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Intensity-ratio and color-ratio thin-filament pyrometry: Uncertainties and accuracy

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A B S T R A C T

Thin-filament pyrometry (TFP) has been proven to be a useful approach to measure flame temperature. It involves placing a thin filament (SiC fiber typically) in hot gases and inferring the gas temperature from the radiance of the glowing filament. 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 physical backgrounds of two TFP approaches, namely the intensity-ratio approach and the color-ratio approach, are reviewed along with the required radiation correction. Several sources of error, such as the fiber aging behavior (fiber properties varying with time), spectral emissivity and calibration, have been investigated. Measurements in well-calibrated laminar flames show very good agreement with reference temperatures based on N_2 coherent anti-Stokes Raman scattering (CARS) measurements. Uncertainty analysis has also been performed and provides insights on improving TFP measurement accuracy.

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 filament. In the most common usage, TFP involves placing a thin filament, typically 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. Compared to laser-based techniques, the TFP approach has the advantages of low-cost and simplicity, and it is useful in situations in which laser-based techniques are difficult to apply (e.g., in high pressure environments where laser-based techniques suffer beam steering problems and spectroscopic issues). Compared to thermocouple measurements, SiC fibers were found to have better resistance to oxidation and catalytic effects [1]. The higher melting temperature (~2673 K) [2] of SiC enables the fibers to survive in most flames. The TFP approach also offers line measurements as opposed to point measurements by thermocouple.

The TFP approach for measuring temperature has been investigated and applied in a number of studies over the last decades. Vilimpoc et al. [2] first demonstrated the feasibility of measuring temperature using the TFP intensity-ratio approach with a 15 μm SiC fiber, and they estimated the temporal response to be ~1.5 ms and the spatial resolution along the fiber (based on thermal conductivity) to be ~120 μm. Bédat et al. [3] performed TFP measurements in a weakly turbulent flame at a rate of 2500 Hz in the infrared and extended the lower temperature limit to 550 K. In their experiments, fiber greybody behavior was assumed. Temperature was measured from a calibrated spectral signal using a tungsten filament and a blackbody light source. Pitts applied TFP in flickering laminar diffusion flames [4], and also investigated the effects of finite time response and soot deposition [5]. The intensity-ratio approach was employed for temperature measurements in their studies with temperature calibrated in a steady calibration flame. Blevins et al. [6] found TFP is more appropriate than thermocouple thermometry for measuring gas temperatures in partially premixed flames because TFP avoids the surface-ignition problems of a thermocouple in the rich unburned fuel/air mixture. Ravikrishna and Laurendeau [7] performed intensity-ratio TFP in counterflow diffusion flames and used a flat Hencken flame for temperature calibration. Struk et al. [1] performed TFP measurements in a steady diffusion flame using a spectrometer based on the greybody assumption, and compared the results with thermocouple measurements. The temperature uncertainty was shown to be ±38 K. Maun et al. [8] performed TFP measurements in a steady diffusion flame with temperature calibration performed with a butt-welded type B thermocouple. The derived gas temperature

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uncertainty was estimated to be ±60 K. Santa et al. [9] performed TFP in gaseous spherical diffusion flames in microgravity. Blunck et al. [10] applied the TFP intensity-ratio approach in unsteady hydrogen flames with temperature calibration performed in a McKenna burner. The fiber temperature uncertainty was estimated to be 6% at 1000 K and 10% at 2400 K. Kuhn et al. [11] developed a color-ratio approach based on a greybody assumption and utilized a digital color camera for single-shot measurements. Dambach et al. [12] applied TFP to estimate the temperature in the near-flame field resulting from hypergolic ignition. They performed the same temperature calibration as in Ref. [10]. Fiber temperature uncertainty was estimated to be 5% at 1000 K and 8% at 1500 K. Some studies [1,8] evaluated TFP accuracy by comparison to thermocouple measurements, and others [5] compared with Rayleigh scattering measurements.

Despite numerous studies and applications of TFP, there are still open questions and implementation challenges. All TFP approaches are based either on a temperature calibration or a greybody assumption. However the accuracy of thermocouple calibration, or more generally thermocouple temperature measurement, is affected by the thermocouple junction geometry and radiation correction. In this paper, an effective method for manufacturing thermocouples with a cylindrical junction has been used to reduce thermocouple measurement uncertainty. The spectral emissivity of the SiC fiber has also been directly measured in the visible range and the greybody assumption is verified for certain kinds of SiC fibers. Fiber aging behavior, which causes the fiber spectral emissivity to change over time, was found to affect the measurement accuracy and has not been investigated in detail in previous studies. In this work, fiber aging behaviors were studied for four kinds of SiC fibers, and the results can be used to effectively reduce the measurement uncertainty. Previous TFP measurements were normally assessed by thermocouple measurements that suffer from uncertainties associated with radiation correction. In this study, well-calibrated flames available at Sandia National Laboratories were used as accurate temperature references to directly assess the accuracy of thermocouple-based and TFP-based temperature measurements. In order to facilitate better usage of TFP approaches and address their uncertainties, the paper reviews and discusses current TFP approaches, identifies and investigates their associated error sources, and directly assesses different TFP approaches against N_2 CARS measurements in well-calibrated flames. Finally, results of uncertainty analysis are presented along with suggestions on ways to reduce measurement uncertainty.

