

Simultaneous Measurements of In-Cylinder Temperature and Velocity Distribution in a Small-Bore Diesel Engine Using Thermographic Phosphors

Nicholas James Neal, Jonny Jordan and David Rothamer
University of Wisconsin-Madison

ABSTRACT

In-cylinder temperature and velocity fields were quantified simultaneously in an optically accessible, small-bore diesel engine. A technique utilizing luminescence from Pr:YAG phosphor particles aerosolized into the intake air was used for temperature determination while particle image velocimetry (PIV) on the aforementioned phosphor particles was used to simultaneously measure the velocity field. The temperature and velocity fields were measured at different points throughout the compression stroke up to -30 CAD. Systematic interference due to emission from the piston window reduced the accuracy of the measurements at crank angles closer to TDC. Single-shot simultaneous measurements of the temperature and velocity fields were made using both unheated and heated intake temperatures. In both cases, cycle-to-cycle variations in the temperature and velocity fields were visible. The single-shot temperature precision was estimated to be 30 K and 20 K respectively for the unheated and heated intake air cases at -30 CAD. Temperature determined with the diagnostic agreed with conventionally accepted methods for estimating the in-cylinder bulk gas temperature.

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INTRODUCTION

Temperature and velocity are fundamental to studying the fluid mechanics and heat transfer of gaseous flows. This is especially true in the operation of reciprocating engines. Factors such as the ignition properties and chemical timescales of combustion are functions of temperature [1], while thermal efficiencies depend on the amount of heat transfer occurring during the cycle [2]. Velocity gradients introduced through piston and intake geometry affect mixing, and therefore local equivalence ratios. Thus, there is a need for accurate, precise, spatial measurements of temperature and velocity.

Temperature is an inherently difficult property to measure in an engine. Traditional methods such as thermocouples or RTDs tend to operate at timescales many times longer than that of the engine, and cannot easily provide non-intrusive high-resolution information about the in-cylinder flow, which typically displays high spatial variance throughout the cycle. Estimation of temperatures using thermodynamics through methods such as two-zone ideal gas models or isentropic compression assumptions have also been utilized [3], but

only provide information about the bulk gas (average) temperature.

The use of phosphor-based optical techniques involving lasers for temperature measurement and velocity measurements have been explored in previous work. The first demonstration of simultaneous two-dimensional temperature and velocity imaging using thermographic phosphors was performed by Omrane et al. in a heated jet and a bluff body flow [4]. Due to sparse phosphor seeding they were not able to calculate single-shot temperature fields for their data and were only able to acquire average image results. Recently, Fond et al. [5] demonstrated single-shot simultaneous velocity and temperature imaging using a $\text{BaMg}_2\text{Al}_{10}\text{O}_{17}:\text{Eu}^{2+}$ (BAM:Eu) thermographic phosphor in a heated jet.

Hasegawa et al. [6] used Dy:YAG phosphor particles to measure the gas temperature in an optical engine running HCCI, but were unable to take quantifiable data around TDC due to interference from combustion-based chemiluminescence background. This problem was exacerbated by the requirement of long camera exposure times for the Dy:YAG phosphor (100 μs). Takada et al. conducted two-dimensional temperature measurements in a

diesel piston bowl [7]. In this study, BAM:Eu was used as a second phosphor to image near TDC in an attempt to counteract the effects of chemiluminescence background emission. The BAM:Eu phosphor has a shorter radiative lifetime allowing shorter camera exposure durations. However, similar problems were encountered around TDC, although it is possible that thermal degradation of the BAM particles (which occurs at temperatures above 800 K) could have also affected signal levels and intensity ratios [8].

The previous studies using BAM and Dy:YAG for temperature determination utilized 355 nm laser excitation from Nd:YAG lasers. It is evident from these works that choosing a phosphor with short radiative lifetimes and high luminescence signals, as well as, survivability at high temperatures, are necessary for obtaining archival-quality data.

The focus of the current study was to apply the simultaneous PIV and temperature imaging (PIV+T) concept in an internal combustion engine and to demonstrate single-shot simultaneous imaging of temperature and velocity. Having these correlated sets of data will aid in the determination of convection coefficients, better validation of computational fluid mechanics models, and understanding the turbulent mixing processes seen in the engine during operation.

