

Experimental Investigation of Piston Heat Transfer in a Light Duty Engine Under Conventional Diesel, Homogeneous Charge Compression Ignition, and Reactivity Controlled Compression Ignition Combustion Regimes

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ABSTRACT

An experimental study has been conducted to provide insight into heat transfer to the piston of a light-duty single-cylinder research engine under Conventional Diesel (CDC), Homogeneous Charge Compression Ignition (HCCI), and Reactivity Controlled Compression Ignition (RCCI) combustion regimes. Two fast-response surface thermocouples embedded in the piston top measured transient temperature. A commercial wireless telemetry system was used to transmit thermocouple signals from the moving piston. A detailed comparison was made between the different combustion regimes at a range of engine speed and load conditions. The closed-cycle integrated and peak heat transfer rates were found to be lower for HCCI and RCCI when compared to CDC. Under HCCI operation, the peak heat transfer rate showed sensitivity to the 50% burn location.

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INTRODUCTION

Increasingly stringent regulations on engine emissions and fuel economy have motivated research to improve the internal combustion engine. Currently the modern direct-injected diesel engine is the most efficient engine developed for automotive application. The direct injection of diesel fuel relies on a mixing-controlled combustion event with a diffusion flame 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. Therefore, government regulatory agencies limit their emission.

Currently, significant research has been focused on low temperature combustion (LTC) regimes, including reactivity controlled compression ignition (RCCI), partially premixed combustion (PPC), and homogenous charge compression ignition (HCCI). Low temperature combustion avoids PM and NOx formation by keeping the local equivalence ratios less than unity and sufficiently dilute to keep the temperature below the NOx production threshold while avoiding PM production. In all these LTC strategies the ignition and combustion event is controlled by chemical kinetics, which makes combustion control difficult over a large range of speeds and loads.

HCCI relies on a completely premixed charge of air and fuel. The ignition process is kinetically controlled which depends on temperature, pressure, equivalence ratio and fuel properties [3, 4]. Researchers have reported simultaneous low NOx and PM with high efficiencies. However, high peak pressure rise rates (PPRR) limit the load of HCCI due to practical 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 utilizing 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, 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 percent of directly injected fuel on the fly, which provides control of the combustion phasing.

The in-cylinder heat transfer has been studied for both convention diesel (CDC) engines and engines that operate using a LTC strategy [8, 9]. The heat transfer for CDC has been studied on both piston surfaces and on stationary locations such as on the engine head and cylinder liners [10, 11]. More recently, measurements have been made on the

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piston surface with engines operating under RCCI and CDC combustion [12]. Measurements made on the piston surface are harder to make than those on fixed locations. Mechanical grasshopper linkage systems have been used to connect piston-mounted thermocouples to data acquisition systems [8, 9]. These systems have a limited life and must avoid higher engine speeds due to vibration concerns.

Wireless telemetry systems alleviate many of the problems encountered with a mechanical grasshopper linkage and have been used to acquire piston temperature data [8, 13, 14]. A wireless telemetry system will typically outlast the useful life of most fast-response thermocouples. The bandwidth of many wireless systems is sufficient to make crank-angle-resolved measurements.

To calculate heat flux from time-resolved surface temperature measurements, a one-dimensional assumption must be made. Periodic boundary conditions are applied to obtain a sustained solution. Many researchers have used a Fourier series representation to recover the surface heat flux [9, 15]. This method relies on a Fast Fourier Transform (FFT) and is many times referred to as such. More recently, Hendricks used an inverse solver with Tikhonov regularization to calculate surface heat flux [16]. The inverse solver has the advantage of additional stability when analyzing noisy data without relying on direct filtering of the data. It does, however, effectively filter the data, see ref. [16] for details.

This experimental study seeks to understand the differences in piston heat flux for HCCI, RCCI, and CDC. Operating the engine at a variety of conditions allowed a detailed analyses to be conducted. The results presented seek to add understanding to an important difference between LTC and CDC which is heat transfer.

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 1 (adapted from Dempsey et al. [5]) shows the specifications for the engine.

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. There are two swirl-control vanes that provide an adjustable

swirl ratio between 1.5 and 4.8. The engine has an additional 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.

