heck for

applied optics

Comparison of pyrometry and thermography for thermal analysis of thermite reactions

CONNOR WOODRUFF,¹ STEVEN W. DEAN,² AND MICHELLE L. PANTOYA^{1,*}

¹Mechanical Engineering Department, Texas Tech University, Lubbock, Texas 79404-1021, USA ²Sandia National Laboratories, Albuquerque, New Mexico 87123, USA

*Corresponding author: michelle.pantoya@ttu.edu

Received 2 March 2021; revised 12 May 2021; accepted 14 May 2021; posted 17 May 2021 (Doc. ID 423924); published 1 June 2021

This study examines the thermal behavior of a laser ignited thermite composed of aluminum and bismuth trioxide. Temperature data were collected during the reaction using a four-color pyrometer and a high-speed color camera modified for thermography. The two diagnostics were arranged to collect data simultaneously, with similar fields of view and with similar data acquisition rates, so that the two techniques could be directly compared. Results show that at initial and final stages of the reaction, a lower signal-to-noise ratio affects the accuracy of the measured temperatures. Both diagnostics captured the same trends in transient thermal behavior, but the average temperatures measured with thermography were about 750 K higher than those from the pyrometer. This difference was attributed to the lower dynamic range of the thermography camera's image sensor, which was unable to resolve cooler temperatures in the field of view as well as the photomultiplier tube sensors in the pyrometer. Overall, while the camera could not accurately capture the average temperature of a scene, its ability to capture peak temperatures and spatial data make it the preferred method for tracking thermal behavior in thermite reactions. © 2021 Optical Society of America

https://doi.org/10.1364/AO.423924

1. INTRODUCTION

Temperature is an important parameter for characterizing thermite combustion. Thermites can be specifically formulated to burn at a desired temperature. A historical example is the classic aluminum (Al) and iron oxide (Fe_3O_4) reaction patented by Goldschmidt in Germany in 1895 and in the United States in 1897 [1-3]. The Al/Fe₃O₄ thermite burns at temperatures high enough to produce molten iron and is still used for repairing castings, butt welding, and general railway repairs. A thermite formulation may be purposefully selected to reach a temperature that exceeds the alloying temperature of its reactants. For example, the Goldschmidt formulation was later modified to include nickel (Ni) because the alloying reaction between Ni and Al improved cutting performance by serving a dual role as a preheater to the oxidation reaction and liquid medium to increase the temperature and heat output [4]. In contrast, for combating weapons of mass destruction that disperse biological agents, a thermite that maintains high temperatures for extended durations can help neutralize spore forming bacteria and sterilize environments [5]. These are two different examples of how temperature is considered in the selection of a thermite formulation. Other thermodynamic properties of common interest include heat of reaction and gas generation. Fischer and Grubelich provide a useful reference of adiabatic flame temperature, heat of combustion, and gas generation tabulated for hundreds of reactive material formulations based on thermal equilibrium modeling software [6].

Measuring reaction temperatures is a challenge for many reasons. Reactive materials burn quickly (generally in microseconds to milliseconds) at high temperatures (generally >2500 K [6]) and with large temperature gradients. Therefore, high temporal and spatial resolution are needed to capture a reaction's temperature accurately and thoroughly. Intrusive instruments like thermocouples lack high temporal resolution, are commonly limited to lower temperature regimes, usually do not survive more than one experiment, and can influence the multiphase flow field of the reaction zone, thereby resulting in temperatures that do not accurately describe the reaction. The chemical and thermal emission properties of the reacting flame can also compromise temperature sensors either through secondary reactions for intrusive instruments or by emission interference when using nonintrusive optical sensors. In recent years there have been considerable advances in pyrometry and thermography that have opened new opportunities to examine temperature in combustion clouds resulting from metal combustion [7].

Pyrometry is a nonintrusive method of determining temperature. Studies implementing pyrometry in thermite reactions have investigated temperatures within multiphase combustion clouds using two to three channels (also called colors) [8,9]. More elaborate systems have been designed consisting of up to 32 channels that diminish the influence of variations in emissivity as a source of error in temperature calculations [10]. While traditional pyrometry methods provide convenience and flexibility in data capturing across multiple test settings and at time scales relevant to the reaction, pyrometry lacks the ability to provide spatial information and is treated mostly as a point source measurement.