The current measurements were accomplished by seeding thermographic phosphors into the intake flow of the engine. Previous work by Jordan and Rothamer [9] characterized the Pr:YAG phosphor luminescence properties as a function of temperature and demonstrated temperature imaging using the phosphor in a heated jet. Thermographic phosphors possess many beneficial characteristics for use in the engine, such as: a high melting point to survive the combustion environment, strong luminescence emission over the necessary range of temperatures, luminescence that is independent of pressure and seeding concentration, and distinct particles to track allowing the integration of PIV measurements. The current work advances the state of the art by demonstrating simultaneous temperature and velocity imaging in an engine using thermographic phosphors. The work also introduces the use of the Pr:YAG phosphor for temperature measurements in engines and discusses the difficulties of applying the technique in an internal combustion engine application.

MEASUREMENT BACKGROUND

The simultaneous velocity and temperature measurements presented here rely upon Mie scattering from the seeded phosphor particles for particle image velocimetry (PIV) measurements with temperature (T) determined from the laser-excited luminescence emission from the phosphor particles. The resulting PIV+T diagnostic allows for simultaneous single-shot measurements of the temperature and velocity fields. Since PIV is a standard technique, the focus for the discussion on measurement background will be on the phosphor-based temperature measurements.

Temperature Measurements

For the current work, a phosphor consisting of trivalent praseodymium ions (Pr^{3+}) doped into yttrium aluminum garnet (YAG) is used for temperature determination. Praseodymium is an attractive dopant ion due to its high emission rates for certain 4f-4f transitions and its ability to generate multiple emission photons per an absorbed photon (quantum splitting) [10, 11]. A recently published paper [9] gives details on the temperature imaging technique using Pr:YAG as the phosphor so only a brief description will be given here.

The temperature measurements rely upon imaging luminescence from two transitions with different upper states in Pr^{3+} . An energy level diagram for the 4f states in Pr:YAG is shown in Figure 1. For temperature measurements one band of emission originates from the $^3\text{P}_0$, $^3\text{P}_1$, $^1\text{I}_6$, and $^3\text{P}_2$ states which are referred to as the $^3\text{P}_J$ states throughout the paper. Emission collected in the $^3\text{P}_J$ band used for measurements corresponds to emission to the $^3\text{H}_4$ ground state and emission to the $^3\text{H}_5$ state (for $^3\text{P}_2$ only). The emission from these transitions is centered at 480 nm, as shown in Figure 2. This emission was captured using a camera with filters matching “Band 1” in Figure 2 (see Table 2 in Experimental Setup for more information). The second wavelength band used for measurements corresponds predominantly to the $^1\text{D}_2 \rightarrow ^3\text{H}_4$ transition, although some emission from $^3\text{P}_J \rightarrow ^3\text{H}_6$ transitions also overlaps this wavelength band. The $^1\text{D}_2$ transition is also shown in Figure 1 (with emission centered at 610 nm), and a second camera with filters capturing emission from “Band 2” in Figure 2 was used for emission from this transition.

To measure temperature, the ratio of the emission from the two wavelength bands is calculated. This ratio is temperature dependent as can be seen from the normalized emission spectra shown in Figure 2 and from the ratio versus temperature plot shown in Figure 3. The ratio displayed in Figure 3 was calculated from the measured spectra and filter transmission curves shown in Figure 2. To avoid laser generated fluorescence or incandescence interference signals, the camera integration duration was delayed 100 ns from the laser pulse time for the data shown. An integration duration of 50 μs was used for the measurements shown in Figure 3.

From Figure 3 it is observed that the ratio shows strong temperature dependence, especially in the temperature range between 600 and 1000 K. This is advantageous for measurements near TDC prior to the start of combustion. It is also observed that the ratio is double valued, meaning that temperature cannot be determined unambiguously without knowing that the temperature is either above or below 1100 K, where the ratio peaks. For measurements prior to combustion in the engine this not a significant issue since it is possible to accurately estimate the in-cylinder average temperature from the pressure trace. Therefore, the situation

where a double valued ratio would be present in the images acquired is avoidable under these circumstances.

