

Optical Engine Operation to Attain Piston Temperatures Representative of Metal Engine Conditions

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ABSTRACT

Piston temperature plays a major role in determining details of fuel spray vaporization, fuel film deposition and the resulting combustion in direct-injection engines. Due to different heat transfer properties that occur in optical and all-metal engines, it becomes an inevitable requirement to verify the piston temperatures in both engine configurations before carrying out optical engine studies. A novel Spot Infrared-based Temperature (SIR-T) technique was developed to measure the piston window temperature in an optical engine. Chromium spots of 200 nm thickness were vacuum-arc deposited at different locations on a sapphire window. An infrared (IR) camera was used to record the intensity of radiation emitted by the deposited spots. From a set of calibration experiments, a relation was established between the IR camera measurements of these spots and the surface temperature measured by a thermocouple. Transmissivity of the chromium spot was investigated by using different background media. The deviations between the thermocouple readings and SIR-T measured temperatures were noted to be within 10°C for the working range of 75°C to 180°C. The technique was demonstrated to measure the optical piston temperature during engine operation at 1500 rpm and 2000 rpm. A piston warm-up strategy was implemented for optical engine studies to attain metal engine steady state piston temperatures. The effect of piston warm-up on in-cylinder soot formation was studied using high-speed imaging.

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INTRODUCTION

Improvement in thermal efficiency and a reduction in criteria emissions continue to be major challenges to the IC engine community. Optically accessible engines have proven to be a powerful tool for investigating in-cylinder topics such as air flow motion, fuel spray, ignition, flame propagation, and combustion product speciation [1]. In these engines, a transparent window, typically made of quartz or sapphire, is installed in the cylinder head, cylinder wall, or employed as a piston insert. Aluminum, commonly used as the production piston material [2], has a higher thermal conductivity than the sapphire used in optical engines. Kashdan and Thirouard [3] measured the piston surface temperatures of both engines: optical and an equivalent all-metal engine. From these measurements, a skip-firing strategy was developed to compensate for differences in heat transfer properties in their optical engine.

An essential requirement to understand the combustion events when employing optical engines is to create thermal boundary conditions that are representative of the metal engine. Performing optical engine experiments before reaching metal engine representative temperatures can result in injecting the fuel into a low piston temperature environment. A lower piston window temperature hinders fuel vaporization and aggravates wall impingement and fuel film build-up,

possibly resulting in higher soot formation in the optical engine. This notion was the motive behind developing the current temperature measurement technique. In addition, the measured optical piston temperatures can be useful for boundary conditions employed in fuel spray modeling. Previous temperature measurement techniques to determine surface temperatures of different engine components (piston rings, top land, crown and liner) can be classified into two types: Sensor measurements and radiation-or photon-based measurements.

Sensor Measurements

The most widely used temperature sensor for engine applications is the thermocouple. Steeper and Stevens [4] instrumented surface thermocouples on a quartz piston and determined a skip-firing sequence that allowed a target temperature range of 145-160°C as determined separately in an all-metal engine. Thermocouples used for piston temperature measurements in the past had a slow response time [5]. This problem was overcome by the fast response J-type and K-type NiCr-Ni thermocouples that offered the ability to measure surface temperatures with 0.3 μs response time [6, 7]. For an engine speed of 2000 rpm, this response time corresponds to 0.0036 CAD. Another daunting task in using thermocouples is to lead the signal out of the piston to the data acquisition system. Addressing this

problem, several designs have been developed based on two major mechanisms: mechanical linkage wiring systems and wireless mechanisms. Linkage wiring systems have been used in a number of piston heat transfer studies [8, 9, 10]. Such systems, however, are noted to have short lifetimes due to cyclic bending of the wires leading to wire fatigue and breakage [11]. Alternatively, thermocouple signals can be transferred through “wireless” mechanisms such as electromagnetic induction [12, 13] or Bluetooth technology [14, 15]. However, higher accelerations in a piston-cylinder assembly make the wireless systems complex to install and prone to short lifetimes.

