance in this study and are presented below.

Combustion Timing Control

Traditionally CA10 (the crankshaft position in degrees at which 10% of the fuel has burned) was used as a measure of combustion timing. However, more recently HCCI researchers have shifted towards CA50 as a more appropriate measure of combustion timing due to the extremely fast burning rates of natural gas in an HCCI engine (3). CA50 is used for this study.

Figure 2 compares CA50 and IMEP for the engine with both combustion systems. As the mixture is richened and more boost pressure is applied to raise the IMEP, the CA50 of the pure natural gas HCCI advances towards TDC. This advance has a detrimental effect on the engine efficiency at some point where the combustion occurs too early to make efficient use of the pressure rise.

With DI-HCCI, the mean CA50 is maintained at a constant (and later) timing over the IMEP range. This is an indication that the combustion efficiency can be optimized for higher load engine operation as the CA50 can be controlled to remain within the efficient range for the engine cycle.

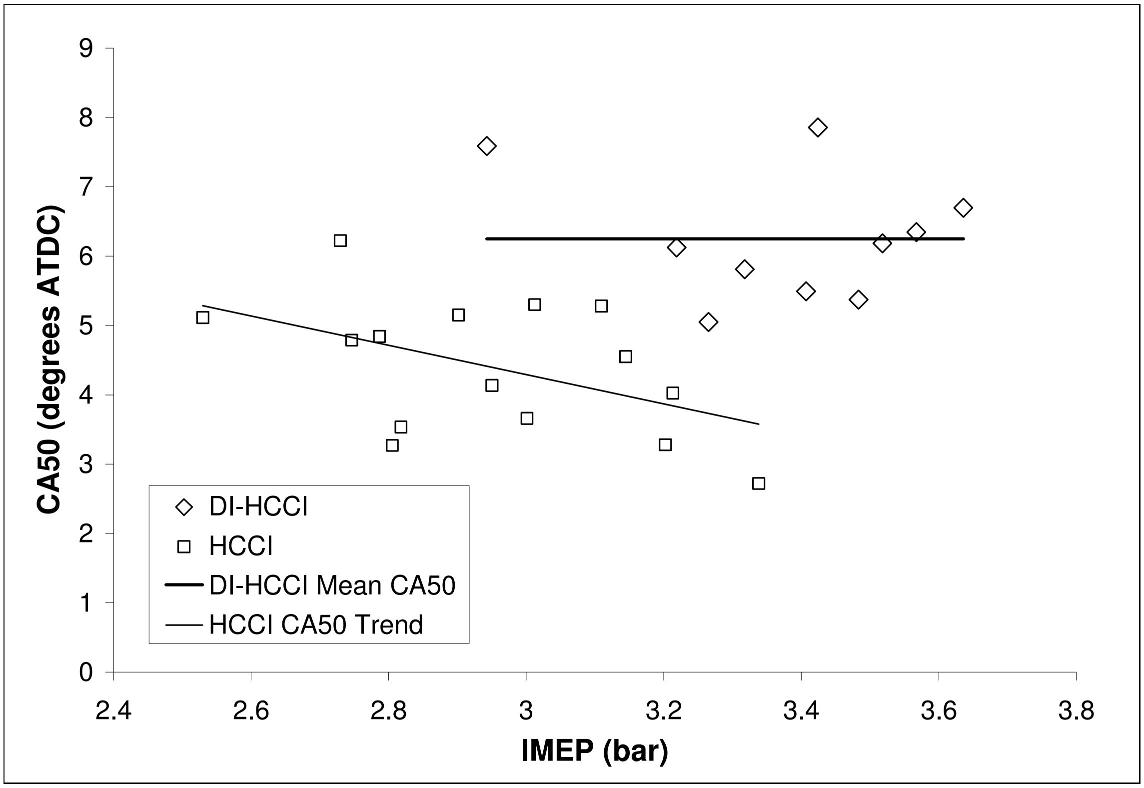

Figure 2: Combustion timing (CA50) over an IMEP range for HCCI and DI-HCCI modes