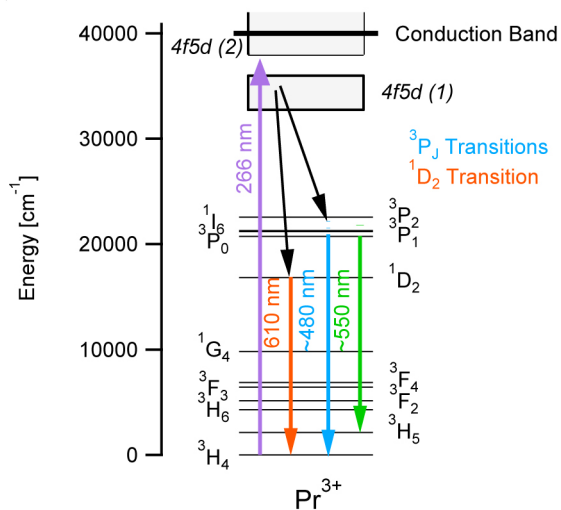


Figure 1. Dieke diagram showing Pr:YAG energy levels for transitions between 4f states, energy levels are from [12]

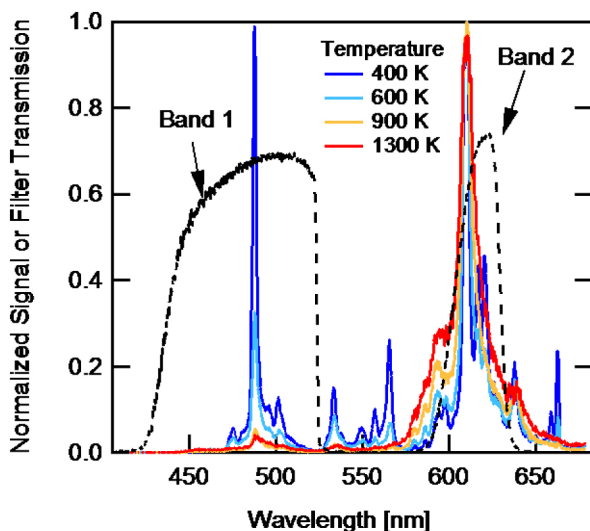


Figure 2. Pr:YAG spectrum normalized to the peak at 610 nm for several temperatures.

A technique has been developed that overcomes the double-valued ratio problem. The method involves running the cameras in “dual-image mode” enabling two images to be captured on each camera during the phosphor luminescence process. The two images on each camera are captured with different image delays allowing additional temperature dependent ratios to be measured. The additional ratios can be used to determine which side of the peak at 1100 K the original ratio is on. Measurements prior to combustion during the compression stroke are the focus for the current study and only one image is captured on each camera for the current work.

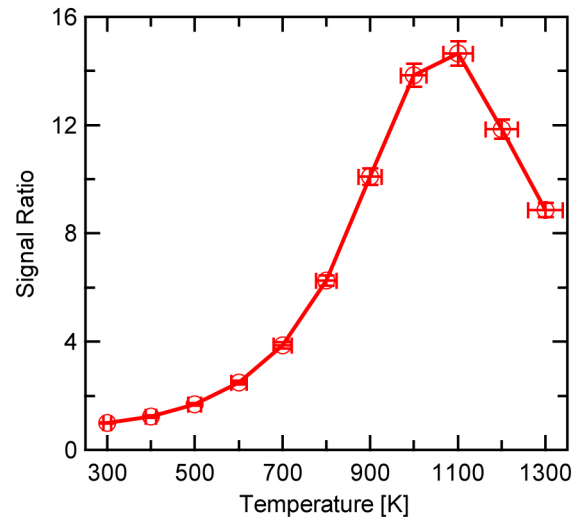


Figure 3. Ratio of emission from the $^1D_2 \rightarrow ^3H_4$ transition to the $^3P_J \rightarrow ^3H_5$ transitions for the Pr:YAG phosphor.

