Flame temperature measurement using color-ratio pyrometry with a consumer grade DSLR camera

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Abstract

A CANON EOS-550D DSLR camera with a 100 mm zoom macro-lens was calibrated for measurement of whole field temperature using color-ratio pyrometry (CRP). The spectral response curve of the camera-lens system was obtained with the help of a laser power meter and a tunable laser source. The response curves thus obtained were used to generate look up tables for black body as well as soot radiation. The black body look up table was validated with the help of temperature measurements in the range 750-1500 °C. The assumption that the emissivity of the soot particles varied as $\lambda^{-\frac{1}{3}}$ was utilized to generate soot lookup tables. The result obtained using CRP for a candle flame was compared against thermocouple measurements. These results indicate that CRP applied using a consumer grade camera is a suitable technique for obtaining flame temperatures greater than 1000 K with reasonable accuracy, for sooty flames. The method allows 2D, non-intrusive temperature measurement at very low costs.

1 Introduction

Measurement of flame temperature forms one of the cornerstones of combustion diagnostics. It is important to determine the temperature distribution with the combustion zone from a perspective of efficiency as well as design and safety. Flame temperatures have a direct impact on combustion efficiency and emission control, including mechanisms of soot formation and destruction [1]. Thus it is imperative to accurately estimate the temperature distribution for the combustion phenomenon being studied.

Various tools and techniques for measurement of temperature has been developed over the past century [2]. The techniques may be broadly categorized as intrusive and non-intrusive in nature. The simplest intrusive technique is the use of thermocouples. These are typically used for point measurements and are restricted by the maximum temperature that can be measured, owing to limitations placed by the material of construction of the thermocouple. In addition to this, the accuracy of flame temperatures measured using thermocouples is quite limited due to several reasons. Often, the uncertainty in measurements may be of the order of 10% or more, owing to heat losses from bead, errors in estimating flame emissivity, and soot deposition on the thermocouple bead. Non-intrusive techniques benefit from their ability to determine temperatures using optical means without affecting the thermal and flow field. Laser based techniques such as Rayleigh scattering, Coherent Anti Raman Spectroscopy and other methods [3] typically provide higher degrees of accuracy. Their sensitivity comes at the expense of high initial investments and the requirement of extensive care during handling such instruments. In addition concerns regarding safety and space limitations limit their usage in certain environments [4].

Temperature estimation methods based on detecting the intensity of light emitted by soot particles in a flame is conventionally known as soot pyrometry. This technique can be classified into different categories based on its implementation. The most popular among these are the two-color pyrometry method and the color-ratio pyrometry (CRP) method. The wavelengths used for detection may be narrow band or broad band. Soot pyrometry in various forms has been previously utilized to measure the flame temperatures in several applications such as burner flames [5, 6], diesel engines [7], and, coal fired boilers [8]. Kuhn et.al [6] demonstrated that DSLR cameras may be suitably calibrated as pyrometers to acquire whole field temperature distribution. The present work discusses the steps involved in calibrating a consumer grade DSLR camera to evaluate flame temperatures, using detection of light emitted by soot particles in the visible spectrum, based on CRP. Once calibrated, the method provides a cost-effective and easy-to-implement solution for measuring 2D temperature profiles of sooty flames with reasonable accuracy. A candle flame was characterized and the measured thermal field was compared with thermocouple measurements. Results are presented for a candle flame.

2 Theory behind calibration of a DSLR camera

2.1 Working of a DSLR

A DSLR camera usually consists of a Charge Coupled Device (CCD) sensor or a Complementary Metal-Oxide-Semiconductor (CMOS) sensor, coated with a Color Filter Array (CFA). The CFA in turn consists of an array of three distinct filter elements designated as Red (R), Green (G) and Blue (B) filters, which selectively allow only a fraction of the visible radiation emitted by the source to reach the sensor. One of the most popular arrangements of the filter elements in the CFA is known as the Bayer pattern [9]. It consists of repetitive units of a 2x2 pattern of square pixels with the R, G, and B elements appearing at least once in each unit. In order to recreate the image of an object under consideration, each pixel must have its own set of RGB values. This is obtained by interpolating the information from the neighbouring pixels through demosaicing. The built-in processor within the camera also applies several other corrections to the input signal for ease of processing and to render the processed image visually appealing to the human eye [10].
2.2 Image processing details

One of the basic requirements of CRP is that the output signal generated by the detector of the camera must be directly proportional to the input signal received. This requires the elimination of unwanted image processing steps, such as white balancing and gamma correction. As it is often difficult to determine the sequence and extent of post-processing performed on the input data by the camera’s processor, it is advisable to record the images in the RAW mode for pyrometry applications. The RAW mode is a proprietary format which functions as a digital negative for the camera. The steps to be followed for generating a tiff image from an image in the RAW format for analyzing the required temperature distribution using the open source code (dcrw) and MATLAB is shown in Fig. 1.