Thermal and Engine Efficiency

Figures 3 and 4 show thermal efficiency for both combustion systems as a function of engine IMEP. Figure 3 excludes the parasitic loss to run the supercharger and Figure 4 includes it. (Supercharger drive power was calculated assuming a 70% isentropic efficiency based on typical values from Stone (3) and 85% mechanical efficiency). While excluding supercharger power, the engine thermal efficiency is lower for the DI-HCCI mode than for the pure natural gas HCCI. However, Figure 4 shows that, when including supercharger power, the DI-HCCI mode efficiency increases with power level and becomes significantly better at higher power. This interesting result occurs because DI-HCCI can achieve higher power with less boost pressure and thus less supercharger loss. The result indicates the necessity for mode switching since, at low power demand, the engine is more efficient using pure HCCI. However as power demand increases it is more efficient to use direct injection than to increase supercharging.

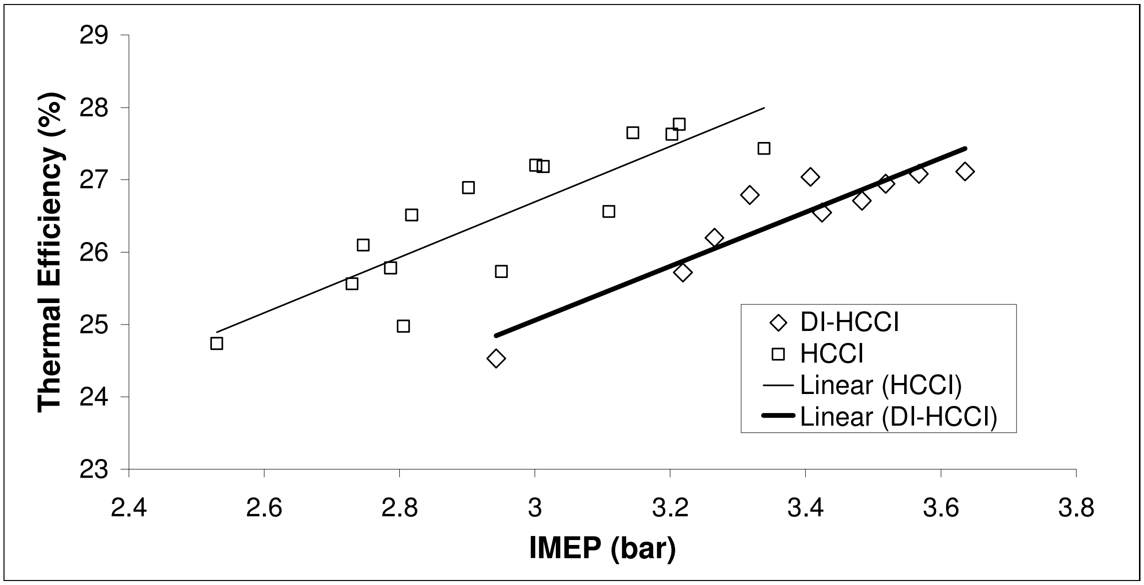

Figure 3: Thermal Efficiency vs. IMEP for HCCI and DI-HCCI modes, excluding supercharger power.

