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Digital Imaging Holography and Pyrometry of Aluminum Drop Combustion in Solid Propellant Plumes

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Abstract: Aluminized propellants produce molten particulates of variable size and temperature. In this work, sizes and three-dimensional positions are determined using digital in-line holography with a pulsed laser. Simultaneously, particle temperatures are measured using two-color pyrometry.

OCIS codes: (090.1995) Digital holography; (120.1740) Combustion diagnostics; (110.6820) Thermal imaging; (100.6890) Three-dimensional image processing; (120.6780) Temperature.

1. Introduction

Solid propellants often contain metal particulates in order to increase specific impulse and combustion stability. The small particulates often melt and form spherical agglomerates due to the heat released from the reaction of the oxidizer and fuel binder [1]. The temperature of the gas, the temperature of the metal particulates and other combustion properties are an important area of study that can inform modeling efforts. In the past, efforts to image and size the burning particles have been limited by camera focal depth. By using digital in-line holography (DIH), the authors have been able to characterize the position, size, and velocity of the burning particles in three-dimensions at high speeds [1, 2]. The temperature of the gas near solid propellants [3–5] well as fixed metal particulates [6] have been studied by several groups using pyrometry and coherent anti-Stokes Raman spectroscopy. This paper combines the capabilities of DIH using a nano-second pulsed laser with pyrometry. The effect of focal depth on temperature estimation accuracy is also assessed. This preliminary study represents the first known simultaneous measurement of particle temperatures, diameters, and positions with DIH and pyrometry during a propellant burn.

2. Experimental Configuration

Simultaneous particle tracking and temperature estimation is achieved by using the three-camera system in Fig. 1. A double-pulsed ND:YAG laser (Continuum MiniLite PIV, 532 nm, 5 ns pulse duration, pulse separation of 40 μs) is spatially filtered and collimated before passing through the pyrometry focal plane. The diffraction images for DIH are then magnified (Infinity K2 DistaMax with CF2 objective) and imaged with a LaVision sCMOS monochrome camera.

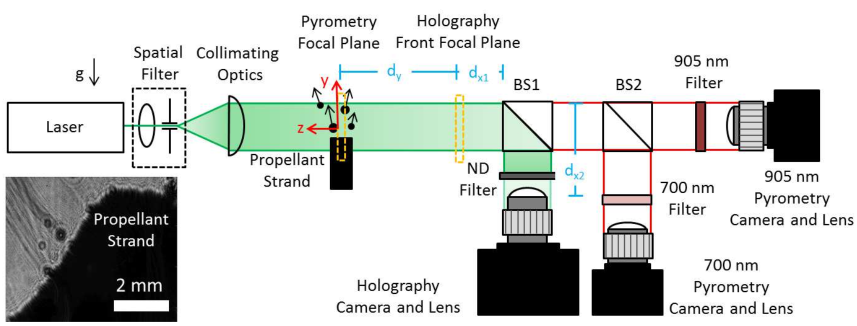

Fig. 1. The experimental setup is shown for the pyrometry and DIH experiment. An example hologram of a propellant strand and particles is shown in the inset. ND - neutral density filter, BS1 - beam splitter (reflection @ 532 nm and transmission @ 650 to 900 nm), BS2 - beam splitter (reflection @ 650 to 750 nm and transmission @ 850 to 950 nm), both pyrometry camera filters have a bandwidth of 10 nm.

The DIH images can be numerically refocused to a variety of focal depths. First, a conjugate object wave is obtained by multiplying the recorded hologram h with the conjugate reference wave E_r^*. The reconstructed complex amplitude of the hologram is then obtained by numerically propagating to a specific depth z by solving the diffraction equation,

$$E(x,y;z) = [h(x,y)E_r^*(x,y)] \otimes g(x,y;z), \tag{1}$$

where x and y are spatial coordinates, $\otimes$ is the convolution operator and g is the diffraction kernel. The light field amplitude $A = |E|$ can then be used to determine the in-focus particle images [1].

Because the burning particles are self-luminous, two LaVision ProX 4M monochrome cameras with 700 and 905 nm filters are arranged with Navitar Zoom 7000 lenses (f-stop fully open) to capture the thermal emission. The cameras are used in single-frame mode and are simultaneously triggered with the first DIH frame for an exposure length of 20 μs. The full system is triggered together at a rate of 13 Hz. Due to this low sampling rate, the particles in each frame are uncorrelated. Temperatures can be calculated from images obtained at two different wavelengths by assuming gray body thermal emission from the aluminum particles and using Plank's equation. If $hc/\lambda >> kT$, then Wien's approximation can be used to solve for the temperature by using a ratio of two images, where h is Plank's constant, c is the speed of light, λ is the wavelength, k is the Boltzmann constant, and T is the temperature. The ratio of the calibrated intensities measured by the two cameras is $R = (I_2\eta_1E_1)/(I_1\eta_2E_2)$, where I is the intensity, η is the quantum efficiency and E is the exposure length of the camera at one wavelength. This can be used to estimate the temperature of each pixel as,

$$T = \left[\frac{k}{hc}\frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\left(ln(R) - 5ln\left(\frac{\lambda_1}{\lambda_2}\right)\right)\right]^{-1}. \tag{2}$$

The quantum efficiencies are calibrated using a Princeton Instruments Intellical LED source and referenced with an Ocean Optics USB2000+ spectrometer. The DIH camera is calibrated by placing a 1 mm spacing dot grid at the holography camera front focal plane. The three cameras are then de-warped and transformed to the same field of view using additional dot grid calibrations at the pyrometry focal plane ($d_y = 50\ mm$).