In addition to durability issues with thermocouples and wires, combustion deposits that can accumulate on the piston surface tend to bury the thermocouple junctions. As a result, the measured instantaneous temperature profiles change as deposits grow on top of the hot junctions. Assanis and Friedmann [8] found that the initial deposit formation over a surface causes the most significant reduction in time-averaged heat flux into the surface. In another study, Güralp et al. [16] tried to utilize this event to track the deposit growth by correlating the change in peak temperature phasing to the deposit thickness.

Photon and Radiance Based Measurements

Laser-Induced Phosphorescence

Phosphor thermometry, or laser-induced phosphorescence (LIP), is a non-contact optical measurement technique. In this technique, an inorganic oxide or other phosphorescent material is applied onto the surface of interest using a non-fluorescent binder. When the material is excited with laser light, the resulting temperature-dependent phosphorescence is used to determine the surface temperatures by a temporal method or spectral intensity ratio method [17]. The main advantages of the LIP technique are its higher temporal resolution and its insensitivity to scattered laser light due to long lifetime of phosphorescence. The LIP technique has been employed to measure the temperatures of piston crowns, intake valves and cylinder walls. Fuhrmann et al. [18] utilized phosphorescence decay technique viewing through a borescope and measured the metal engine cylinder wall temperatures to be about 60°C during motoring and 150°C during firing operation at the start of compression. Kashdan and others also employed the LIP technique to measure the piston temperature of an optically accessible engine [3, 19]. In another study, Knappe et al. [20] conducted phosphorescence decay measurements for the wall side and gas side of the phosphor dot, applied on a quartz liner. The authors concluded that LIP for in-cylinder measurements should be applied with caution and suggested a phosphor thickness of well below 30 μm to minimize any insulating effect.

Infrared Detection

Infrared detection systems previously used include an IR microscope, IR camera, and spectral filters. Spikes [5] inserted small sapphire windows on a single-cylinder diesel engine and measured the temperatures that resulted on the faces of piston rings and lands using

infrared emission during a firing cycle. A gold mirror was used to direct the infrared signal from the piston ring/liner contact to an upright IR microscope. In general, an IR camera has a much higher spatial resolution and increased sensitivity than the IR microscope and offers instantaneous capture of full field measurements [21].

Narrowband spectral filtered infrared imaging is another way of determining temperature of the surface of interest. Luo et al. [22] developed a dual wavelength infrared diagnostic for cylinder head surface temperature of an optical engine using an indium antimonide infrared detector. In that work sapphire emission was excluded from the infrared recordings by using two filters of center wavelength 3.275 μm and 3.86 μm , where sapphire was expected to have high transmissivity. Glass and like materials become opaque in the region of about 4-5 μm [23]. Hence, one way to determine surface temperature of a glass-like material is by measuring its emission using an IR filter at 5.1 μm . However, the spectral responsivity of mid-wavelength infrared camera detectors significantly drops beyond 5 μm wavelength [23]. Recently, Buono et al. [24] installed an optical element, “AVL Visioknock lens”, made from a sapphire lens in a modified spark plug. The IR spark plug sensor detected the intensity of radiation emitted from the hot piston surface. The radiation produced by fuel and the hot gases of combustion such as CO_2 and H_2O dominated the IR signal. Hence, the IR spark plug was limited to taking recordings during intake and compression strokes before fuel injection.

In the current work, a technique is developed based on infrared radiation principles to measure the piston sapphire window temperatures of an optical engine. Using the proposed technique, piston window temperatures were measured during engine operation. In addition, soot formation was used as a variable to investigate the effect of piston temperature on combustion in the optical engine.