Thermographic imaging systems have recently been developed to bridge the gap between the high temporal resolution of traditional multiwavelength pyrometry systems and the spatial capabilities of commercially available infrared (IR) cameras. Today's thermal IR cameras either lack the image capture rates needed to capture the fast time scales of thermite reactions, or are incapable of measuring the high temperature gradients common in a thermite reactions [11]. Early work in this field developed a thermographic system to analyze the surface temperatures of explosive fireballs using a high-speed color camera. High-speed color imaging technology has advanced to recording speeds significantly exceeding those of IR cameras and can resolve the visual dynamics of reactions at relevant time scales. The thermography approach introduced by Densmore et al. used a high-speed color camera that relied on the color filter array (CFA) on the camera sensor and careful calibration [12]. Other research groups further developed thermographic techniques consisting of multiple, monochrome high-speed cameras, dichroic mirrors, and bandpass filters that transmit specific wavelengths of light to each camera [13]. McNesby et al. extended the color camera-based technique to include a triple bandpass filter, IR filters, and several calibrations steps that improved the accuracy and reliability of thermography for complex reacting systems [14]. Beyond explosive systems, advanced thermography techniques have been implemented to visualize reactive sintering at the leading edge of burning particles in a thermite reaction on both the micrometer spatial and microsecond time scales, demonstrating the high-spatiotemporal capabilities of advanced thermographic imaging [15].

The goal of this work is to analyze a thermite reaction using thermography and multiwavelength pyrometry. To accomplish this, an in-house thermographic imaging system was developed along with a four-color pyrometer to jointly collect temperature data from Al and bismuth trioxide (Bi_2O_3) thermite reactions. Both technologies are described, as well as data processing techniques. The calculated temperatures from both diagnostics showed a similar trend in transient temperature behavior; however, the thermographic images consistently measured higher average temperatures than the pyrometer. Explanations for measured differences are discussed.

2. EXPERIMENTAL

A. Materials

To make thermite, Al (5 μ m, 99.7% Purity, U.S. Research Nanomaterials) and Bi₂O₃ (150 nm, 99.8% Purity, Aldrich) were combined in a stoichiometric ratio with a total mass of 600 mg. The powders were combined with acetone to form a slurry, and then they were mixed with a sonicator (Misonix 3000, Qsonica) for a total of 4 min at 10 s intervals. The interval setting ensured limited heating of the slurry while providing improved mixture homogeneity. The mixed slurry was poured into a ceramic dish and dried in a fume hood for 24 h. Once dried, powder was reclaimed from the dish with a grounded brush to prevent electrostatic discharge (ESD) that can result in unintentional ignition of the powder mixture. The powder was sieved through a wire mesh (size 325) to help break up agglomerates.

For laser ignition, 60 mg of mixed thermite was loaded into a 70 μ l alumina crucible (DSC72001, DSC Consumables, Inc.). These ceramic crucibles are commonly used in differential scanning calorimetry instruments but worked well for this experimental design. The crucibles improved consistency between experiments by containing loose powder at a constant bulk density of ~11.5% of the theoretical maximum density and simplified alignment with the laser ignition apparatus.

B. Laser Ignition Cell

Figure 1 illustrates the combustion cell used in this study. This cell was originally developed by Shancita *et al*. but was modified for use in these experiments [16]. The chamber is composed of a six-way vacuum "cross" that has ports for laser ignition and diagnostics. The thermite filled crucible was placed on a mounting block in the cell and aligned with the laser beam path. The cell was designed with multiple ports that allowed simultaneous diagnostics to monitor ignition and combustion, including pyrometry, spectroscopy, and high-speed photography.

The ignition source was a 60 W CO_2 laser (10.6 μ m, Firestar TI-series, Synrad). The laser was fired for 10 ms at max output, providing 0.6 J of energy to ignite the thermite powder located in the center of the cell (Fig. 1). Three diagnostics monitored ignition and the ensuing reaction from the plume coming out of the crucible containing the thermite powder sample. The first was a photomultiplier tube (PMT)-based four-channel pyrometer designed and built in-house to resolve thermite reaction temperatures [Fig. 1(a)]. The second diagnostic was an UV-VIS-NIR spectrometer [200-1025 nm, Insight FX-XR1, Ocean Optics, Fig. 1(b)], which was used to monitor atomic and molecular emission peaks from species generated during the reaction. This is an important inclusion in the temperature measurement process because various intermediate and product species can emit at wavelengths used to quantify temperature. Monitoring emission spectra aids in ensuring that wavelengths used to quantify temperature are not compromised by unexpected emissions from the reaction. Lastly, a high-speed color camera (Phantom v710, Vision Research) coupled with a triple bandpass filter and IR cutoff filters was used for high-speed visual, or thermographic, imaging. A visual image from the camera is shown in Fig. 1(c) illustrating the ceramic crucible containing the thermite powder. By combining pyrometry with thermography, limitations of measuring temperature in these complex, multiphase, transient reaction environments can be identified.

