

Experimental Investigation of the Impact of In-Cylinder Pressure Oscillations on Piston Heat Transfer

Eric Gingrich
U.S. Army TARDEC

Daniel Janecek and Jaal Ghandhi
Univ of Wisconsin Madison

ABSTRACT

An experimental investigation was conducted to explore the impact in-cylinder pressure oscillations have on piston heat transfer. Two fast-response surface thermocouples embedded in the piston top measured transient temperature and a commercial wireless telemetry system was used to transmit thermocouple signals from the moving piston. Measurements were made in a light-duty single-cylinder research engine operated under low temperature combustion regimes including Homogeneous Charge Compression Ignition (HCCI) and Reactivity Controlled Compression Ignition (RCCI) and Conventional Diesel (CDC). The HCCI data showed a correlated trend of higher heat transfer with increased pressure oscillation strength, while the RCCI and CDC data did not. An extensive HCCI data set was acquired. The heat transfer rate - when corrected for differences in cylinder pressure and gas temperature - was found to positively correlate with increased pressure oscillations. It is important to normalize the data before drawing conclusions as the magnitude of the effect was diminished significantly by the normalization procedure.

CITATION: Gingrich, E., Janecek, D., and Ghandhi, J., "Experimental Investigation of the Impact of In-Cylinder Pressure Oscillations on Piston Heat Transfer," *SAE Int. J. Engines* 9(3):2016, doi:10.4271/2016-01-9044.

INTRODUCTION

Increasingly stringent regulations on engine emissions and fuel economy have motivated research to continue to improve the internal combustion engine. Currently the modern direct-injected diesel engine is the most efficient engine developed for automotive applications. The direct injection of diesel fuel sets up a mixing-controlled combustion event that is heterogeneous in nature leading to fuel-rich areas that produce particulate matter (PM) and stoichiometric regions that produce nitric oxides (NOx) [1, 2]. NOx and PM emissions have been shown to have a negative impact on the environment and human health, and this has led government regulatory agencies to limit their emission. These regulations require the use of aftertreatment and or the detuning of the combustion process, leading to a reduction in the overall system efficiency.

Low Temperature Combustion

Dilute, low temperature combustion avoids PM and NOx formation by keeping the local equivalence ratios low enough to avoid production of soot and providing sufficient dilution to keep the temperature below the NOx-production threshold. A significant amount of research has been focused on low temperature combustion (LTC) strategies, including reactivity controlled compression ignition (RCCI), partially premixed combustion (PPC), and homogenous charge compression ignition (HCCI). The thermal efficiencies of LTC strategies exceed those observed in spark-ignition engines (SI) and

are often comparable to, or greater than conventional diesel combustion (CDC). But, because the NOx-levels are low, there is a lower aftertreatment requirement and there may be advantages to overall system efficiency. In all LTC strategies the ignition and combustion event is controlled by chemical kinetics, which makes combustion control difficult over a wide range of speeds and loads.

HCCI relies on a completely premixed charge of air and fuel. The ignition process is kinetically controlled, which results in a dependence on temperature, pressure, equivalence ratio and fuel properties [3, 4]. Researchers have reported simultaneous low NOx and PM with high efficiencies using HCCI. However, the peak pressure rise rate (PPRR) limits the maximum load of HCCI due to mechanical engine limitations. Additionally, HCCI lacks a fast-response combustion phasing control, such as spark timing or injection timing, when a single fuel is used.

RCCI utilizes in-cylinder fuel reactivity stratification by employing a second fuel. Typically, a low reactivity fuel (such as gasoline) is premixed with the intake charge and a high reactivity fuel (such as diesel) is directly injected. The spatial variation in fuel reactivity causes a sequential auto-ignition event, reducing the PPRR relative to HCCI combustion [5, 6, 7]. RCCI has the same low-NOx and PM benefits as HCCI, but has the added benefit of being able to adjust the fraction and timing of the directly injected fuel on a cycle-by-cycle basis, which provides control of the combustion phasing.

