Recent Developments of Thin-Filament Pyrometry

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Thin-Filament Pyrometry (TFP) has been proven to be a useful approach to measure flame temperature. It involves placing a SiC fiber in hot gases and correlating the radiance of the glowing fiber to a calibrated temperature reference. The TFP approach offers simplicity and low cost, and it is useful in situations where other techniques are difficult to apply, such as high-pressure environments. In this paper, some recent developments of TFP are discussed. The accuracy of radiation correction, a procedure that is necessary for all TFP measurements, was evaluated by comparing thermocouple derived gas temperature and gas temperature measured by laser techniques (CARS and Raman/Rayleigh scattering) at the same position above a laminar flat premixed CH\textsubscript{4}/air calibration flame. The aging behavior (emissivity changing with time) that could affect the accuracy of TFP measurements was studied by examining the fiber spectral signal over hours at high temperature. Two TFP approaches were tested and discussed. The first approach utilizes one narrowband interference filter and relies only on a calibration at one temperature. Other temperatures can be inferred according to Planck’s law as long as the material is stable (no significant aging effect) and the optical setup is kept unchanged. This approach avoids the need for spectral characterization of the detector and knowledge of the emissivity model of the fiber. The second approach based on color-ratio principles was applied to yield simpler and more robust measurements. It relies on the fiber greybody assumption and camera spectral response characterization, but is free of temperature calibration.

1. Introduction

Thin-Filament Pyrometry (TFP) has been proven to be a useful approach to measure flame temperature. It offers one dimensional temperature measurement along the length of the fiber. The TFP approach has the advantages of low-cost and simplicity, and it is useful in situations where other techniques are difficult to apply, for example in high pressure environments where laser-based techniques suffer beam steering problems and spectroscopic issues. In the most common usage, the TFP approach involves placing Silicon Carbide (SiC) fibers in hot gases and determining the fiber temperature from the incandescence of the glowing fiber. The local gas
temperature is then derived from the fiber temperature after radiation correction. SiC fibers were found to have good strength at flame temperature and were resistant to oxidation and catalytic effects. The high melting temperature (~2673 K) [1] of SiC enables the fibers to survive in most flames.


For all TFP measurements, radiation correction is a necessary step to determine the local gas temperature from the fiber temperature. Often times, the gas temperatures derived from fiber temperatures after radiation correction are compared against those derived from thermocouple measured temperatures. The gap between TFP/thermocouple derived gas temperature and the “true” gas temperature depends on the accuracy of the radiation correction procedure. An accurate gas temperature measured by an independent approach is favored to address the uncertainty associated with the radiation correction. The TFP approach normally assumes stable behavior of the glowing SiC fiber. However caution must be taken when treating SiC fibers as a stable emitter and some pre-conditioning of the fiber is generally necessary to reduce errors as will be discussed in the following sections. In general, TFP accuracy is limited by the fiber aging effects, the applicability of the greybody assumption, the accuracy of the radiation correction, and ultimately by the calibration method.

In this paper, some recent developments of the TFP approach are discussed. Fiber aging behaviors were investigated for commonly used 15 µm SiC fibers as well as for 75 µm - 150 µm fibers, which are of more interest for industrial use due to their higher strength. The principle and application of two TFP approaches based on Intensity-Ratio pyrometry and a Color-Ratio technique are discussed. Gas temperatures derived from TFP measurement are directly compared against the temperature measured by laser-based techniques.

2. Experimental setup

2.1 Calibration flames

Two very similar CH₄/Air premixed flat flames were used in this study, one from Yale and the other from Sandia National Laboratories. The fuel tubes of both burners are 5 cm in diameter surrounded by air and N₂ coflow for the Yale and Sandia flames respectively. The fuel tube is filled with small glass beads and covered with a honeycomb to provide a flat temperature distribution. The Yale flame was mainly used for fiber aging study. The flame temperature was measured by a S-type thermocouple with a cylindrical junction. Compared to most commercially
available thermocouples without well-defined junction geometry, the cylindrical junction could potentially reduce the error associated with radiation correction. More details and the welding procedure of the thermocouple are available in Ref [8]. The Sandia flame was mainly used for an assessment for the absolute temperature accuracy. The flame temperatures in a 6 mm region at 3 cm height above the burner (HAB) of eight conditions from fuel lean to rich were used as calibration points. The temperatures have been measured by Coherent Anti-Stokes Raman Scattering (CARS) and by Raman/Rayleigh scattering. The Raman measurement determined the concentration of major species, from which the effective Rayleigh cross-section of the mixture was calculated and used for Rayleigh thermometry. On average the CARS measurements were ~ 35 K below adiabatic equilibrium, with overall uncertainties of ± 25 K.