C. Pyrometry

Pyrometry is defined as the derivation of temperature from collected thermal radiation of a body based on predictions from Planck's law [17]. Planck's law describes radiation emitted by a blackbody, which is the maximum radiation that could



Fig. 1. Laser ignition apparatus with multiple ports for simultaneous data collection. The sample is located in the center of the cell such that the laser beam path is aligned with the top of the powder sample contained in a crucible and residing on a mounting block within the cell. Each schematic shown in (a)–(c) illustrates what is being measured from that view port. (a) Data from a reflective fiber collimator used for four-color pyrometer measurement of light intensity as a function of time for four wavelengths throughout ignition and reaction, (b) UV-VIS-NIR spectrometer measurement of emission intensity as a function of wavelength and time throughout ignition and reaction, and (c) a high-speed camera still frame image taken from this view port showing the crucible containing the powder thermite that is residing in the center of the reaction cell. The high-speed camera provides visualization and thermography of ignition and the reaction event. Note the purple dashed line corresponds with the laser beam path shown above the reaction cell as viewed from the port.

be emitted at a particular temperature. Emissivity, ε , is the property (ranging from zero to unity) that describes how the emission from a real body deviates from that of an ideal blackbody. Emissivity can be a complicated function of temperature, wavelength, and many other parameters. In this work, due to the complex nature of the reactive system being studied, the gray body assumption is applied. In this assumption ε is treated as a constant independent of wavelength and temperature. Therefore, the measured radiative intensity, I, of a body at a given temperature, T, emitted at a particular wavelength, λ , is proportional (through ε) to the calculated radiative intensity of a blackbody, I_{b} , at the same temperature and wavelength, as shown in Eq. (1),

$$I(\lambda, T) = \varepsilon I_b(\lambda, T).$$
(1)

In addition to the gray body assumption, another common approximation in calculating temperature is substituting Wien's approximation for Planck's law [17]. A simplified variation of Planck's equation, Wien's approximation is shown in Eq. (2) in which radiation constants C_1 and C_2 are equal to $3.742 \times 10^{-16} \text{ W/m}^2$ and $1.439 \times 10^{-2} \text{ m} \cdot \text{K}$, respectively [18],

$$I(\lambda, T) = \frac{C_1}{\lambda^5 \left(\exp\left(\frac{C_2}{\lambda T}\right) \right)}.$$
 (2)

Wien's approximation allows the relationship for intensity to be expressed in linear form to extract temperature data more easily. Wien's approximation is highly accurate at combustion temperatures (\sim 2500 K to \sim 4500 K) and in the visible spectrum, as the error in calculated temperature is less than 1% when the product $\lambda T < 3130 \,\mu\text{m K}$ [17,19]. Figure 2 shows



Fig. 2. Normalized emission spectrum of 2700 K and 4000 K blackbodies calculated using Plank's law (solid lines) and Wien's approximation (dotted lines).

normalized 2700 K and 4000 K blackbody spectra determined using Planck's equation and Wien's approximation. From Fig. 2, Wien's approximation accurately represents intensity values compared with Planck's law in the wavelengths of interest in this study (450 nm to 850 nm). The curves in Fig. 2 begin to deviate at wavelengths greater than 1500 nm for 2700 K and 1000 nm for 4000 K, both outside the range detectable by the sensors used in this study.

The four-color pyrometer used in this study is shown schematically in Fig. 3. The design included four PMTs (PMT1001, Thorlabs), three short-pass dichroic mirrors (DMSP567R, DMSP650R, and DMSP805R, all Thorlabs), four bandpass filters with 10 nm pass widths (FB500-10, FB600-10, FBH660-10, and FBH850-10, all Thorlabs), three kinematic cage cubes (DFM1, Thorlabs), and various other optomechanics to make a light-tight path inside the pyrometer. Emitted light from the thermite reaction was collected using a reflective fiber collimator (RC12SMA-P01, Thorlabs) attached to the laser cell view port.



Fig. 3. Schematic of the pyrometer along with a diagram showing the position of short-pass and bandpass filters, and PMTs with corresponding bandpass value. Colors highlight visible spectra with 500–850 nm channels used for temperature.

This light then passed into an optical fiber (200 μ m, BF2LS01, Thorlabs) and finally was sent into the pyrometer through another reflective fiber collimator (RC08SMA-P01, Thorlabs) [shown in Fig. 1(a)]. The PMTs were controlled through a software interface. For all data collected here, the PMT bandwidth was set to 250 kHz, and the gain was set to 1. The output of the PMTs was captured using a digitizer (5000, PicoScope) at a sampling rate of 100 kHz providing 10 μ s temporal resolution.