Pressure Waves in Engines

Rapid localized combustion events, such as knock in an SI engine, can excite resonant pressure waves in the cylinder. The frequency at which pressure oscillations resonate is determined by the combustion chamber geometry and the in-cylinder conditions. The high rate of energy release will induce an expansion that releases a compression wave that traverses the combustion chamber at the local speed of sound. For complex combustion chamber geometries, numerical solutions using Finite Element Analysis (FEA) may be necessary to characterize the frequencies. If a cylindrical combustion chamber is assumed an analytical solution for the resonant frequencies can be found [8]. The frequency, $f_{m,n}$, can be found by equation (1), where the mode-specific constant, $\alpha_{m,n}$, can be found in Table 1, $\sqrt{\gamma \cdot R \cdot T_{cyl}}$ is the acoustic velocity estimated by the in-cylinder bulk gas temperature, T_{cyl} , and B , is the cylinder bore. The subscript m , designates the circumferential mode number, and n , the radial mode number.

$$f_{m,n} = \alpha_{m,n} \frac{\sqrt{\gamma \cdot R \cdot T_{cyl}}}{\pi \cdot B} \quad (1)$$

Table 1. Resonant modes for cylinder shaped combustion chamber [8]

(m,n)	(1,0)	(2,0)	(0,1)	(3,0)	(1,1)
$\alpha_{m,n}$	1.841	3.054	3.832	4.201	5.332

In-cylinder pressure waves and the accompanying audible noise produced have been studied for a range of different combustion regimes. Eng developed a Ringing Intensity (RI) correlation for HCCI in an effort to quantify cylinder pressure wave intensity [9]. Many researchers have attempted to use RI as a surrogate for engine noise, but Shahlari et al. have shown that RI does not always correlate well with engine noise [10]. They proposed an algorithm for calculating the Combustion Noise Level (CNL) that matches well with the widely accepted AVL Combustion Noise Meter. Vressner et al. [11] used multiple in-cylinder pressure transducers to characterize HCCI ringing. It was found that the directions of the pressure waves appear to be random with large cycle-to-cycle variations in the frequency domain. Wissink et al. [12] conducted a study of audible noise in RCCI, HCCI, and CDC and found that HCCI and RCCI exhibited a similar PSD for non-ringing cases. Additionally, in all three combustion strategies the first two circumferential modes contained the majority of the acoustic power.

In-Cylinder Heat Transfer

Heat transfer to the combustion chamber surfaces has been studied for both CDC engines and engines that operate using a LTC strategy [13, 14]. The heat transfer for CDC has been studied on the piston surface and on the stationary parts of the engine such as the engine head and cylinder liner [15, 16]. Recently, heat flux measurements have been made on the piston surface with engines operating under

RCCI and CDC combustion [17]. Under most operating conditions LTC has superior heat loss characteristics when compared to conventional diesel (CDC) [18]. These characteristics can be credited to the lower combustion gas temperatures and a significant reduction of in-cylinder radiation from particulate matter. Some of the thermal efficiency gains can be attributed to the reduction in heat transfer.

HCCI cases with overly advanced CA50 can exhibit in-cylinder acoustic oscillations. Sometimes described as 'ringing' or 'knock' these pressures oscillations have been observed to have lower thermal efficiency when compared to comparable, more-quiet combustion. Dec et al. suggested that advancing HCCI CA50 as much as possible while keeping (RI) less than 5MW/m² to achieve the highest efficiencies and prevent significant acoustic oscillations [19].

Significant research has been conducted studying the increased heat transfer associated with SI engine knock. Lu et al. [20] used a square piston optical engine instrumented with a thin film thermometer. Schlieren images detected the auto ignition region and corresponded to an increase in integrated heat flux in the near knock zone and less impact in regions further away from the knock zone. Hargaya et al. used an L-type combustion chamber with fast-response thermocouples installed in the cylinder head [21]. Near the knock location, the peak heat flux was found to be about two times larger under knocking conditions when compared to non-knocking conditions. Symmis et al. measured heat flux on the piston surface while moving the spark plug location (and therefore the end gas location) [22]. Their results showed similar trends, with the heat flux increasing at the end-gas location for knocking conditions.