The ratio curve in Figure 3, and the calibration curves used in the current work, were obtained through a set of experiments detailed in [13]. A fused silica cell with a phosphor sample was held in a furnace, and the measured emission from various transitions was correlated to the temperature of the cell (cell temperature was measured with a thermocouple). Error bars for the ratio represent the variance in the data over multiple collections of data and error bars for the temperature represent the uncertainty in the thermocouple measurement of the cell temperature. A similar plot is shown in Figure 11 using camera settings optimized for maximum precision.

Even with the relatively high emission rates for Pr:YAG, in comparison to other commonly used thermographic phosphors such as Dy:YAG, emission lifetimes are still on the order of 10 to 100 μ s under room temperature conditions. The lifetimes for the two emission bands used are different and change as a function of temperature. This offers the opportunity to gain additional temperature dependence by using different combinations of delay and integration duration for the two wavelength bands. To study this an optimization process was performed and is detailed in [14].

The optimization process used measurements from single-point silicon photodiodes outfitted with the filters used for the current study. These measurements were used to predict the measured camera signals as a function of gate delay from the laser pulse and integration duration. All possible combinations were predicted by numerically integrating the time-resolved measurements. The gate delay and integration durations were varied in 500 ns increments. The total time for delay plus exposure was limited to 50 μ s to avoid issues related to signal blurring across several pixels in the measurements.

For the current work, measurements in-cylinder near TDC were desired, so the integration duration and delay which gave the best predicted temperature precision over the temperature range from 625 to 775 K (range estimated using technique in [Appendix A](#)) were chosen. The camera settings for these measurements are given in [Table 1](#). These settings are compared to the “standard” method which uses the same integration duration and delay for both cameras. The “standard” settings use a 500 ns delay and a 49.5 μ s exposure duration. As seen in [Table 1](#) the optimized settings use longer delays for both wavelength bands. The optimized settings also use a shorter exposure duration for the $^3\text{P}_j$ band, which was possible without significant loss in signal due to the shorter emission lifetime of this band.

Table 1. Exposure and start of exposure delay from the laser pulse timing for the standard and optimized settings.

Settings	$^1\text{D}_2$ Camera		$^3\text{P}_j$ Camera	
	Delay [μ s]	Exposure [μ s]	Delay [μ s]	Exposure [μ s]
Standard	0.5	50	0.5	50
Optimized	6.4	43.4	1.5	11.1

Velocity Measurements

Particle image velocimetry (PIV) is an optical technique that allows for the determination of spatially resolved velocity vectors, typically in a two-dimensional plane. This is accomplished through the use of a double-pulse laser paired with a CCD array capable of capturing images of both laser pulses. The laser beam, propagated through the space being imaged in sheet form, is scattered by the phosphor particles seeded in the flow. The cameras are filtered to capture this scattered light (Mie scattering). The timing between the laser pulses (and requisite images) is selected such that the particle movement can be tracked, allowing for the determination of in-plane velocities from the displacement of the particles and the time between pulses. The imaged region is divided into “interrogation regions,” areas over which statistics can be applied on the movement of the particles using a correlation method.

Studies by Keane and Adrian [15] provided the following conclusions on optimization of PIV using the aforementioned double-pulse system: a.) the seeding density must provide greater than 15 particles per interrogation region, b.) the particles must not displace greater than a quarter of the interrogation region, c.) particle movement perpendicular to the laser sheet must be restricted to less than a quarter of the sheet thickness, and d.) particle velocity variation due to local gradients must not exceed 20% of the total magnitude. Although the exact seeding density in the interrogation regions was not known (as explained in Experimental Setup), estimations of the particle in-plane density from the images

taken yield much higher values than the requirement of 15 particles per interrogation region. For the current study, the value of Δt (time between laser pulses), was carefully selected to limit maximum particle movement to less than $\frac{1}{4}$ of the distance of an interrogation region. A pulse spacing of $\Delta t = 55 \mu$ s was found to satisfy this requirement for the engine conditions and camera magnification chosen for this study.