D. Thermography

Based on techniques developed by McNesby *et al.* [14], imaging thermography was performed along with pyrometry to compare diagnostic techniques. Thermography provides spatial temperature distributions lacking in the single point pyrometry measurements.

The high-speed camera used for thermography captured images at 22,000 fps (i.e., a 45.4 μ s temporal resolution) with a resolution of 320 x 240 pixels and at an exposure time of 7 μ s. As is the case in many color cameras, the camera sensor is coated with a CFA, specifically a Bayer mask filter containing red, blue, and green partitions that decipher light intensity into color information at the pixel level [12,14]. The spectral response of the camera with the Bayer filter is shown in Fig. 4. A triple bandpass filter with values 633 nm, 533 nm, and 451 nm is attached to the camera lens (Nikkor 105 mm, Nikon) to filter incoming light into single bands, much like the individual bandpass filters on the pyrometer. The spectral response in Fig. 4 shows that without the triple bandpass filter, the Bayer filter allows for



Fig. 4. Spectral response of Phantom v710 camera with a Bayer mask segmenting the intensity data into red, blue, and green wavelength regimes with overlay of triple bandpass filter channels (black curve).

overlap among the red, blue, and green. The triple bandpass filter reduces this source of error by narrowing the color regions to single bands, i.e., the channels for three-color pyrometry.

E. Calibration

For calibration of both the pyrometer and high-speed camera, a high temperature light source is required to represent temperatures approximating a thermite reaction (i.e., >2500 K). A tungsten-halogen lamp (SLS201L, Thorlabs) was used to generate intensity calibration factors at specified wavelengths and calibrate both diagnostics to a known temperature ranging from 3200–3500 K. Lamp intensities collected by the pyrometer and camera were compared to published values from the manufacturer to provide intensity corrections (x = raw/pub) that are used to correct raw data captured during testing.

Due to intricacies of the camera system, additional calibration steps were needed to mitigate further sources of error such as camera IR sensitivity and pixel bleed. Calibration methods described by McNesby *et al.* were implemented here [14]. The first method filtered undesired NIR light that could pass through the triple bandpass and CFA filters and be detected by the camera sensor. Two short-pass filters at 675 nm (64-613, Edmund Optics) and 725 nm (64-667, Edmund Optics) were used in sequence removed NIR light, as shown in Fig. 5.

To ensure that no emission overlap existed between the bands of the triple bandpass filter, monochromatic light emitting diodes (LEDs) were used with wavelengths of 625 nm, 530 nm, and 455 nm (M625L4, M530L4, and M455L4, all Thorlabs). Images taken of these LEDs with the camera are shown in Fig. 6. The spectra included in Fig. 6 show that the light emitted from the LEDs aligns with reported values from the manufacturer and that they have no emission at wavelengths other than those desired. While the LED wavelengths are slightly different from the bandpass filter wavelengths, they offer an inexpensive method for evaluating emission overlap between bands.

The LEDs were directed at the camera lens, and calibration images were analyzed to ensure that, for example, when collecting data from the 625 nm (red) LED neither the 533 nm (green) nor the 451 nm (blue) channels detect light. If spectral bleed-through was detected, the signal was corrected using Eqs. (3)–(5) developed by McNesby *et al.* but repeated here for convenience [14]. This correction removed the influence of bleed-through on the total intensity collected by a specific channel,



Fig. 5. Three spectra of the calibration lamp: the first shows no filtration (black line), the second shows a 725 nm short-pass filter (green line), and the third shows both the 725 and 675 nm filters (red line).



Fig. 6. Images of light from LEDs and their corresponding spectra indicating accuracy in reported wavelength and no emission at undesired wavelengths.

$$G_t = c R_r + G_r + d B_r, \qquad (4)$$

$$B_t = e R_r + f G_r + B_r.$$
 (5)

In Eqs. (3)–(5), variables a and b represent the amount of green and blue light being interpreted as red, c and d represent the amount of red and blue light interpreted as green, and e and f represent the amount of red and green light interpreted as blue. Variables a - f are constants determined in calibration by viewing the monochromatic LEDs and taking ratios of reported RGB light for each LED. R_r , G_r , and B_r represent the portions of red, green, or blue light contributing to the total intensity reported, respectively. Finally, R_t , G_t , and B_t are the total red, green, and blue intensity values from an image, respectively.

Equations (3)–(5) are solved for each pixel of an image matrix to correct each pixel's RGB response. For this study, there was very little bleeding between colors, and the only non-zero variables were *a* and *f* with values of 0.1881 and 0.2456, respectively. It is noted there is slight deviation from these values and Fig. 4 that may be a result of the LEDs not precisely aligned with the filter peaks.