2.2 Thermocouple and Radiation correction

Thermocouple-based calibration that involves a radiation correction is often used as a standard for TFP measurements. In this work, a thermocouple measurement was performed at the same position above the flame where accurate gas temperatures were measured by laser-based techniques. This comparison is useful to establish confidence in thermocouple-based calibration, or to evaluate the uncertainties associated with the radiation correction.

Two S-type thermocouples with 50 µm and 200 µm cylindrical junctions were used to measure the calibration flame temperature. The thermocouple temperatures were measured over 50 samples in ~ 3 minutes; the maximum temperature variation was ~ 20 K for the small thermocouple and ~ 5 K for the larger thermocouple. The temperature variation was mainly due to flame variation and thermocouple voltage readout noise. The average temperature over 50 samples was used for the comparison. The 50 µm thermocouple cannot survive temperatures higher than 2000 K; therefore only three temperatures from this thermocouple are shown in Fig. 1 where the temperature readings of both thermocouples are plotted. The gas phase temperature is derived from a radiation correction procedure by considering convective heating and radiative cooling of the filament in steady state. The gas temperature can be calculated by Eq. (1).

\[
T_g = \frac{\varepsilon \sigma (T_f^4 - T_\infty^4)}{h} + T_f
\]

Eq. (1)

where the \(T_g\), \(T_f\) and \(T_\infty\) are the gas phase temperature, fiber temperature and ambient environment temperature respectively. \(\varepsilon\) is the total emissivity of thermocouple wire and is chosen to be 0.2 [5]. \(h\) is the convective heat transfer coefficient expressed as

\[
h = \frac{Nu \ k_{\text{gas}}}{D_f}
\]

Eq. (2)

where \(Nu\) is the Nusselt number, \(k_{\text{gas}}\) the thermal conductivity, and \(D_f\) the fiber diameter. \(Nu\) is calculated by

\[
Nu = C \times Re^m \times Pr^{0.37}
\]

Eq. (3)

where \(C = 0.908\) and \(m = 0.280\) for 0.09 < \(Re\) < 1 and \(C = 0.902\) and \(m = 0.384\) for 1 < \(Re\) < 35 [9]. \(Re\) and \(Pr\) are Reynolds and Prandtl number respectively. All gas transport properties were
calculated using online software [10] given the Raman measured major species concentration for each equivalence ratio. The temperature readings from the 200 µm and 50 µm thermocouples are plotted as red and green crosses respectively. The derived gas temperatures after radiation correction are shown as red and green asterisks. The gas temperatures measured by CARS are connected by a blue curve with an error bar of ±25 K. Good agreement was achieved between the radiation-corrected thermocouple measured and laser-measured temperatures on the lean side. The results presented in Fig. 1 are a direct evaluation of thermocouple-based gas phase temperature measurement using more accurate and direct laser-based measurement. The same radiation correction procedure is applied to the following TFP measurements.

![Graph showing temperature vs equivalence ratio]

**Fig. 1.** Comparison of TC-derived gas temperatures and laser-measured temperatures.

### 3. Results and Discussion

#### 3.1 Fiber Aging Behavior

The schematic of the setup used to study the aging behavior of SiC fibers is shown in Fig. 2. The SiC fiber was mounted horizontally above a stable flat premixed CH₄/air flame (5 cm in diameter). Tension was applied to the fiber by hanging a small weight (0.5 g) to prevent sagging. The incandescence of the heated SiC fiber was imaged by an 85 mm focal length Canon camera lens into the horizontal slit of a spectrometer (Jarrell-Ash MonoSpec 27) with a 150 groove/mm grating. The f-number of the lens was matched to that of the spectrometer to reduce stray light. The width of the slit is 550 µm, which is wide enough to pass all the fiber incandescence into the spectrometer without clipping the signal. A ground glass diffuser (DG20-1500) was aligned at the focal plane of the spectrometer on which an image of the spectrum was formed. The image was then demagnified and imaged onto an interline CCD camera (Cooke SensiCam with super
VGA sensor) to capture wavelengths from 400 to 700 nm while filling the entire image sensor to maximize the spectral resolution. The wavelength was calibrated by a mercury-vapor lamp. The horizontal axis and vertical axis of the two-dimensional image retained the spatial and spectral information respectively.

Fig. 2. Fiber aging setup.