EXPERIMENTAL SETUP

Phosphor Particles

The particles used in this work were the smallest which were available from the manufacturer (Phosphor Technologies, Ltd.), with a particle diameter of 1.8 μ m. The thermographic phosphor used consisted of Pr^{3+} doped into a yttrium aluminum garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$, or YAG) host. The YAG host was chosen because of its high melting point of 2213 K [16] and relatively low phonon energies [17]. A doping concentration of 0.5% Pr^{3+} in YAG was used for the current work. Previous work by the authors tested doping concentrations of 0.5%, 1%, 2%, and 4% Pr^{3+} in YAG [13]. It was shown that below 1000 K, the 1% doping concentration showed the highest integrated signal levels, however, it was anticipated that the increase in the cross-relaxation and concentration quenching with temperature would actually allow the 0.5% concentration to perform better at temperatures above 1300 K. For future applications to combustion conditions a 0.5% doping level was chosen. A thin aluminum oxide (Al_2O_3) coating ($\sim$ tens of nm in thickness) is applied to the particles by the manufacturer to reduce agglomeration. Additionally, to improve the flow properties and to prevent caking the phosphor particles were dried and mixed with 5% by mass fumed Al_2O_3 (Evonik, Aerioxide).

Phosphor Seeding System

The phosphor particles were seeded into the intake flow using a custom built seeding system. The system contained a helix screw-based hopper to feed the phosphor particles down a plastic tube. A hole was cut in the plastic tube where the phosphor particles would drop into a turbulent air stream and become aerosolized. The entire system was enclosed in a pressurized tank, allowing the particles to be seeded into flows which were above atmospheric pressure.

The flow rate through the seeding system and helix screw rotation rate were tuned to provide the optimal seeding density required for acceptable luminescence signal levels, while simultaneously avoiding over-seeding for PIV measurements (which also caused particle buildup on optics and clogging of the piston rings). At the outlet of the seeding system, a particle impactor was implemented to remove large agglomerates from the seeded flow. The impactor inlet diameter and distance from the inlet to the metal disk were calculated based on the results from Marple and Liu [18], and Rader and Marple [19]. The 50% cut-point diameter versus

air flowrate plot is shown in Figure 4. The inlet diameter and distance of the impaction plate from the entrance can be modified to give different 50% cut-point versus flowrate curves. The impactor used had a 50% cut-point diameter of approximately 12 μm for the seeder flowrate of 0.44 SCFM used for the current study.

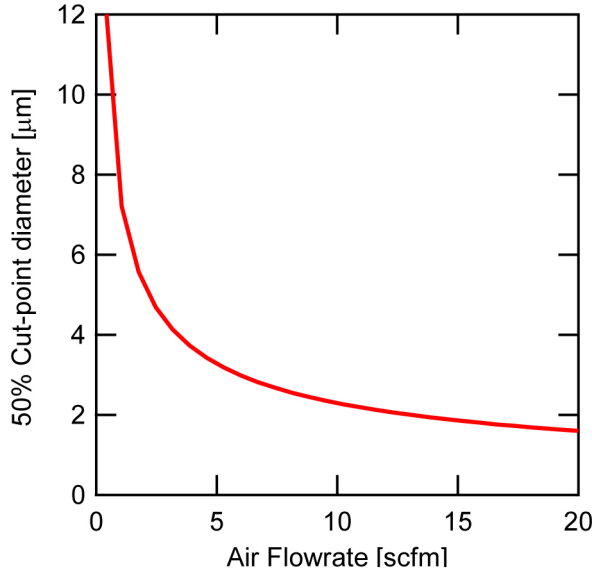


Figure 4. Impactor diameter for 50% transmission (50% cut-point diameter) versus air flowrate.

Camera Setup

Three cameras were used to simultaneously image temperature and velocity. The temperature measurements were made by capturing the luminescence emission with two 1024×1024 pixel ICCD cameras (Princeton Instruments, PI-Max3: 1024i) with Gen-III filmless photocathodes and P46 phosphors. When taking data both temperature cameras were binned 4×4 on chip resulting in a 256×256 pixel image. Both of the temperature cameras were outfitted with 85 mm f/1.4 Nikkor lenses operated at f/1.4. This combination of camera, lens, and on-chip binning resulted in a pixel size in the object plane of $295 \mu\text{m} \times 295 \mu\text{m}$. The spatial resolution of the temperature imaging system was measured using a 1951 U.S. Air Force resolution target and estimated to be between 0.5 and 1.0 mm, i.e., approximately 2 to 3 pixels.