F. Data Processing

Custom MATLAB (Mathworks) scripts were developed to process and analyze temperature data from both the pyrometer and high-speed camera. Typical pyrometer data from a thermite combustion experiment is shown in Fig. 7, along with processing steps and the corresponding temperature data from the experiment.

To calculate a temperature from the pyrometer PMT outputs, the data were first calibrated using factors determined with the calibration lamp, then the data were processed using a derivation from Eq. (2) shown in Eqs. (6)-(8),

$$\ln\left(\exp\frac{C_2}{\lambda T}\right) = \ln\left(\frac{C_1}{\lambda^5 I}\right),\tag{6}$$

$$\frac{C_2}{\lambda T} = \ln(C_1) - \ln(\lambda^5 I),$$
(7)

$$T = \frac{C_2/\lambda}{\ln C_1 - \ln \lambda^5 I}.$$
 (8)



Fig. 7. (a) Pyrometer data from a thermite reaction. (b) Linear manipulation of Wien's equation to extract temperature from the slope for one time point in the data. (c) Calculated temperatures for the entire experiment.

The temperature calculation shown in Eq. (8) allowed a linear curve-fit to extract temperature shown as the slope in Fig. 7(b) [20]. The temperature calculation process illustrated in Figs. 7(a)–7(c) is performed for each time step of pyrometry data and each image of video data from the camera; the only difference is that, while this calculation is performed once per time step for the pyrometer, it is carried out for each pixel of every frame of the high-speed video. For consistency in comparing the diagnostics, temperature calculations were always performed with the maximum available channels (i.e., four for the pyrometer and three for the camera). Therefore, significantly more data are processed in thermography than pyrometry, which can take significantly more time.

To assess functionality and calibrate both diagnostics, temperature calculations were performed with both the pyrometer and camera using the tungsten-halogen lamp. Wien temperature calculations using Eq. (8) can be seen in Fig. 8 for wavelengths corresponding to the triple bandpass filter of the camera [Fig. 8(a)] and wavelengths corresponding to the bandpass filters of the pyrometer [Fig. 8(b)] and their corresponding intensity values published by the manufacturer [as data symbols in Figs. 8(a) and 8(b)]. Note that as the lamp is not



Fig. 8. (a) Wien temperature calculation performed using camera specific wavelengths and corresponding manufacturer intensity values. (b) Pyrometer specific wavelengths and corresponding manufacturer intensity values. (c) Raw calibration image (left) with corresponding reconstructed thermographic image (right) with calculated average temperature. (d) Pyrometer temperatures calculated as a function of time when directed at lamp. (e) Camera certainty with 90% confidence bands. (f) Pyrometry certainty with 90% confidence bands.

a true blackbody, its color temperature depends on wavelengths chosen for analysis. As the pyrometer and camera filter out different wavelengths, the same lamp has two different effective temperatures.

Figures 8(c) and 8(d) show the calculated temperatures of the calibration lamp for the thermographic setup and pyrometer, respectively. An unprocessed color image of the lamp can be seen in Fig. 8(c) (left) along with the corresponding reconstructed thermal image (right) for a representative instant in time. For the camera, to mitigate erroneous temperature measurements from either low or saturated pixel intensities, a low cutoff threshold of 8 and high cutoff of 250 were implemented. Averaging across multiple frames, the camera visualizes a temperature of 3280 K [Fig. 8(c)], a difference of 149 K from the theoretical prediction [Fig. 8(a)]. As a single point measurement, the temperature calculations for the pyrometer were performed as a function of time, as shown in Fig. 8(d). The pyrometer calculates a temperature of 3195 K [Fig. 8(d)], within 31 K of the theoretical temperature predicted from published values [Fig. 8(b)]. As a point source measurement and because radiant intensity varies as a function of temperature to the fourth power, the pyrometer temperatures are not average values but biased toward higher temperatures.

To discern a measure of uncertainty, Wien temperature calculations were performed on the data collected by the camera and pyrometer [Figs. 8(c) and 8(d)] applying a 90% confidence level, shown in Figs. 8(e) and 8(f). Using this approach as the basis for uncertainty, the pyrometer has a ± 1 K uncertainty, and the camera has a ± 351 K uncertainty. The larger uncertainty of the camera may result from averaging across the entire frame, which introduces potential errors due to aberrations associated with the more complex lens optics. Overall, the agreement between calculated versus theoretical temperatures confirms that the diagnostics are functioning properly.

