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An inexpensive high-temperature optical fiber thermometer

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ABSTRACT

An optical fiber thermometer consists of an optical fiber whose tip is coated with a highly conductive, opaque material. When heated, this sensing tip becomes an isothermal cavity that emits like a blackbody. This emission is used to predict the sensing tip temperature. In this work, analytical and experimental research has been conducted to further advance the development of optical fiber thermometry. An inexpensive optical fiber thermometer is developed by applying a thin coating of a high-temperature cement onto the tip of a silica optical fiber. An FTIR spectrometer is used to detect the spectral radiance exiting the fiber. A rigorous mathematical model of the irradiation incident on the detection system is developed. The optical fiber thermometer is calibrated using a blackbody radiator and inverse methods are used to predict the sensing tip temperature when exposed to various heat sources.

1. Introduction

An optical fiber thermometer (OFT) consists of an optical fiber whose tip is coated with a highly conductive, opaque material. When heated, this sensing tip becomes an isothermal cavity that emits like a blackbody. The sensing tip temperature can be estimated based on measurements of the spectral intensity exiting the distal end of the fiber. Some advantages of OFTs include long-term stability, wide dynamic range, high sensitivity, fast response, the ability to withstand harsh environments, and imperviousness to electromagnetic interference [1]. These advantages make OFTs an attractive alternative to thermocouples or other temperature sensors in oxy-coal combustion or other harsh environments as well as in high irradiation conditions such as those found in solar thermal applications [2].

The concept of the optical fiber thermometer was initially proposed in 1977 [3] and successfully proved in 1982 [4]. Dils [4] used a single crystal sapphire fiber with an iridium cavity sputtered on the tip to measure temperatures from 600 to 2000 °C. Absorption and emission by the fiber were neglected and error due to the temperature difference between the sensing tip and calibration source was not addressed. Other experimental and analytical studies have been performed in an attempt to advance the technology [5–7]. Cheung [5] used a similar OFT to that developed in [4] to measure exhaust gas temperatures in gas turbine engines. He accounted for the temperature difference between the OFT sensing tip and the exhaust gases due to convection and radiation. Jones and Barker [6,7] accounted for absorption and emission by the optical fiber and used inverse methods to predict the sensing tip temperature.

All OFTs developed up to this point have utilized sapphire optical fibers because of the high melting temperature of sapphire (2050 °C). Single crystal sapphire fibers are significantly more expensive than traditional silica optical fibers. The sputtering process used to deposit the metallic sensing tip onto the fiber is also expensive and is limited by the size of the sputtering chamber, which is typically small and cannot accommodate long optical fibers. The objective of this work is to investigate the use of inexpensive materials in the construction of an OFT by applying a thin coating of a mixture of a high-temperature cement [8] and nickel-oxide onto the tip of a silica optical fiber. The cement has a maximum service temperature of 1426 °C. A Fourier-transform infrared (FTIR) spectrometer is used to detect the spectral radiance exiting the fiber. A rigorous mathematical model of the irradiation incident on the detection system is developed [9]. The OFT is calibrated using a blackbody radiator and inverse radiative heat transfer methods are used to predict the sensing tip temperature when the OFT is inserted into various heat sources.

2. Experimental setup

The experimental setup used in this work is shown in Fig. 1. A sensing tip cavity was created by mixing 1 g of Sauereisen Electrotemp Cement No. 8 [8] with 0.1 g of green nickel oxide powder and five drops of distilled water. The core of an optical fiber was

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Nomenclature

D	fiber diameter (m)
G	irradiation (W/m^2 Hz)
$\bar{h}$	convection coefficient (W/m^2 K)
I	radiative intensity (W/m^2 Hz)
IRF	instrument response function
k	fiber thermal conductivity (W/m K)
L	fiber length (m)
m	roots of auxiliary equation
M	detector signal
P	path attenuation
q	heat flux (W/m^2)
Q	calibration coefficient
R	calibration coefficient
s	direction of radiant energy
S	calibration coefficient
T	temperature (K)
z	axial coordinate