SPOT INFRARED-BASED TEMPERATURE (SIR-T) AND RADIANCE CALIBRATIONS

In this Spot Infrared-based Temperature (SIR-T) measurement technique, metal spots were vacuum-arc-deposited on sapphire window surfaces. Vacuum arc deposition is a physical vapor deposition technique in which an electric arc vaporizes and ionizes material from a cathode (metal in this case). The location and motion of the arc are controlled by an applied magnetic field. The vapor condenses and is deposited on the substrate (sapphire). Chromium was selected as the spot material as it bonded well to the sapphire surface. Chromium was vacuum-arc-deposited up to a spot thickness of approximately 200 nm at different locations on the piston window: outer top, bowl, and piston bottom as shown in Figure 1. The bowl spots and outer top spots are located at an axial distance $t=15.5$ mm and $t=25$ mm from the piston bottom surface as shown in Figure 2. An infrared camera was used to record the radiation along the metal spot, referred to as “radiance digital counts.” All the results presented in this work were obtained when the window was positioned such that the piston bottom was facing the camera as shown in Figure 2. This window orientation was chosen to be consistent with the view of the combustion chamber looking through the piston window of an

optical engine. The calibration procedure that correlates the radiance digital counts along the chromium spot image to the measured temperature is described in the following section.

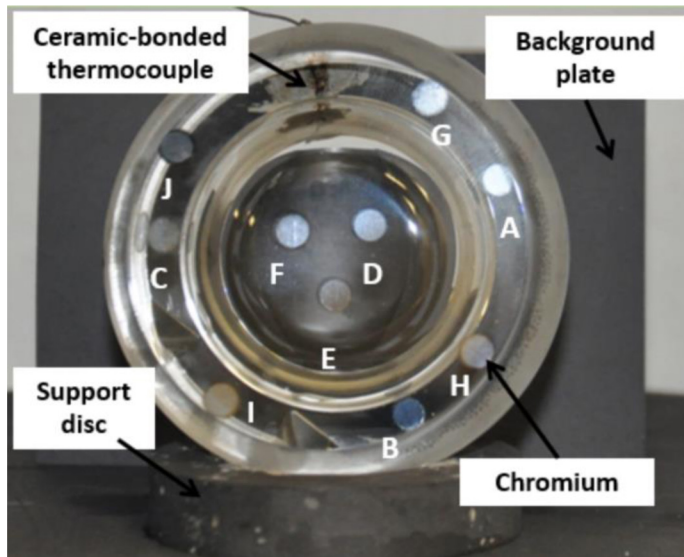


Figure 1. Sapphire window with chromium spots deposited on different surfaces: (A,B,C) – Outer top surface; (D,E,F) – Bowl surface; (G,H,I,J) – Piston bottom surface.

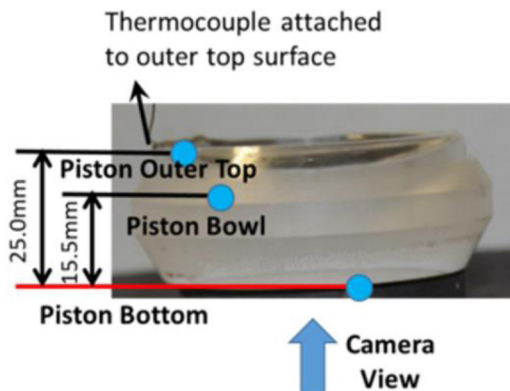


Figure 2. Chromium spot locations on the piston window.

Sensor Measurements

Bench top oven heating experiments were used to calibrate the IR camera measurements versus piston top temperature measurements. The sapphire window with its bottom spots facing the camera was placed inside an oven. A time span of 1.5 hrs was required for the window temperature to reach 180°C. A K-type thermocouple was ceramic-bonded to the outer top surface and monitored using a temperature meter placed outside the oven. As seen in [Figure 1](#), the chromium-coated sapphire piston window was placed in the oven with a black plate in the background.

A mid-wavelength infrared camera (FLIR Phoenix: MWIR Camera) was used whose viewable wavelength region is from 3-5 μm . The camera incorporates an indium antimonide detector which is

photovoltaic and generates current when exposed to infrared radiation. It is cryogenically cooled to 77 K using liquid nitrogen. The detector has 11° field of view and its response time is less than 1 ns, thus offering real-time measurement values. A Janos Technology ASIO 100 mm MWIR lens was attached to the detector. The integration time of the camera detector was set to 0.02 ms. A two-point non-uniformity correction (NUC) was performed before taking the IR recordings to avoid anomalies in recordings. Infrared images were recorded every 15-20°C during the time the window was air-cooled from 180°C to 75°C by turning off the oven heat and opening the oven door.