The cameras were binned 4×4 to increase signal levels on the temperature cameras, as well as to avoid non-linearity caused by saturation of the micro-channel plate (MCP) of the intensifier. Intensifiers using P46 phosphors tend to suffer more from MCP saturation due to the higher level of gain needed from the MCP to compensate for the lower efficiency of the P46 phosphor relative to a P43 phosphor. Linearity of the signal for both cameras at high signal levels was verified by imaging an LED array for different exposure durations. Figure 5 shows the results of the linearity test. With 4×4 binning at the gain used for the measurements the cameras show good linearity at signals above 2000 counts. However,

for low signals there appears to be significant non-linearity. This could be due in part to the LED array used for the measurements, but it is believed that at least some of the non-linearity is real and the potential influence on the measurements will be discussed in the results section. For the current measurements, the camera non-linearity at low signals is not corrected for. In the future it would be possible to calibrate for this non-linearity in the camera response and apply a correction in the data post-processing.

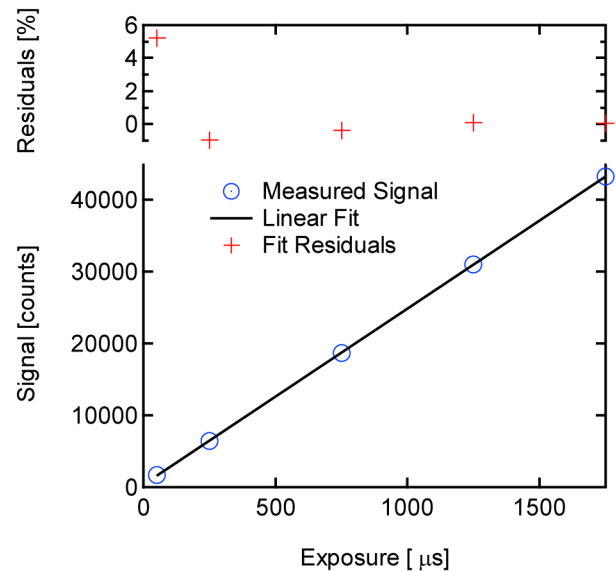


Figure 5. Intensified camera linearity test results.

Each camera was filtered to capture a different spectral portion of the luminescence emission. The filters used are listed in Table 2. The filter band used for the $^3\text{P}_J$ emission is wider than needed and the width could be decreased with limited signal loss.

Table 2. Filters used for temperature cameras.

$^3\text{P}_J$ Camera	$^1\text{D}_2$ Camera
Dielectric longpass filter with a 450 nm cutoff (Asahi Spectra, ZVL0450)	Dielectric shortpass filter with a 630 nm cutoff (Asahi Spectra, ZVS0630)
Dielectric shortpass filter with a 526 nm cutoff (Semrock, SP01-532RU-50)	600 nm colored glass longpass filter (Hoya R60)
Colored glass bandpass (Schott BG39)	

The PIV images were captured using a 1300×1030 pixel interline transfer CCD camera (Princeton Instruments, MicroMax: 1300YHS-DIF). A 10 nm FWHM narrow-band filter centered at 532 nm (Edmund Optics, 65216) was used to transmit the Mie scattering off the phosphor particles and to block the luminescence signals. The PIV camera was outfitted with a 50 mm f/1.2 Nikkor lens operated at f/5.6.