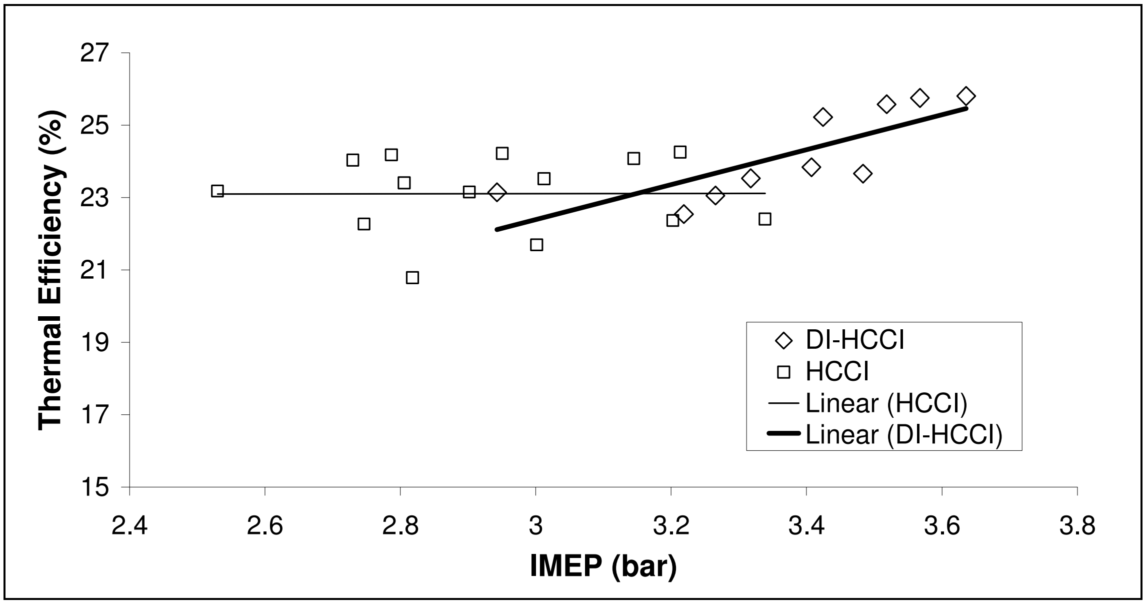

Figure 4: Engine efficiency vs. IMEP for HCCI and DI-HCCI modes, including supercharger power.

Combustion Stability

The coefficient of variance of engine IMEP (COV_{IMEP}) is used as a combustion stability measure for this study. As shown in Figure 5, combustion stability is better for the HCCI mode than for the DI-HCCI mode. Both modes exhibit similar trends when plotted against IMEP, and the combustion stability improves as the engine load increases. The range of IMEP with acceptable combustion stability (<10% COV_{IMEP}) is reasonable for both modes and given the ability to control CA50 at higher loads, it is expected that DI-HCCI will complement the high-load capability of the engine.