Table 1. Engine specifications

Engine Geometry	
Base Engine	GM 1.9L Diesel
Compression Ratio	16.3
Displacement (Liters)	0.477
Stroke (mm)	90.4
Bore (mm)	82
Intake Valve Closing	-132° aTDC
Exhaust Valve Opening	112° aTDC
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

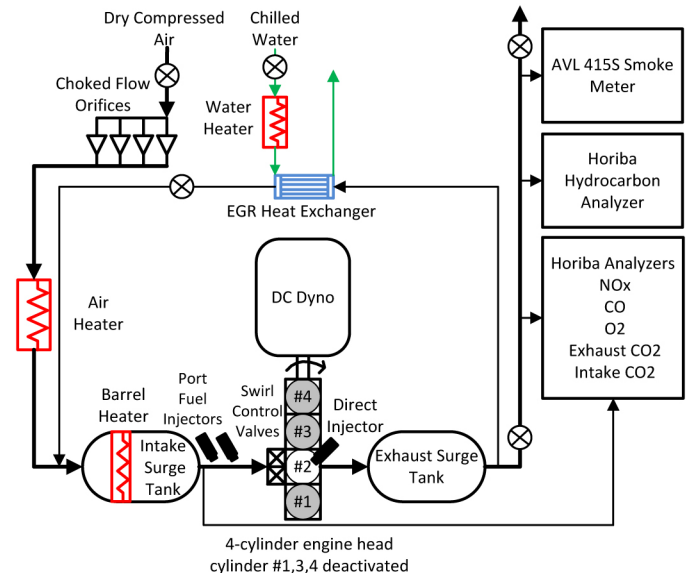


Figure 1. Experimental engine layout

The engine is controlled with National Instruments LabView system. The fuel injection systems are controlled by Driven PCI controller cards. The system controls and records, engine airflow, emissions data, EGR valve, pressures, low speed temperatures, and other critical engine parameters. The fuel mass flow rates were measured separately by 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.

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 a 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 [17]. Similar systems have been used by other researchers[12, 13].

The microwave transmitter only broadcasts data from one channel at a time; it cycles through the seven different channels (+1 marker channel). Thermocouple data was only recorded on two channels due to sensor failure (which will be discussed later). 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 is collected for a fixed amount of time and the data are saved to a local computer.

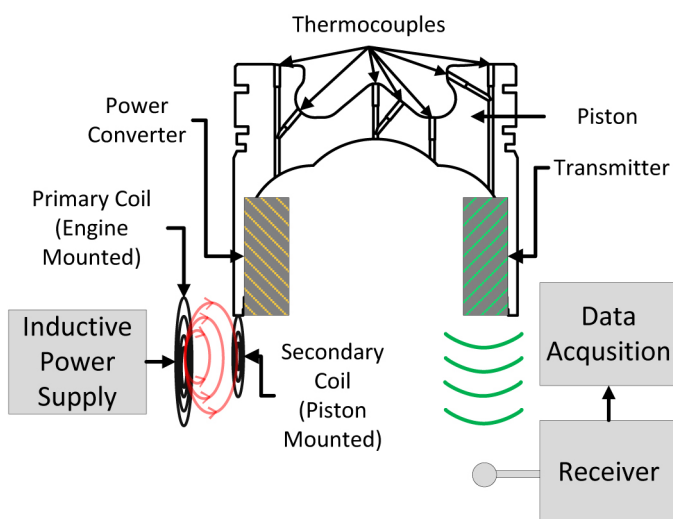


Figure 2. Wireless Telemetry System

The electronics associated with the wireless telemetry system are powered by an inductive power supply. An exciter coil, mounted on the underside of the piston liner, is powered by an inductive power supply. 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.

Thermocouple Specifications

Seven fast-response coaxial thermocouples were installed in the piston crown to measure dynamic surface temperature. Thermocouple data was only recorded on two channels due to sensor failure. 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. Thermocouples with both plated and slivered junctions were installed in the piston. Surface thermocouples can either have a plated junction formed by plating the surface of the probe [18], or a sliver junction, formed by cold-weld slivers of one material onto the next. Both types of probes were utilized in this work. The thermocouples were J-type, with the center wire consisting of Constantan 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 microsecond time constant for the sliver junction probes [19].

Table 2 and Figure 3 list and depict the location 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.

Upon engine startup thermocouples 4, 5, and 6 registered no signal. A problem with the thermocouples, wiring or telemetry system did not allow any data to be collected on these channels. Throughout testing thermocouples, 1 and 2 reported data intermittently. It is believed that deposit buildup may have caused these issues. Thermocouples 3 and 7 provided repeatable data throughout the duration of testing.