Calibration Process

For a thermocouple reading, the corresponding averaged radiance digital counts were recorded along each region of interest (ROI) on the infrared image of chromium spots. After this step was repeated for several temperatures, a calibration curve was generated between the radiance digital counts of chromium spots and the surface temperature. [Figure 3](#) shows an infrared image with radiance digital counts recorded at a window temperature of 180°C; also highlighted are the average count values along the spots on each of the three surfaces.

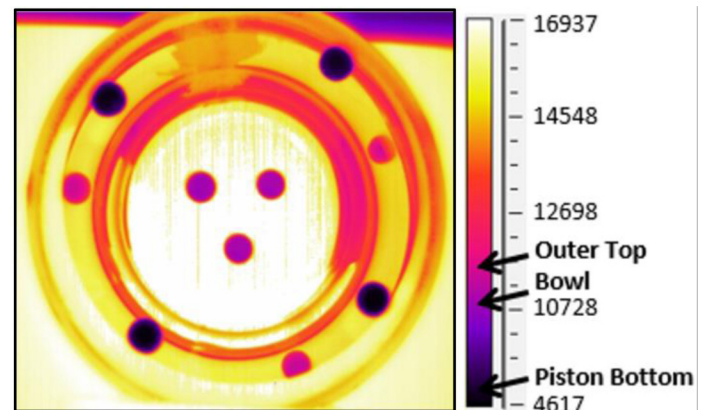


Figure 3. Infrared image of the piston window with a background plate at a window temperature of 180°C.

Using similar experimental and camera setups, radiance digital counts were calibrated for a chromium spot (approx. 200 nm thick) deposited on another sapphire piece having a thickness of 6.5 mm. The calibration data obtained for spots on the three surfaces of the window as well as for the spot on the sapphire piece at different temperature readings are shown in [Figure 4](#). In this figure, the axial distance (t) from the piston bottom surface are noted along with the piston window locations. The dashed lines represent the fourth order polynomial fits. A common observation in [Figure 3](#) and [Figure 4](#) is the contrasting difference between the average counts of spots facing the camera (piston bottom) and those that are away from the image surface (outer top and bowl). Possible factors that could have given rise to these differences in digital counts among bowl and piston bottom spots were investigated further and will be presented in the next Section.

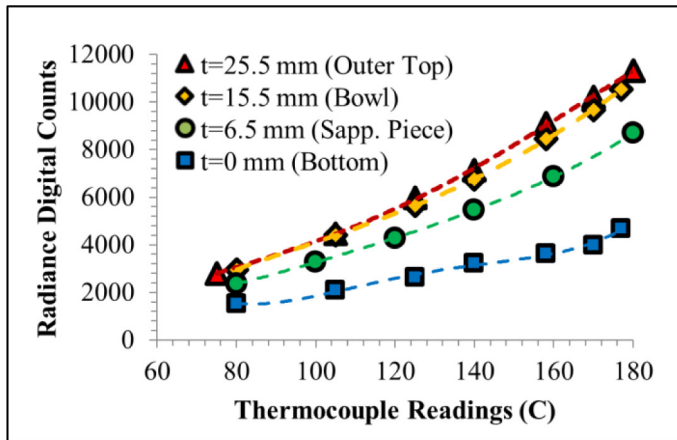


Figure 4. Radiance counts-to-temperature calibrations for chromium spots coated on different surfaces.

The temperatures measured using the SIR-T technique were compared to the thermocouple measurements as shown in Figure 5. The dashed line represents the identity line with respect to the thermocouple readings. The SIR-T measured temperatures were observed to deviate by a maximum of 10°C from the thermocouple measurements. Hence, the accuracy of the SIR-T technique is within 10°C for the considered working temperature range. The K-type thermocouple used in this work had a standard error above 2.2°C while the remaining error is attributed to data acquisition and curve fit calibration.