Greek

ε	emittance
θ	polar angle (rad)
κ	absorption coefficient (m^{-1})
μ	cosine of intensity direction
ν	frequency (Hz)
τ	transmittance
σ	Stefan-Boltzmann constant (W/m^2 K^4)
Ω	solid angle (sr)

Subscripts

b	blackbody
C	cavity
D	detector
f	fiber
i	critical angle
L	at right boundary
R	radiative
p	particular solution
sur	surroundings
ν	spectral dependence
∞	ambient

Superscripts

$+$	forward direction
$-$	backward direction

dipped into the mixture and the hardened cement formed the cavity sensing tip. The nickel oxide was added to increase the opacity and the thermal conductivity of the coating. Nickel oxide was chosen as the opacifier for several reasons. It has IR absorption bands that make the cavity opaque while still remaining relatively small [10]. In addition, at elevated temperatures in somewhat reducing atmospheres, nickel will be reduced to nickel metal yielding a cermet. Fine-grained cermets tend to be black over a large range of frequencies in the visible and near IR because the free motion of electrons in the tiny metallic particles is interrupted by collisions with the particle surfaces [11,12]. Indeed, the tips turned black after placement in a high-temperature environment. The coating length was at least ten times the diameter of the fiber core resulting in an effective cavity emittance near unity [4,13]. The coating was applied to an optical fiber two meters in length with a 400 µm diameter pure fused silica core, a 440 µm diameter fluorine doped fused silica cladding, and a 470 µm diameter polyamide jacket. The jacket and cladding were removed from the tip of the fiber so that the coating could be applied directly to the fiber core. The numerical aperture of the fiber was 0.22. The optical fiber was connected by an SMA connector to a reflective collimator [14] which directs the radiant energy from the fiber into an external access port on an FTIR spectrometer. The FTIR spectrometer outputs a spectral signal. A mercury cadmium telluride (MCT) detector was used in this work because of its high sensitivity.

3. Mathematical model

In order to infer the OFT sensing tip temperature from measurements obtained by the FTIR spectrometer, a relationship between the cavity temperature and the detector signal is required. Development of this relationship requires that the spectral irradiation incident on the detector be modeled. Assuming that the collimated radiation from the reflective collimator into the FTIR spectrometer is the only source of radiative energy and that the solid angle subtended by the collimator when viewed from the detector, $\Delta\Omega_{D\rightarrow C}$, is small, the irradiation incident on the detector is given by

$$G_{\nu,D}=I_{\nu,D}\ \Delta\Omega_{D\rightarrow C} \tag{1}$$

The spectral radiative intensity incident on the detector, $I_{\nu,D}$, is directly proportional to the spectral intensity exiting the uncoated end of the optical fiber,

$$I_{\nu,D}=P_\nu I_{\nu,f} \tag{2}$$

where P_ν represents attenuation along the optical path due to reflections and transmission through components in the collimator and the FTIR spectrometer. An equation representing the spectral intensity exiting the fiber, $I_{\nu,f}$, can be obtained by solving the Radiative Transfer Equation (RTE) in the fiber. Fig. 2 shows a schematic of the coordinate system used to determine $I_{\nu,f}$.

The fiber is assumed to be an emitting, absorbing, non-scattering medium [15]. In order to account for the multiple reflections of a beam within an optical fiber, it is convenient to approximate the intensity propagating in the s direction at a distance z along the axis of the fiber by the intensity of a ray emitted by an image of the cavity that traveled a distance z_s into the medium, as illustrated in Fig. 2 [16]. Therefore, the optical fiber can be treated as a one-dimensional medium of length L.

An integrating factor is used to solve the RTE for the spectral intensity in the positive direction, I_ν^+, for which $0 < \theta < \pi/2$, and for that in the negative direction, I_ν^-, for which $\pi/2 < \theta < \pi$. The intensity at $z = 0$ is the intensity coming from the sensing tip cavity. The intensity at $z = L$ is that which is reflected from the interface between the uncoated end of the fiber and the air. The details of this solution can be found in [9,13]. The spectral radiative intensity exiting the fiber is equal to the portion of the intensity at $z = L$ which is transmitted through the end of the fiber and is given in the following equation.