The aging behavior of three kinds of β-SiC fibers manufactured by Nippon Carbon Co., Ltd. and distributed by COI Ceramics, Inc. was tested. The fibers tested included Hi-Nicalon™, Hi-Nicalon™ Type S and Ceramic Grade (CG) Nicalon™ with nominal diameters of 14 µm, 12 µm and 14 µm respectively. The composition of Si:C:O of the fibers are 62:37:0.5, 69:31:0.2 and 57:32:12 respectively [11]. The typical aging behavior (derived from more than three repeated experiments) for each of the three kinds of fibers is shown in Fig. 3. The spectral signal of a central portion of the investigated fiber is plotted as a function of wavelength in the visible range over ~90 minutes aging time. The aging time was grouped by 30 minutes into three groups to show the start, middle and end period of aging, and they are expressed by red, green and blue curves respectively in Fig. 3. As can be seen, the spectral signals of the first two kinds of fibers were unstable during the aging period. The spectral signal kept dropping until the data acquisition stopped or the fiber was broken in the flame. For the CG Nicalon™ fiber, it became stable after an initial ~15 minutes aging as indicated by the overlap of the curves.

Fig. 3. Typical spectra of three kinds of fibers over 90 minutes aging time (red: 1-30 minutes; green: 31-60 minutes; blue: 61-90 minutes).
In an attempt to find better SiC fibers for industrial application, where the commonly used 15 µm SiC fibers don’t survive in the harsh environment, stronger SiC fibers with larger diameters distributed by Specialty Materials, Inc. [12] were tested. An SCS-6 fiber with 140 µm diameter was tested in the flame. Prior to the test, a high temperature acetylene/oxygen micro torch with a 150 µm orifice (Smith little torch with tip size 2) was used to treat a ~3 mm region in the center of the fiber. The torch was manually tuned to a lean condition where a small blue flame was established. The same flame was used to weld a thermocouple, and the video is available in the supplemental material of Ref [8]. The treating was monitored under a microscope and changes on the fiber surface could be observed. Initially, small bubbles formed on the surface and then disappeared. The occurrence of the observed phenomena was sensitive to the equivalence ratio of the torch flame, and the distance between the torch and fiber. It is believed that the torch removed certain coatings on the fiber. Further investigation of the composition and properties of the fiber are needed to better understand the treating process and hence establish a controlled procedure. The aging behavior of the pre-treated fiber was studied in a CH₄/air premixed flame for one hour and is shown in Fig. 4. The torch-treated central region showed a very small variation of less than ~5% over the aging time, while an adjacent untreated region (~1 mm away from the treated region) showed a variation of up to ~35%. The peak signal of the untreated region decreased from ~3500 at start of the aging to ~2600 at the end of data acquisition. Though it appears to be more stable close to the end of the aging test, the last 20 minutes of both treated and untreated spectral signals are plotted in the right part of Fig. 4 for a better comparison. It is seen that the signals from the treated region are more stable and are different from those of the untreated region.

![Fig. 4. Comparison of aging behavior of torch treated and untreated regions on an SCS-6 fiber.](image-url)
3.2 Intensity-Ratio TFP Technique

For the Intensity-Ratio technique, a narrowband interference filter was used to restrict the measurement in a narrow spectral window. Comparing to wideband filters, using narrowband filters doesn’t require the knowledge of detector spectral response and fiber spectral emissivity since they can be considered as constants. It simplifies the experiment and reduces potential error associated with improper spectral dependency used for the detector response or emissivity model.

An SCS 9-A fiber (75 µm diameter) from Specialty Materials, Inc. [12] was tested in the Sandia calibration flame. A narrowband interference filter centered at 673 nm (FWHM = ~ 10 nm) was used in the test. The flame temperature of 2197 K from laser measurement at equivalence ratio of 1.012 was chosen as the reference point. The fiber temperature at this point was determined to be 1816 K as $T_0$ in Eq. (4) through the inverse radiation correction process discussed in the previous section. Given the narrow spectral region detected, the spectral response and spectral emissivity can be assumed to be constants and be canceled out in calculating the signal ratios at different fiber temperatures.

The ratio of the radiance at different temperatures is calculated as

$$I_R = \frac{\varepsilon I_b(\lambda, T)}{\varepsilon I_b(\lambda, T_0)} = \frac{I_b(\lambda, T)}{I_b(\lambda, T_0)} = \frac{e^{\frac{c_2}{kT_0}} - 1}{e^{\frac{c_2}{kT}} - 1} = \frac{e^{\frac{c_2}{kT_0}}(1 - e^{-\frac{c_2}{k(T_0 - T)}})}{e^{\frac{c_2}{kT}} - 1}$$

where $I_b(\lambda, T)$ is the spectral radiance calculated by Planck’s equation at the central wavelength $\lambda$ of the interference filter and fiber temperature $T$. $T_0$ is the normalization fiber temperature taken as 1816 K in this case. Before the test, the fiber was aged in the flame until the incandescence signal became stable. The overall measurement time is ~ 30 minutes, including the calibration procedure. Within the relatively short measurement time, the fiber spectral emissivity $\varepsilon$ at wavelength $\lambda$ is assumed to be a constant and is canceled out by taking the ratio. The lookup table showing the signal ratio vs. temperature calculated using Eq. (4) is shown on the left in Fig. 5. The red dot on the curve is the reference point. The fiber temperatures at other equivalence ratios were determined from the relative signals and the calculated lookup table. The corresponding measured flame temperatures were obtained after the radiation correction. As seen on the right in Fig. 5, the Intensity-Ratio TFP measured flame temperature is in very good agreement with the laser-measured temperatures.