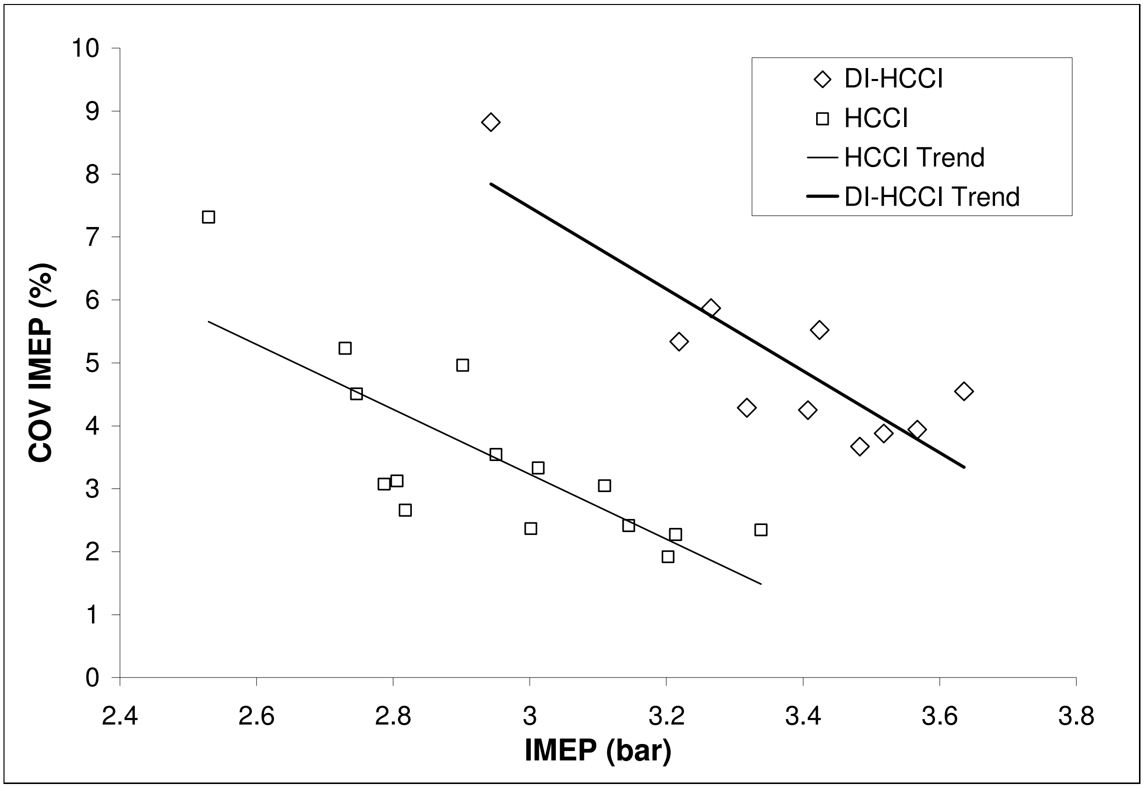

Figure 5: COV IMEP vs. IMEP for HCCI and DI-HCCI modes.

<u>Combustion Severity</u>

HCCI is typically limited by the combustion noise generated during high load operation due to the high reaction rates and extremely fast pressure rise. A good measure of the severity of the combustion, and of the combustion noise level that can be expected from the engine, is the maximum rate of pressure rise that occurs during the cycle. Typically the combustion is considered acceptable if the maximum rate of pressure rise remains below 10 bar/CAD during the cycle (4). This threshold has been used to differentiate acceptable operation from unacceptably severe combustion for this study.

Figure 6 shows the decrease of combustion severity achieved through the DI-HCCI mode. DI-HCCI extends the high-load range of the engine under these conditions, and provides an alternative method to increasing boost pressure to achieve higher loads. The combustion severity can also be reduced during lower load operation.

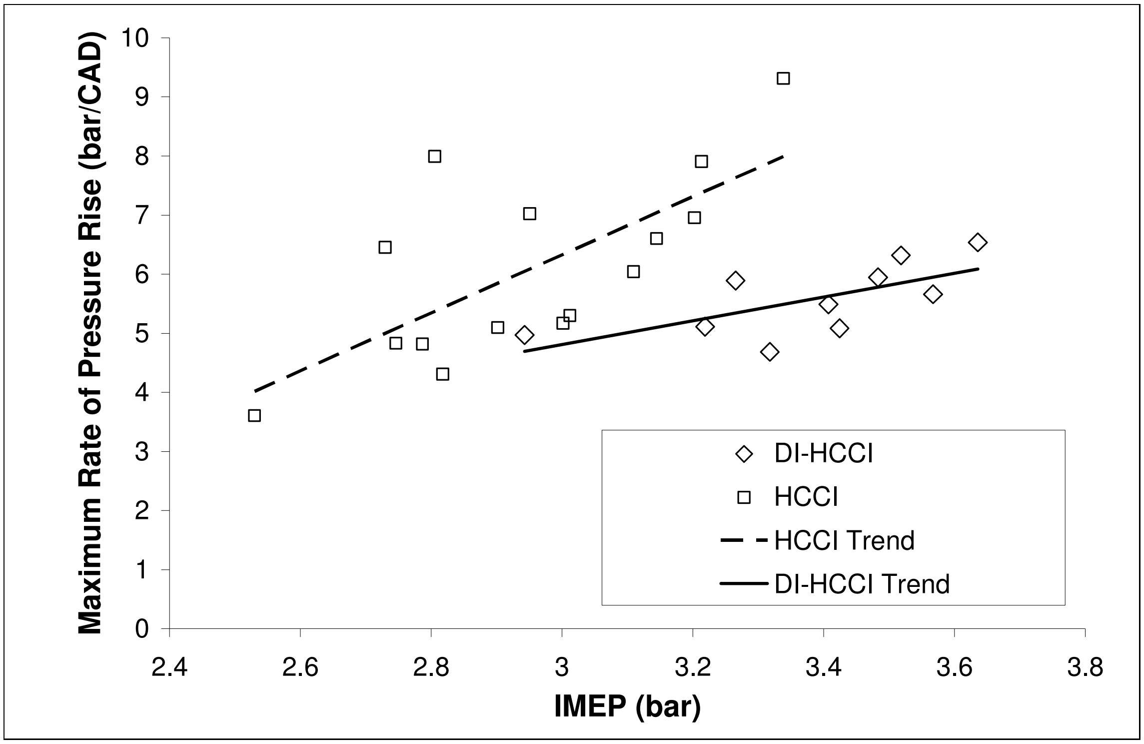

Figure 6: Maximum Rate of Pressure Rise vs. IMEP for HCCI and DI-HCCI modes.