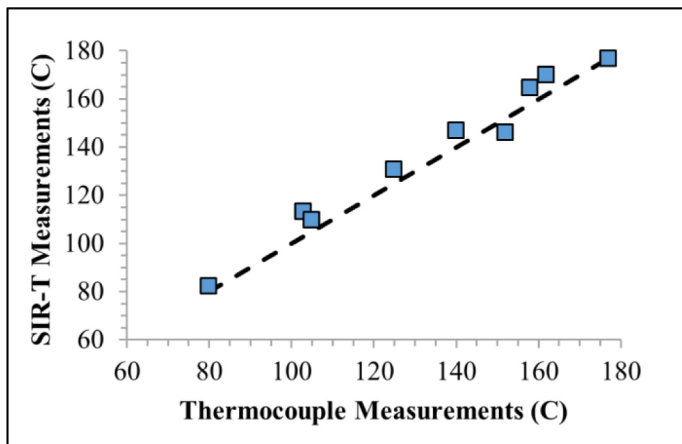


Figure 5. Thermocouple vs. SIR-T measured temperatures.

SURFACE-TO-SURFACE RADIANCE DIFFERENCES

The differences seen in radiance digital counts between chromium spots on the bowl and those on the piston bottom were better understood by identifying different sources of thermal emission as shown in Figure 6. The major thermal factors identified were 1) room air convection, 2) external radiance of background/oven walls, and 3) sapphire radiance.

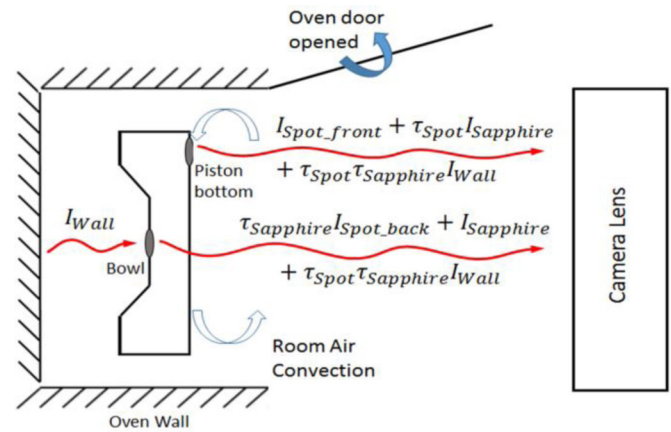


Figure 6. Sources of IR emission from piston window and its surroundings.

The total radiance captured by the camera along a region of interest on the chromium spot can be written as,

$$I_{ROI_{PistonBottom}} = I_{Spot_Front} + \tau_{Spot} I_{Sapphire} + \tau_{Spot} \tau_{Sapphire} I_{Wall} \quad (1)$$

Similarly,

$$I_{ROI_{Bowl}} = \tau_{Sapphire} I_{Spot_back} + I_{Sapphire} + \tau_{Sapphire} \tau_{Spot} I_{Wall} \quad (2)$$

where τ is the transmissivity in the IR spectrum. Subscripts "spot" and "wall" represent the chromium spot and wall behind the piston window. In the camera's spectral response of 3-5 μm , there is negligible absorption by oxygen and nitrogen [25, 26]. Hence, absorptivity due to air is excluded in the above formulations.

The terms I_{Spot_back} and I_{Spot_front} indicate the radiance of chromium spots from its two sides: back side touching the sapphire surface and front side exposed to surroundings. Surface roughness has an effect on infrared emissivity [27]. During vacuum-arc deposition of chromium onto the sapphire window, the surface roughness of the two sides of chromium spot could be different, thereby resulting in different emissivity. This possibility was checked by placing another spot-deposited sapphire piece behind the window. The front side of chromium deposited on the sapphire piece and the back side of chromium deposited on the sapphire window shared similar optical paths as shown in Figure 7. The corresponding radiance digital counts, shown in Figure 8, from back side of the chromium spot (on window) and front side of the chromium spot (on sapphire piece) differed by 6% to 10% depending on the temperature measured. A separate test was completed that confirmed the emissivity of front sides of chromium spots on the sapphire piece and piston bowl were similar such that comparisons between the two sides of the piston window could be made. Based on the ratio of radiance counts, the emissivity of front side of chromium spot is determined to be about 0.94 times the emissivity of back side of the chromium spot (see emissivity ratio curve in Figure 8).