2. Experimental approaches

Thin-filament pyrometry does not measure gas phase temperature directly. Instead, fiber surface temperature is determined in the first step, followed by a radiation correction to calculate the difference between the gas and fiber temperature. This second step is accomplished by solving the energy conservation equation on a segment of the fiber. For determination of the fiber temperature, two approaches, based on intensity-ratio and color-ratio, will be discussed. This section focuses on reviewing the physical background of the experimental approaches.

2.1. Fiber temperature determination

2.1.1. Intensity-ratio approach

The intensity-ratio approach has been widely used in the past decades since the first use of TFP [2]. The signal of the glowing fiber is correlated to temperature using Planck's law. The intensity ratio, I_R, is defined as the ratio of signal at a measuring temperature over the signal at a reference temperature. The ratio can be numerically determined by integrating Planck's equation over the spectral response of the detection system [1,2,4]. Constant emissivity over the spectral window (greybody behavior) is normally assumed and knowledge of the detector's spectral response is needed if wideband detection is employed. In the current study, narrowband interference filters were used to restrict the measurement to a narrow spectral window. With narrowband filters, knowledge of the detector spectral response and fiber spectral emissivity are not required, since both can be considered as constants. This simplifies the experiment and reduces potential error associated with uncertainties in the detector response or emissivity model. The intensity ratio, I_R, at different temperatures can be calculated as

$$I_R = \frac{\varepsilon I_b(\lambda, T)}{\varepsilon I_b(\lambda, T_0)} = \frac{e^{\frac{hc}{\lambda k T_0}} - 1}{e^{\frac{hc}{\lambda k T}} - 1} \approx e^{\frac{hc}{\lambda k}\left(\frac{1}{T_0} - \frac{1}{T}\right)} \quad (1)$$

where $I_b(\lambda, T)$ is the spectral radiance calculated by Planck's equation at the central wavelength λ of the interference filter and fiber temperature T. h, c, and k are the Planck constant, the speed of light, and the Boltzmann constant, respectively. T_0 is the reference fiber temperature. Assuming the aging effect is small within a relatively short measurement time of one hour, the fiber spectral emissivity ε at wavelength λ is assumed to be a constant over the spectral region and is canceled out by taking the ratio. A lookup table correlating the signal ratio and temperature can be calculated using Eq. (1) and is shown in Fig. 1. The red circle on the curve is the reference point with $I_R = 1$ and $T = T_0$. Other fiber temperatures can be determined from the relative signals by applying the calculated lookup table. The reference temperature T_0 is normally obtained through a calibration procedure that associates a known fiber temperature with its measured signal to quantify the optical throughput of the setup. It should be noted that such calibration is setup specific; once the setup is changed, a new calibration must be performed. The accuracy of the measurement is dependent on the accuracy of calibration (determination of T_0). In the ideal case, the calibration should be performed at a well-characterized flame condition where the gas temperature, velocity and species concentrations are known. These quantities are used in conjunction with a radiation loss calculation to determine T_0. Any uncertainties associated with the gas properties will adversely affect the accuracy of T_0. In the less ideal and more common case, the flame temperature is unknown and a thermocouple (along with a separate radiation correction) is used to infer the flame temperature. The accuracy of the thermocouple measurement and radiation correction as well as the

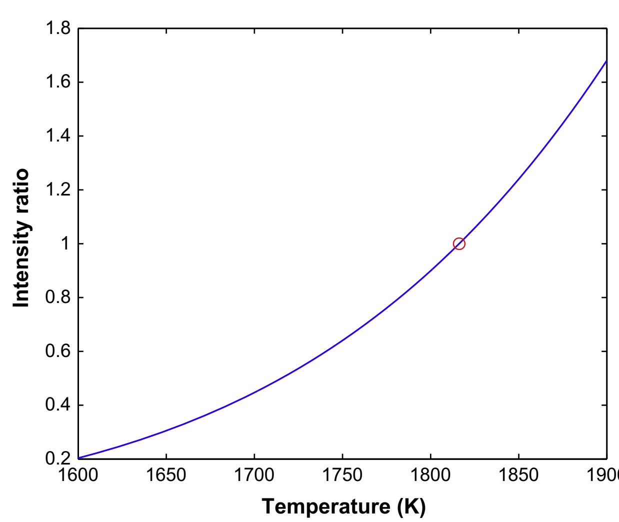

Fig. 1. Calculated lookup table with one calibration point at T_0 = 1820 K.