G. Spectroscopy

During ignition experiments spectroscopic data were concurrently collected to ensure that the wavelengths used in temperature calculations were not influenced by non-blackbody emission from the reaction. A representative spectrum is shown in Fig. 9. The spectrometer integration time was set to $825 \ \mu s$, and the spectra were corrected using the same tungsten lamp used for calibration. Figure 9 illustrates that, while this reaction has a complicated spectral landscape, the wavelengths used for pyrometry and thermography do not fall on any major emission features.

The commonly observed AlO emission bands, centered around 484 nm [21], do not appear to be significant in the Al/Bi₂O₃ reaction studied here. It is not clearly understood why the AlO bands are not more prominent in this reaction. It may be that, due to the large mismatch in particle size between the reactants (5 μ m Al versus 150 nm Bi₂O₃), the oxidation of Al proceeds in a more heterogenous manner, rather than as a diffusion flame seen in the combustion of Al in air [22]. It is also noted in Fig. 7(b), which is representative of the thermite reaction, that Wien's approximation is linear, further indicating no emission peaks interfere with the wavelengths of interest.



Fig. 9. Emission spectra of a thermite reaction showing intensity as a function of wavelength for a snapshot of time, with select peaks identified. Colored bands indicate the pass regions of the filters used for pyrometry and thermography.

3. RESULTS

A. Pyrometry

A total of seven tests were performed to ensure repeatability across the diagnostics. Figure 10(a) contains a representative temperature curve from the pyrometer. In order to better represent the data, a moving average was performed to reduce the total data down to 100 points. Standard deviations determined through this averaging are shown as the shaded region surrounding the temperature data. Additionally, represented in Fig. 10(a) is the time in which the laser was on (10 ms, red area). The observed temperature behavior was consistent across all experiments and time intervals, with the largest standard deviation at the beginning and end of the combustion event, attributed to inherently lower light emission at those times. As the signal-to-noise ratio diminishes with lower light emission, error increases in the temperature calculation. Intensity data from the 850 nm PMT channel are shown in Fig. 10(a), where lower light emission is observed at the beginning and end of the event with the larger intensities in the middle more steady-state region.

B. Thermography

For direct comparison to the pyrometer, camera temperature data were initially reduced to average, minimum, and maximum temperatures reported for an entire frame and reported in Fig. 10(b) for the duration of the high-speed video. Both data sets in Fig. 10 are from the same experiment. A similar trend in the transient temperature behavior of the pyrometry data is observed for the camera data, specifically the larger standard deviation at the beginning and end of the event, again, attributed to the diminished emission at those times, confirmed by the green intensity curve in Fig. 10(b).

Figure 11 shows a series of unprocessed color images, corresponding processed thermal images, and zoomed-in sections tracking a particle agglomerate location through time. Figure 11 demonstrates the full extent of possible data analysis techniques



Fig. 10. (a) Pyrometer temperature data (black curve, running average of 100 time steps, shaded region represents one standard deviation), corresponding intensity data from the 850 nm PMT channel (green curve), and region of time that laser was fired. (b) Camera average, minimum, and maximum temperature data (black, red, and blue curves, respectively, averaged over 100 time steps; shaded region represents one standard deviation), corresponding intensity data from the 625 nm channel (green curve), and region of time that laser was fired.

of the thermographic camera diagnostic. The inaccurate temperatures do not diminish the value of the high-spatiotemporal capabilities for comparative analysis and further the ability to track agglomerates of interest and monitor their transient surface temperatures on micrometer and microsecond scales, while at the same time providing a macroscopic observation of the thermal behavior of the entire combustive event.

4. DISCUSSION

The adiabatic flame temperature for the stoichiometric $Al + Bi_2O_3$ reaction is 3520 K [5] and used in the discussion as a reference temperature for comparison. The higher temperatures in Fig. 10(a) between \sim 40 and \sim 50 ms, as well as most of the average and maximum calculated temperatures reported in Fig. 10(b), exceed the adiabatic flame temperature (drastically more at the beginning and end time intervals of Fig. 10(b) and may be inaccurate. Under ignition and extinction burning conditions, a reduced signal-to-noise ratio causes the numeric values of measured temperature to be less reliable. Quantifying a specific threshold for signal-to-noise ratio would not be a consistent metric across diagnostics or experiments because many variables influence the measurement, such as exposure setting and the intensity of the reaction event. Therefore, thresholding for an appropriate signal-to-noise ratio must be a user defined parameter that is specific to the experimental conditions.



Fig. 11. First column consists of raw camera images at selected times. Second column shows processed thermographic images providing spatially resolved temperature measurements. Third column details a burning particle and shows pixel level temperature values (N = Not a Number; intensities for these pixels were below the cutoff threshold, so no temperature was calculated).