Using an optical engine, Grandin et al. attempted to measure the thermal boundary layer with Coherent anti-Stokes Raman Spectroscopy (CARS), and also installed a heat flux probe in the cylinder head to measure heat flux and surface temperature [23]. They found the thermal boundary layer to be on the order of half a millimeter thick with steep temperature gradients. Draper concluded that the energy associated with pressure waves in a CRF engine was not large enough to cause engine damage by itself [8]. Additional effects such as a scrubbing action on the boundary layer and its subsequent impact on heat transfer must be considered.

The effect of HCCI knock on heat loss was studied by Tsurushima et al. using fast-response thermocouples installed in the piston and cylinder head [24]. They concluded that the pressure fluctuations that are observed in HCCI combustion are the same phenomenon as knock in SI engines. It was found that previously developed heat transfer correlations needed to be modified by a pressure rise rate term to have them better match knocking HCCI combustion.

Current Study Objectives

This study seeks to explore the relationship between acoustic mode resonance and heat transfer during LTC. HCCI and RCCI are compared over a range of conditions; CDC is used as an additional reference. The RCCI and HCCI data were acquired at similar loads and speeds, allowing comparisons to be performed for a wide range in magnitude of pressure oscillations.

EXPERIMENTAL SETUP

Single-Cylinder Engine Laboratory

Experiments were conducted in a light-duty single-cylinder engine based on the General Motors/Fiat JTD 1.9L four-cylinder diesel engine. A stock four cylinder head was installed atop a single cylinder block. Valves for cylinder #2 were activated by the dual overhead cams. The valvetrain for the remaining three cylinders was deactivated by removing the valve rocker arms. Table 2 (adapted from Dempsey et al. [5]) shows the specifications for the engine.

Table 2. Engine specifications

Engine Geometry	
Base Engine	GM 1.9L Diesel
Compression Ratio	16.3 / 9.5
Displacement (Liters)	0.477
Stroke (mm)	90.4
Bore (mm)	82
Intake Valve Closing	-132 degATDC
Exhaust Valve Opening	112 degATDC
Swirl Ratio	1.5 -4.8
Piston Bowl Type	Stock (Re-entrant)
Port Fuel Injectors	
Included Spray Angle	20°
Injection Pressure (bar)	2 to 10
Rated Flow (cc/sec)	< 10
Bosch Common Rail Injector	
Number of Holes	7
Hole Diameter (mm)	0.14
Included Spray Angle	155°
Injection Pressure (bar)	250 to 1000 bar

The research engine is equipped with a choked orifice air flow metering system that is fed with building air. An electrical heater is used to increase the temperature of the air. The air system includes an exhaust gas recirculation loop (EGR) to provide dilution when necessary. The EGR-air mixture enters a heated intake surge tank to dampen wave dynamics. Two port fuel injectors (PFI), plumbed with separate fuel systems, deliver up to two different fuels to create the premixed charge. Additionally, a fuel vaporizer upstream of the intake surge tank can be used to homogeneously fuel the engine. There are two swirl-control vanes that provide an adjustable swirl ratio between 1.5 and 4.8. The engine also has a high pressure common rail fuel injector that allows for direct injection of a third fuel. After leaving the engine, the exhaust enters a surge tank to dampen wave dynamics and enhance mixing. Small samples of the exhaust gas are acquired by an AVL 415S smoke meter and Horiba gas analyzers. Figure 1 shows the experimental laboratory schematically.

The engine is controlled with National Instruments LabView system. The fuel injection systems are controlled by Driven PXI controller cards. The system both controls and logs the, engine airflow, emissions data, EGR valve, pressures, low speed temperatures, and other critical engine parameters. The fuel mass flow rates were measured using Coriolis flow meters. A shaft encoder, with 1440 pulses per revolution, was used to trigger the high-speed data

acquisition system. In-cylinder pressure was measured with a Kistler 6125A pressure transducer in series with a Kistler 5010 charge amplifier.