![Image processing steps in CRP](image)

Figure 1: Image processing steps in CRP

2.3 Theory behind CRP

Soot pyrometry measures the temperature of soot particles in the flame. These particles are usually very small and attain thermal equilibrium with the surrounding combustion gases within 1 to 10 µs [11]. Hence the soot temperature may be safely approximated to be the same as the surrounding gas temperature. The intensity of light (I) emitted by an object at a given wavelength (λ) is a function of temperature (T) and is given by (1).

\[
I(\lambda, T) = \varepsilon(\lambda) \frac{2\pi \hbar c^2}{\lambda^4 (\exp(hc/\lambda kT) - 1)}
\]  

(1)

where \(\varepsilon(\lambda)\) is the emissivity of the object at the given wavelength, \(h\) is Planck’s constant, \(c\) is the velocity of light, and \(k\) is the Boltzmann constant. The signal received by the detector of the camera \(S_P\) for a given exposure time \(t\), after the light has passed through the lens and CFA is given by (2)

\[
S_P = 2\pi \hbar c^2 \int_\lambda^L \frac{\varepsilon(\lambda) \eta(\lambda)}{\lambda^4 (\exp(hc/\lambda kT) - 1)} d\lambda
\]  

(2)

where \(\eta(\lambda)\) accounts for combined efficiency of the detector, the lens array, the transmission efficiency of the CFA as well as a geometric factor [6]. In this case, \(\lambda_1\) and \(\lambda_2\) are the limits of visible wavelength range, whose values are of 400 and 700 nm respectively. The ratio of signals received by each pixel of the camera can then be found using the relation provided in (3)

\[
\frac{S_F}{S_P} = \frac{\int_\lambda^L \eta_F(\lambda) \varepsilon(\lambda) \exp(hc/\lambda kT) d\lambda}{\int_\lambda^L \eta_F(\lambda) \varepsilon(\lambda) \exp(hc/\lambda kT) d\lambda}
\]  

(3)

where \(F_1\) and \(F_2\) represent filters 1 and 2 respectively (either of R, G, and B). For a black or gray body, the emissivity may be eliminated from the numerator and denominator. Equation (3) is integrated numerically to generate look up tables for the color-ratio values, for a given range of temperatures. For generating soot look up tables, the soot emissivity is assumed to vary as \(\lambda^{-5}\) [6].

3 Experimental Work

3.1 Experiments for characterizing the spectral response of a DSLR camera

A schematic of the experimental setup used to characterize the spectral response of the camera is given in Fig. 2.

![Schematic of the experimental setup used for characterizing the camera’s spectral response](image)

Figure 2: Schematic of the experimental setup used for characterizing the camera’s spectral response

A tunable laser source, Fianium Whitelase SC400, whose wavelength and intensity could be varied, was the most important component of the setup. The emission from the laser was imaged onto the camera sensor through the chosen lens system. The aperture, ISO setting, and f-stop value of the camera were kept unchanged during the course of calibration. The laser power settings used for the experiments were typically less than 0.5 µW and was measured with the help of a FieldMate laser power meter. In order to ensure that the power readings remain unaffected by the ambient light, the calibration experiments were conducted in a dark room. The images were shot in the RAW mode and the ISO setting was kept at the minimum value possible to reduce ambient noise. The inbuilt image processing by the camera was minimized by avoiding all image enhancement options or by setting them to their default values.

3.1.1 Detector linearity check

The linearity of the CMOS detector was confirmed at a fixed wavelength by holding all the camera and lens settings constant, except shutter speed which was varied gradually. The RGB values of the resulting images were obtained with the help of MATLAB, using the procedure outlined in the section 2.2. The results presented in Fig. 3, show that the response of the detector is indeed linear for the camera-lens system utilized.
3.1.2 Characterization of spectral response

For characterizing the spectral response of the system, experiments were conducted from 400 to 700 nm at intervals of 10 nm. The laser power setting for each trial was noted and the values were measured by a laser power meter. The images were processed as explained in section 2.2, to obtain the RGB data for each pixel. The ratio of intensities R/B and R/G were also computed separately. The response function for the red filter was calculated in an arbitrary scale by (4).

$$\eta_{R_{-\text{arb}}} = \frac{R}{P \times \tau}$$  \hspace{1cm} (4)

where, $R$ is the normalized value of the red signal between 0 and 1, averaged for a central zone inside the imaged laser spot, $P$ is the measured power value of the laser beam for the given setting, and $\tau$ is the time interval of data acquisition.