Table 2. Thermocouple Locations

Number	R (in)	Z (in)	Angle (deg)	Plating
1	0	-0.217	VERTICAL	Chromium
2	0.3	-0.425	39.6	Chromium
3	0.644	-0.605	VERTICAL	Chromium
4	-0.861	-0.527	40	None
5	0.813	-0.113	60	None
6	-1.118	-0.006	VERTICAL	None
7	1.31	0	VERTICAL	Chromium

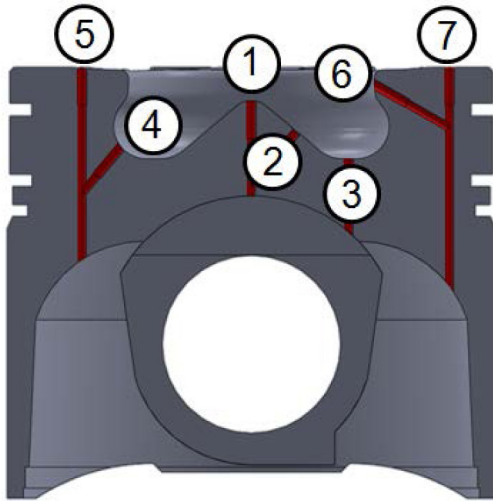


Figure 3. Piston cross-section showing fast response surface thermocouples



Figure 4. Piston top view showing fast response surface thermocouples

TEMPERATURE DATA PROCESSING

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 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 (i.e. near TDC), the transmission efficiency is degraded. Figure 5 shows the raw temperature data as recorded by the vendor software. Useful temperature data are buried among the non-reasonable points that include negative values and values beyond the melting point of the piston.

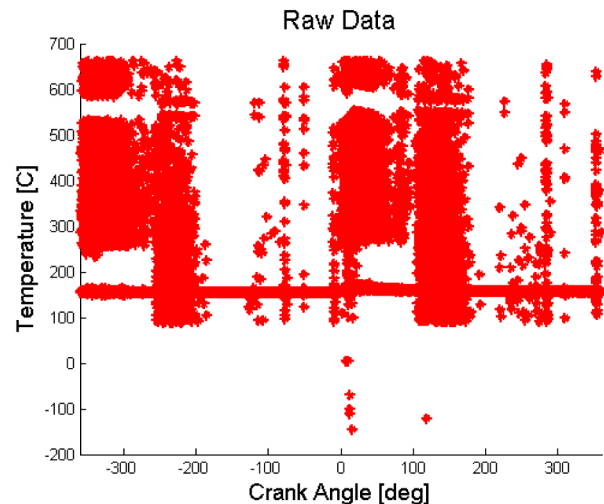


Figure 5. Temperature data including spurious spikes before processing on a sample data set

Spurious raw data were eliminated by applying the generalized extreme Studentized deviate (ESD) test at each crank angle. The ESD test is used to detect one or more outliers in a data set that approximately follows a normal distribution [20]. This statistical tool is preferred over other tests because it does not require that the number of outliers be predefined before the test is run [21]. Typically 5% of all data was removed by this procedure. In the region between -20degATDC and 20degATDC, approximately 25% of the data were removed. Figure 6 shows temperature data after the ESD test was applied.

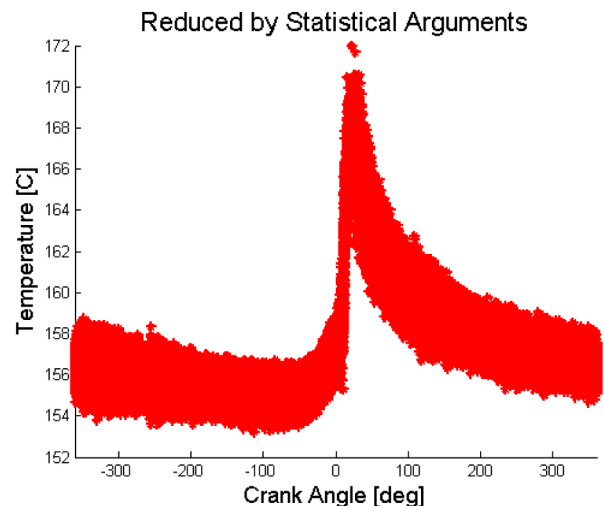


Figure 6. Temperature data after application of ESD outlier elimination on a sample data set

After the ESD test was applied the remaining data were averaged at each crank angle degree. Figure 7 shows the resulting temperature plot