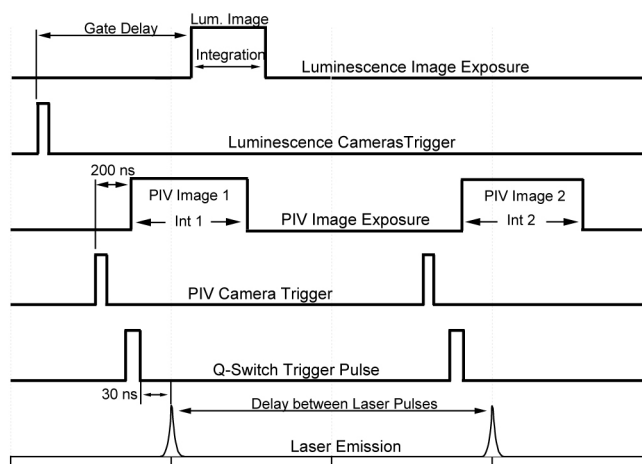


Figure 6. Timing diagram for triggering and exposure settings for all cameras.

The combination of the MicroMax camera and the lens resulted in pixels of size $63.4 \mu\text{m} \times 63.4 \mu\text{m}$ in the object plane. This camera was used unbinned ($1300 \text{ pixels} \times 1030 \text{ pixels}$) to give the highest resolution PIV measurements possible with the current equipment. The dual-image feature setting on the PIV camera was used to take two successive images based off of a single trigger pulse. The timing between the two images was fixed, so the integration duration was varied to ensure that the laser sheet was captured in both images.

Incoming light from the engine was split amongst the three cameras using the combination of two separate beamsplitting optics. The light for the PIV images was split using a Pellicle beamsplitter that reflected 8% of the light to the PIV camera and transmitted 92% of the light through to the temperature cameras. A broadband visible 50/50 beamsplitter (Edmund optics) was used to divide the light between the two temperature cameras. The beamsplitting optics and camera setup for the engine measurements are shown in Figure 7.

Laser and Optics

A flashlamp-pumped double-pulse Nd:YAG laser (Ekspla, NL 303D-10) operated at 10 Hz was used to excite the thermographic phosphors at 266 nm. The optics in the laser were modified to allow a fraction of the residual 532 nm 2^{nd} harmonic to be co-propagated with the 266 nm 4^{th} harmonic laser light. This was done by replacing the 2^{nd} dichroic beamsplitter in the laser with a right-angle prism. The residual 532 nm light in the beam was co-propagated with the 266 nm light using additional right angle prisms outside of the laser. The residual 532 nm light was used for velocity measurements, as the PIV camera was not sensitive to 266 nm.

The laser beam was formed into a 60 mm wide sheet using the combination of a -50 mm focal length cylindrical lens followed by a 200 mm focal length cylindrical lens, and finally a 1500 mm focal length spherical lens. The laser sheet

was approximately $500 \mu\text{m}$ thick when entering the window in the cylinder liner bore. The laser energy was 35 mJ/pulse at 266 nm and 5 mJ/pulse at 532 nm for all experiments run. The laser optics and sheet formation setup are shown in Figure 7.

Experiment Timing

Image timings, including gate delays and triggering relative to the laser pulses are shown in Figure 6.

Optical Engine

Imaging measurements of the temperature and velocity fields were performed using a single-cylinder engine block paired with an optical piston and optical head. Both the piston and head were designed and built at the University of Wisconsin. Mechanical specifications for the engine are shown in Table 3, and are representative of those in small-bore diesel engines. The optical head was of an oil-less modular design with multiple optical access points. A shrouded intake valve was used to control the swirl ratio. The flow properties of the head were measured using a flowbench (SuperFlow 600), and the shrouded valve was shown to give a range of swirl ratios up to a maximum of 5.5.

Mass flow rates of inlet air were controlled by a calibrated choked flow orifice rack for the main intake flow. A rotameter was used to meter flow to the particle seeding system. These flows were combined far upstream of the intake valve to ensure homogenization of the thermographic phosphors in the intake air.

In-cylinder pressure was measured using a piezoelectric pressure transducer (Kistler, 6053BB60) sampled at 0.25 CAD resolution with a Hi-Techniques Win600 DAQ system. Control of the engine system was provided by a Mototron engine control unit.

The piston consisted of a flat-top crown paired with a Bowditch-style extension [20]. Imaging optical access was available through either a window in the piston crown or through a secondary window in the cylinder head, as seen in