This was then normalized to a scale between 0-1 using (5)

$$\eta_{R_{\text{Scaled}}} = \frac{\eta_{R_{-\text{arb}}} \lambda}{\text{MAX}(\eta_{R_{-\text{arb}}} \lambda)}$$  \hspace{1cm} (5)

where, $\text{MAX}(\eta_{R_{-\text{arb}}} \lambda)$ represents the maximum value of $\eta_{R_{-\text{arb}}} \lambda$, within the range of considered wavelengths. The R/B and R/G ratios were then used to derive corresponding scaled values for blue and green signals as given in (6) and (7).

$$\eta_{B_{\text{Scaled}}} = \frac{\eta_{R_{\text{Scaled}}} \lambda}{(R/B)}$$  \hspace{1cm} (6)

$$\eta_{G_{\text{Scaled}}} = \frac{\eta_{R_{\text{Scaled}}} \lambda}{(R/G)}$$  \hspace{1cm} (7)

where, B and G are the normalized values of the blue and green signals, defined in a manner similar to R.

A final normalization was implemented using the highest of these scaled values at all measured wavelengths ($\text{MAX}(\eta_{R_{\text{Scaled}}} \lambda)$), to obtain the normalized spectral response curve for the camera, shown in Fig. 4. The equations used for the same are as follows:

$$\eta_{R}(\lambda) = \frac{\eta_{R_{\text{Scaled}}} \lambda}{\text{MAX}(\eta_{R/G/B_{\text{Scaled}}} \lambda)}$$  \hspace{1cm} (8)

$$\eta_{G}(\lambda) = \frac{\eta_{G_{\text{Scaled}}} \lambda}{\text{MAX}(\eta_{R/G/B_{\text{Scaled}}} \lambda)}$$  \hspace{1cm} (9)

$$\eta_{B}(\lambda) = \frac{\eta_{B_{\text{Scaled}}} \lambda}{\text{MAX}(\eta_{R/G/B_{\text{Scaled}}} \lambda)}$$  \hspace{1cm} (10)

Figure 3: Detector linearity at a wavelength of 400 nm

3.2 Validation of response curve with black body calibration results

Once the response curves for the camera’s CFA were obtained, the lookup tables were generated as discussed previously. These were compared against black body calibration data from 750 to 1500 °C. The black body calibration was carried out using a CALsys 1500BB calibration source. Readings were obtained in steps of 50 K and the results are presented in Fig. 6. The spectral response curves for R, G and B were modified slightly ($< 4\%$), by multiplication with a scaling factor, for a better agreement with the blackbody results [6]. The scaling factors used were 1.04, 1.01 and 1 for R, G and B respectively.

The curves were found to be reasonably monotonous from 1000 to 3000 K, ensuring unique values of temperature from each pixel.

Figure 5: Color-ratio look up tables for black body and soot radiative emissions, validated against black body calibration data

4. Results and Discussions

The validity of the generated lookup tables was estimated by comparing the whole-field thermal data for a candle flame
obtained using CRP with point measurements from an S-type thermocouple. The thermocouple wires were 80 µm in diameter, with a bead size of approximately 150 µm. The RAW image was captured with the thermocouple located within the flame, to identify its location in the 2D temperature profile obtained for the rest of the flame. The uncorrected thermocouple readings are shown in Fig.6. The 2D temperature contour retrieved from the flame, based on the generated soot lookup tables is shown in Fig. 7. It was observed that the temperature of the gas surrounding the thermocouple was approximately around 1700-1800 K for pixels in the vicinity of the bead, while that measured by the thermocouple showed an average value of about 1650 K at steady state. Since the temperature correction due to radiative losses is expected to be of the order of 100 K, the data obtained using soot pyrometry was determined to be in excellent agreement with the expected values.

![Figure 6: Uncorrected thermocouple readings for candle flame](image)

![Figure 7: 2D temperature distribution of a candle flame (K)](image)

The axisymmetric nature of a candle flame was captured well in the temperature distribution obtained. It should be noted that the CRP technique works well only for yellow sooty flames and fares poorly when applied to bluish flames.

4 Conclusions

The spectral response curve for the camera’s CFA was characterized using a tunable laser source and a laser power meter. The images were shot in the RAW mode with the settings chosen so as to minimize the camera’s inbuilt processing steps. The open source code (dcraw) was used to obtain estimates for dark and saturation values of each image and convert the RAW image to a linearized, 16 bit, unbrightened, un-gamma corrected and un-demosaiced tiff output which could be read in MATLAB. An in-house MATLAB code which used inputs of dark and saturation values of the recorded image and the bayer pattern for the camera’s CFA, was used to generate a linear, normalized and demosaiced image for analysis. The spectral response curves thus obtained were used to generate color-ratio lookup tables for black body and soot radiation. The black body lookup table was validated against black body calibration data from 750-1500 °C. Soot look up tables were validated against S-type thermocouple data for a candle flame. It was observed that the temperature of the gas surrounding the thermocouple was approximately around 1700-1800 K for pixels in the vicinity of the bead, while that measured by the thermocouple showed an average value of about 1650 K at steady state. Since the temperature correction due to radiative losses is expected to be of the order of 100 K, the data obtained using soot pyrometry was determined to be in excellent agreement with the expected values. Once calibrated, a consumer grade DSLR can prove to be cost effective yet useful tool for non-intrusive measurement of 2-D temperature data for sooty flames.

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