3.3 Color-Ratio TFP Technique

One-color pyrometry needs an absolute calibration of temperature, and this calibration becomes invalid once the optical setup has been changed. A robust Color-Ratio technique is desired when the calibration is not available or frequent changes in the optical setup cannot be avoided. This can be achieved when the spectral emissivity model (e.g., the greybody assumption) is given and detector/filter spectral response are measured and calibrated. A single-shot ratio-pyrometry technique using a digital single lens reflex camera was developed and the details of the method are available in Ref [6]. In this study, a new camera (Nikon D300s) was used. A calculated blackbody lookup table that correlates color ratio to temperature has been verified using a
blackbody furnace between 1073 K to 1473 K and a tungsten lamp at high temperature as shown in Fig. 6. The SiC fiber is assumed to be a greybody. Therefore the blackbody lookup table was used to infer the fiber temperature.

Fig. 5. Calculated lookup table with one calibration point (left) and comparison of Intensity-Ratio TFP measured temperatures with laser-measured temperatures (right).

Fig. 6. Calculated blackbody lookup tables and independent calibrations with a blackbody furnace and a calibrated tungsten lamp.

Color-Ratio TFP (setup shown in the right part of Fig. 2) was applied to measure the fiber temperature simultaneously with the spectral aging measurements presented in Fig. 4. A color image of the glowing fiber was separated as RGB images. Signal ratios were taken among the
three color signals and used to infer temperature. For the torch-treated SCS-6 fiber, the measured fiber temperatures over the aging period are shown as green curves between 1600 K and 1700 K in Fig. 7. Notice that the central region near 1.5 cm where the fiber was torch treated has a much smaller temperature variation compared to the adjacent untreated region. This again indicates that the treatment help to stabilized the spectral emissivity. The untreated region has a varying spectral emissivity that deviates from greybody behavior, which contributes to the significant variations in the measured temperature. Temperature measurements using 50 µm and 200 µm S-type thermocouples with cylindrical junctions were also performed at discrete points at the same downstream location in the flame as the fiber measurements. The thermocouple readings are shown in Fig. 7 as red and green circles for the 200 µm and 50 µm thermocouples, respectively. The derived gas temperature after radiation correction from the TFP measurement (shown as blue curves) and two thermocouple measurements (shown as red and green asterisks) agree very well over the central treated region.

![Fig. 7. Comparison of fiber and TC measured temperature across the flame.](image)

The Color-Ratio TFP was also applied to the CG NicalonTM fiber simultaneously during the aging test. The measured temperatures under greybody assumption were plotted as a function of aging time in Fig. 8. In the first 15 minutes, an increase from ~ 1875 K to ~ 1970 K in the measured temperature can be observed, which corresponds to the changing spectral signal in the first part of the aging period shown on the right in Fig. 3. After the initial ~ 15 minutes, the spectral signal became relatively unchanged and this results in a much smaller variation (~ 50 K) over 60 minutes on the Color-Ratio TFP measured temperature. The reason for such variation and decreasing measured temperature can be found in the aging spectral signals in Fig. 3, where the blue curves shifted towards longer wavelength relative to the green curves. Due to fiber
aging, the spectral emissivity may change. Therefore, caution must be taken whenever making measurements based on a greybody assumption as it may not hold under all circumstances.

Fig. 8. Aging effect of CG NicalonTM fiber on measured temperature using color ratio TFP.

4. Conclusion

Recent developments on thin-filament pyrometry were discussed. The radiation correction procedure was evaluated by performing thermocouple measurements in a calibration flame with well-calibrated temperatures; the results indicate that the accuracy of radiation correction is very good when the hot gas transport properties are properly calculated. The aging behaviors of several kinds of SiC fibers distributed by two companies have been studied. It is shown that certain fibers are more resistant to aging effects, and pre-treatment using a high temperature torch could help stabilize the spectral emissivity of certain fibers. Intensity-Ratio and Color-Ratio techniques were tested, and their advantages and limitations were discussed.

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