3. Results and Discussion

The aluminized propellant used in these experiments are 6 mm in diameter, 50 mm long, and are composed of approximately 70 wt. % ammonium perchlorate (AP), 20 wt. % aluminum particulate, and 10 wt. % hydroxyl terminated polybutadiene binder. The propellant strands are coated with an epoxy inhibitor that promotes a downward burn front, consuming the un-reacted propellant below. The aluminum particles in the propellant react, agglomerate and are carried by the exhausted product gas plume. The tests were conducted at 0.83 atm (ambient pressure in Albuquerque, New Mexico). Figure 2 shows the raw hologram, refocused holograms, and images from the pyrometry cameras at the two different wavelengths. Some particle have a small gas-phase reaction zone around them caused by evaporation and diffusion of the molten aluminum. These droplets are carried upward and the reaction-zones are directed by the convective flow. The estimated temperature image of several particles is shown in Fig. 2(f). Each particle shows some variation in temperature, where the hot spot in the pyrometry images and bulge in the holography images indicate the location of the oxide caps.

Although the DIH data contains depth-resolved information, the pyrometry cameras are at a fixed focal depth. In order to investigate the effect of focal depth on temperature, a hot nichrome wire was measured at different z locations as shown in Fig. 3(a). The in-focus locations show a larger temperature variation while out-of-focus locations show more uniform and lower temperature estimates. Overall, the estimated temperature varies by 100 K over 30 mm. Some estimation bias may occur due to the overlap of out-of-focus intensities for two or more particles, but the particle density is relatively low [1, 5] and this effect may be small. Using this information, statistics for a propellant burn can be assessed. Numerical refocusing and particle finding methods [1] are used to extract particle size and position

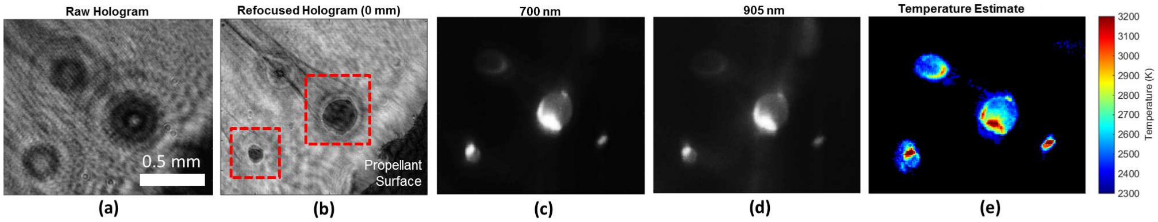

Fig. 2. (a) The raw hologram can be refocused to (b) the pyrometry focal plane in order to show the in-focus features of different aluminum drops, as indicated by the red boxes. The (c) 700 nm and (d) 905 nm pyrometry camera data can be combined to produce (e) an estimate for the particle temperatures.

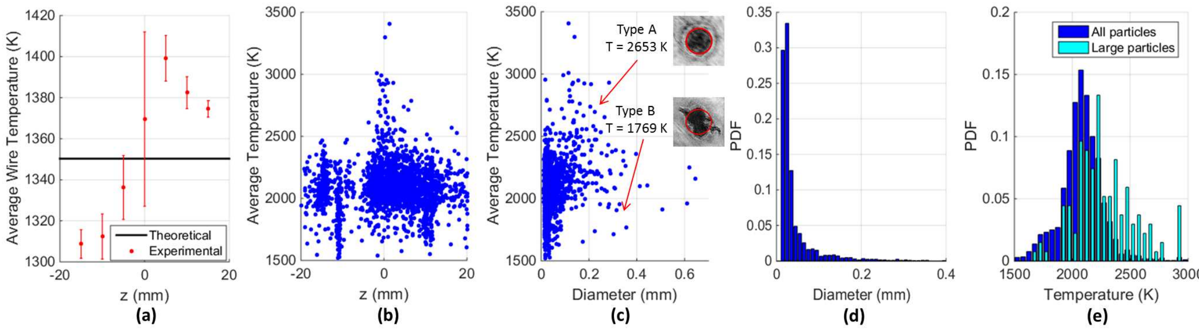

Fig. 3. (a) The temperature for a 240 μm diameter nichrome wire is estimated as it moves in and out of the focal plane. The statistics of a propellant stick burn show (b) the temperature to focal depth variation, (c) the temperature to diameter variation, (d) the diameter distribution and (e) the temperature distribution of all the particles and of only large particles ($\geq$ 125 μm diameter).

information from the DIH data and the corresponding pixels in the pyrometry data are measured. Particles smaller than one pixel on the pyrometry cameras were rejected so the smallest particle diameters used were 11 μm.

Figure 3(b)-(e) show the statistics for one propellant stick burn with 2120 total particles measured over 143 frames. Many of the smaller particles may reach an equilibrium temperature with the gas flow quickly, therefore producing lower temperatures. There are two types of larger particles, A) spherical agglomerates with oxide caps that tend to have hotter temperatures and B) eccentric particles that are expelled from the propellant stick surface that have not yet agglomerated that tend to have lower temperatures. Particles that are closer to the propellant stick and the main body of the propellant at $z = 0$ tend to be hotter, as indicated in Fig. 3(b).

The temperature measurement contains several possible biases. Interference from gas-phase emission and calibration accuracy likely play the largest roles in temperature measurement error. Some additional error at lower temperatures may be introduced by the CCD camera readout for short exposures. In addition, the gray body assumption may break down under certain conditions. Characterizing different potential measurement biases is an important area of future work. In this experiment, the oxide cap temperatures appear to be above 3000 K due to the reaction zone while the aluminum particle temperatures appear to be in the range of 2000 to 2600 K. These results match well with gas [4–6] and particle temperatures estimates [3] from other studies. This work presents a unique dataset for understanding combustion in solid propellant plumes.

Acknowledgments

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