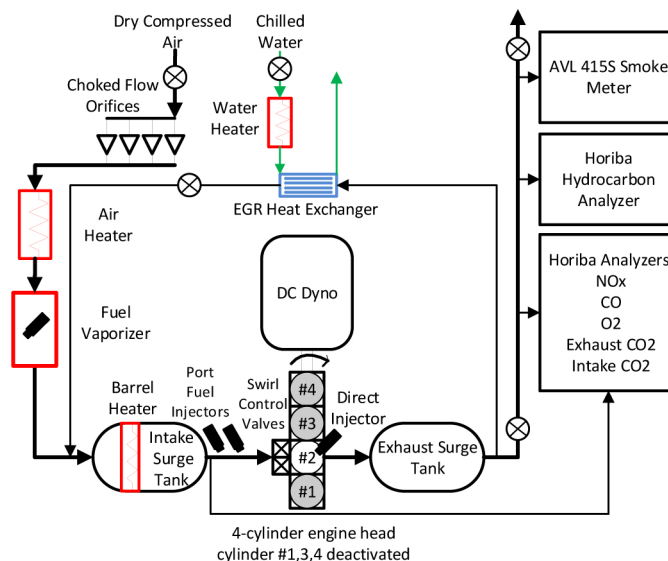


Figure 1. Experimental engine layout

Cylinder pressure acquisition, conditioning, and apparent heat release rate (AHRR) calculation are done as outlined by [5]. The AHRR uses a thermodynamic first-law analysis with an assumption of a constant ratio of specific heats. The AHRR is essentially the chemical heat release minus the heat transfer to piston and combustion chamber walls.

Wireless Telemetry System

Temperature data were transferred from the piston through an IR Telemetrics model 3051 microwave transmitter system. The electromotive force (EMF) generated at each thermocouple was converted to a frequency-modulated square wave over the range of 10-50kHz. A voltage-controlled oscillator then converts the square wave into a microwave signal. The microwave signal is broadcast into the crankcase where four receiving antennas are mounted. The signal is amplified, converted back to a modulated square wave, downconverted, then the original EMF is recorded. The signal conversion process induces a degree of filtering but the advertised bandwidth of the system is 10kHz [25]. Similar systems have been used by other researchers [17, 26].

The microwave transmitter only broadcasts data from one channel at a time; it cycles through the seven different channels (+1 marker channel). The transmitter was configured to broadcast each channel for 0.5 seconds independent of engine speed. At higher engine speed, more engine cycles will be transmitted than at slower engine speeds. The data streaming off the engine are collected for a fixed amount of time and are saved to a local computer.

The electronics associated with the wireless telemetry system are powered by an inductive power supply. An exciter coil is mounted on the underside of the piston liner. When the piston is near bottom dead center (BDC) a secondary coil that is mounted on the piston skirt

interfaces with the exciter coil allowing power to transfer inductively. Capacitors and other electronics store enough energy to power the piston through the entire engine cycle.