The camera data were on average \sim 780 K higher than the pyrometer. The consistently higher readings are attributed in part to the more limited dynamic range of the camera compared to the pyrometer. While both diagnostics are calibrated to measure within combustion temperature regimes, the PMTs of the pyrometer are more sensitive than the pixels of the camera. For the camera to capture intense light emitted by combustion events and not saturated, the camera exposure settings must be reduced. Due to the low exposure the camera is unable to see cooler temperatures, which fall into the background noise. Thus, the more limited temperature range visible to the camera naturally biases calculated average temperatures higher. Though the pyrometer is calibrated to this same thermal regime, the dynamic range of the PMT sensors means it is able to processes less intense, lower light emission. Further, as seen with the calibration image in Fig. 8(c), the more complex optical setup of the camera creates opportunity for error in the temperature measurement from features such as aberrations, potentially resulting in larger temperature hot spots within the flame.

To confirm that the differences in dynamic range were the main contributing factor to the difference in average temperature between the two diagnostics, an additional experiment was performed. Both diagnostics were calibrated to the tungstenhalogen lamp temperature of \sim 3200 K, then set up to visualize a 1150 K blackbody source (M300, Mikron). Due to the limited exposure of the camera, it was incapable of visualizing any emission from the blackbody source (it was too dim for the camera to see), whereas the pyrometer was able to obtain enough signal that a temperature could be calculated. Both the lamp and blackbody temperatures curves can be seen in Fig. 12 for the pyrometer. The pyrometer accurately predicts the lamp



Fig. 12. Pyrometer temperature results for both the calibration lamp (top) and blackbody source (bottom).

temperature, to which it was calibrated, within ~ 2 K, but measures ~ 1580 K for the blackbody, i.e., ~ 430 K higher than the true temperature. The inaccurate reading for the blackbody is expected considering the low signal and that the pyrometer was calibrated to much higher temperatures. Though inaccurate, the ability of the pyrometer to measure temperatures from sources over 2000 K lower than the calibrated regime, while the camera is limited to a much tighter range of temperatures near the calibration value, illustrates the dramatically higher dynamic range capability of the pyrometer and demonstrates that the camera is biased toward higher average temperature measurements.

5. CONCLUSION

Pyrometry and thermography measurements of temperature were compared for the duration of a reaction produced by a powder mixture of Al and Bi_2O_3 . Both diagnostics collected data at the same frequency and over the same time duration. The pyrometer provided a single measurement that is an average

	Pros	Cons
Thermography	• Provides spatial information about temperature distribution	• Limited sensor dynamic range leads to a smaller range of observable temperatures
	• Effectively serves as thousands of three channel pyrometers	• Additional required calibration steps introduce more
	 Measures macroscopic combustion cloud temperatures 	sources of error
	 Identifies agglomerate/particle surface temperatures 	
	Particle tracking is possible	
Pyrometry	• Can record data at much higher speeds than a high-speed camera	• Provides no inherent spatial resolution information
	• Lower cost than many cameras	• Reports a weighted average temperature over large
	• Modular nature allows wavelengths of interest to be easily changed	fields of view, which can be erroneous in highly dynamic
	simply by changing filters	experiments
	• Simplified series of optics	-

Table 1. Pros and Cons of the Pyrometer and Thermographic Camera

value over the field of view as a function of time. The high-speed camera provided a spatial distribution of temperature as a function of time for a similar field of view. The relative advantages and disadvantages of each technique are summarized in Table 1.

Results showed a general correspondence in trend of average temperature over time. Upon ignition and extinction, lower overall light intensity reduced the signal-to-noise ratio and produced higher error in the measured values for both diagnostics. In the steady burning regime, both diagnostics produced highly repeatable data across the all ignition experiments performed. The high-speed camera was determined to be more sensitive to measurement errors due to its more limited dynamic range. The reduced exposure settings required to capture intensities produced by the combustion event constrained the camera to only being able to visualize temperatures near the calibration value. However, the evolution of hot spots and particle agglomerates within the flame zone were identified using the camera. This study shows that pyrometry and thermography offer advantages and disadvantages for measuring temperature in energetic material reactions. Specifically, pyrometry provides more accuracy in quantifying an average temperature due to its ability to measure temperatures outside of its calibration regime, but thermography provides insight on the spatial distribution of temperature and evolution of thermal gradients.

Funding. U.S. Department of Energy (DE-NA0003988, DE-NA0003525); Army Research Office (W911NF1710387); Office of Naval Research (N000141912082).