<u>Extension of HCCI Load Range</u>

Due to the additional energy content of the n-heptane charge, the direct injection assisted HCCI combustion typically provided higher power at similar boost conditions. Figure 7 shows the load range of the engine at different boost pressures for both HCCI and DI-HCCI engine operation. As is evident from Figure 7, even with a great deal of boost it would be difficult to for pure HCCI to achieve the power levels available from DI-HCCI as the pure HCCI combustion becomes too severe under those conditions.

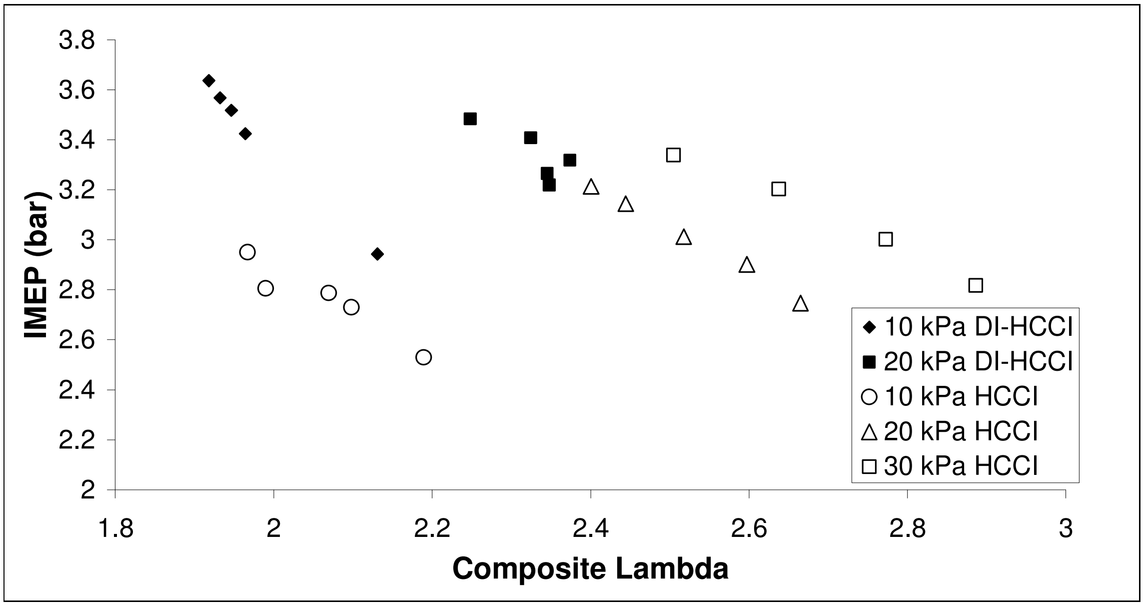

Figure 7: Load ranges of HCCI and DI-HCCI at various boost pressures.

CONCLUSION

Direct Injection assisted HCCI tests have been implemented and carried out on a single cylinder engine to investigate the capability of the direct injection event to control combustion timing and the effects of the direct injection on combustion.

Combustion timing is affected by the injection event, and has been retarded by several CAD in this study. This demonstrates the potential of DI-HCCI to improve the efficiency of natural gas HCCI combustion and to lend some direct control over the combustion timing. Efficiency, although not optimized during this study, has proven to be greater for DI-HCCI engines operating at higher power when including the supercharger parasitic load. At lower loads, natural gas HCCI without direct injection can achieve better efficiency.

Along with retarding ignition timing, the direct injection event has a negative impact on combustion stability. This result is not fully understood and will require further investigation. The combustion severity is, however greatly reduced in DI-HCCI mode which shows promise for high-load range extension capabilities.

Because it can be effectively controlled on a cycle by cycle basis, the direct injection event could be used in a mobile or other transient application as an instantaneous method of controlling the engine load. It has significant advantages compared with slower methods of increasing available power such as raising boost pressure or lowering intake temperature, which cannot be controlled effectively on a cycle to cycle basis.

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