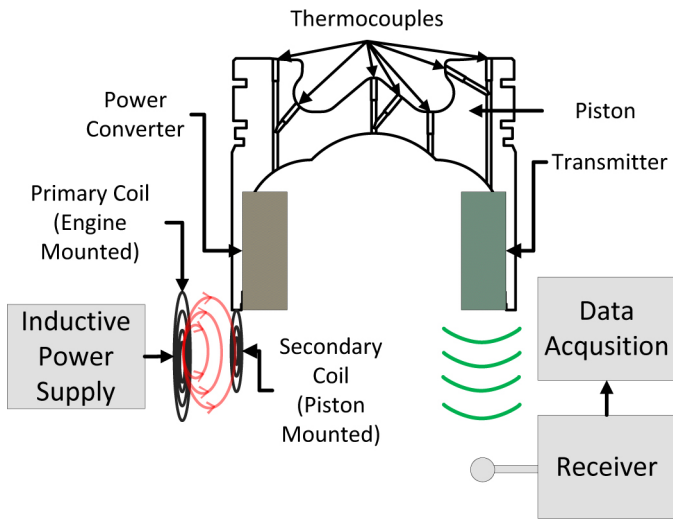


Figure 2. Wireless Telemetry System

Thermocouple Specifications

Seven fast-response coaxial thermocouples were installed in the piston crown to measure dynamic surface temperature. Thermocouple data were only viable on two channels after an extensive experimental matrix. Coaxial thermocouples have been used in a variety of applications. The sensor can survive harsh environments including the high temperatures, pressures and accelerations typically encountered in an engine. Surface thermocouples can either have a plated junction, formed by plating the surface of the probe [27], or a sliver junction, formed by cold-weld slivers of one material onto the next. Both types of probes were utilized in this work but only the plated junction resulted in usable data. The thermocouples were J-type, with a Constantan center wire and the outer tube of Iron. The thermocouples, Medtherm part numbers TCS-061-JU-0.25 and TCS-061-JU-0.25-CR, were claimed to have a time constant of one microsecond for the plated-junction probes and a ten microseconds for the sliver-junction probes [28].

Table 3 and Figure 3 list and depict the locations of the thermocouples mounted in the piston. All the thermocouples were mounted in a plane perpendicular to the wrist pin. Figure 4 shows a top view of the piston. Thermocouple 7 provided repeatable data throughout the duration of testing and is reported for all experiments. Thermocouple 3 provided repeatable data only for the combustion strategy comparison and is not reported in the HCCI study.

Table 3. Thermocouple Locations

Number	R (in)	Z (in)	Angle (deg)	Plating
3	0.644	-0.605	VERTICAL	Chromium
7	1.31	0	VERTICAL	Chromium

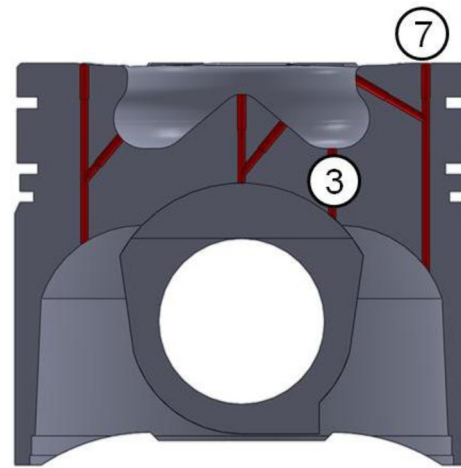


Figure 3. Piston cross-section showing fast response surface thermocouples

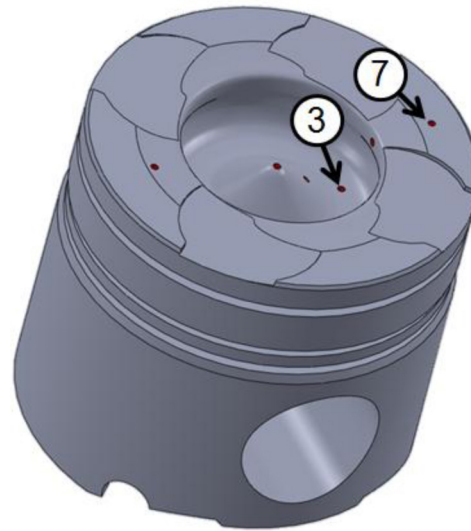


Figure 4. Piston top view showing fast response surface thermocouples

DATA PROCESSING

Temperature Data Reduction

The temperature data recorded by the wireless telemetry system included spurious spikes that needed to be removed before the heat flux could be calculated. The spikes in the data were caused by the wireless telemetry process. When the piston-mounted transmitter has a direct line of sight with one of the receiving antennas, the transfer of data from the piston to the antennas is nearly 100%. During times of the engine cycle when the transmitter does not have good visibility with the antennas, e.g., near TDC, the transmission efficiency is degraded. Spurious raw data were eliminated by applying the generalized Extreme Studentized Deviate (ESD) test at each crank angle [29]. Typically 5% of all data were removed by this procedure. In the region between -20 degATDC and 20 degATDC, approximately 25% of the data were removed. After the ESD test was applied the remaining data were averaged at each crank angle degree. Figure 5 shows a resulting mean temperature plot. A more complete description of the data reduction process is available in [18].