Acknowledgment. The authors are grateful to Dr. Kevin McNesby from the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, for providing the triple bandpass filter for the high-speed camera and many helpful discussions. Dr. Alexandra Reinert from U.S. Naval Surface Warfare Center, Indian Head, MD, is gratefully acknowledged for helpful discussion and mentorship. We sincerely appreciate experimental setup assistance from Mr. Loudon Lee Campbell from Texas Tech University. Additionally, Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Disclosures. All authors declare no conflicts of interest.

Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

REFERENCES

- H. Goldschmidt, "Process for the production of metals or metalloids or alloys of the same," U.S. patent 96317 (13 March 1895).
- 2. H. Goldschmidt, "Method of producing metals and alloys," U.S. patent 578868 (16 March 1897).
- H. Goldschmidt, "Verfahren zur Erzeugung hoher temperaturen (method for the production of high temperatures)," Zeitschrift fur Elektrochemei 6, 53–57 (1899).
- A. G. Rozner and H. H. Helms, "Pyronol torch—a non-explosive underwater cutting tool," in *Conference Proceedings from the Offshore Technology Conference* (1976).
- O. Mulamba, E. M. Hunt, and M. L. Pantoya, "Neutralizing bacterial spores using halogenated energetic reactions," Biotechnol. Bioprocess Eng. 18, 918–925 (2013).
- S. H. Fischer and M. C. Grubelich, "Theoretical energy release of thermites, intermetallics, and combustible metals," in *Conference Proceedings from the 24th International Pyrotechnics Seminar* (1998).
- K.-L. Chintersingh, M. Schoenitz, and E. L. Dreizin, "Boron doped with iron: preparation and combustion in air," Combust. Flame 200, 286–295 (2019).
- N. Glumac, H. Krier, T. Bazyn, and R. Eyer, "Temperature measurements of aluminum particles burning in carbon dioxide," Combust. Sci. Technol. **177**, 485–511 (2007).
- S. Goroshin, D. L. Frost, J. Levine, A. Yoshinaka, and F. Zhang, "Optical pyrometry of fireballs of metalized explosives," Propellants Explos. Pyrotech. 31, 169–181 (2006).
- W. P. Bassett and D. D. Dlott, "32-channel pyrometer with high dynamic range for studies of shocked nanothermites," AIP Conf. Proc. **1793**, 060012 (2017).
- C. Florinpetre, D. Chamberland, T. Ringuette, S. Ringuette, S. Paradis, and R. Stowe, "Low-power laser ignition of aluminum/metal oxide nanothermites," Int. J. Energ. Mater. Chem. Propul. 13, 479–494 (2014).
- J. M. Densmore, M. M. Biss, K. L. McNesby, and B. E. Homan, "Highspeed digital color imaging pyrometry," Appl. Opt. 50, 2659–2665 (2011).
- Y. Chen, D. R. Guildenbecher, K. N. G. Hoffmeister, M. A. Cooper, H. L. Stauffacher, M. S. Oliver, and E. B. Washburn, "Study of aluminum particle combustion in solid propellant plumes using digital in-line holography and imaging pyrometry," Combust. Flame 182, 225–237 (2017).
- K. L. McNesby, S. W. Dean, R. Benjamin, J. Grant, J. Anderson, and J. M. Densmore, "Imaging pyrometry for most color cameras," Rev. Sci. Instrum. (to be published).
- H. Wang, D. J. Kline, and M. R. Zachariah, "In-operando high-speed microscopy and thermometry of reaction propagation and sintering in a nanocomposite," Nat. Commun. 10, 3032 (2019).
- I. Shancita, C. Woodruff, L. L. Campbell, and M. L. Pantoya, "Thermal analysis of an iodine rich binder for energetic material applications," Thermochim. Acta 690, 178701 (2020).
- H. R. B. Orlande, O. Fudym, D. Mallet, and R. M. Cotta, *Thermal Measurements and Inverse Techniques* (CRC Press, 2011).

- 18. F. Incropera and D. Dewitt, *Fundamentals of Heat and Mass Transfer* (Wiley, 2002).
- D. J. Dagel, G. D. Grossetete, D. O. MacCallum, and S. P. Korey, "Four-color imaging pyrometer for mapping temperatures of laser-based metal processes," Proc. SPIE 9861, 986103 (2016).
- F. R. A. Jorgensen and M. Zuiderqyk, "Two-colour pyrometer measurement of the temperature of individual combusting particles," J. Phys. E 18, 486–491 (1985).
- J. M. Peuker, P. Lynch, H. Krier, and N. Glumac, "On AIO emission spectroscopy as a diagnostic in energetic materials testing," Propellants Explos. Pyrotech. 38, 577–585 (2013).
- Y. Huang, G. Risha, V. Yang, and R. A. Yetter, "Effect of particle size on combustion of aluminum particle dust in air," Combust. Flame 156, 5–13 (2009).