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Thermal Radiative Properties and Temperature Measurement from Turbine Coatings[1]

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Recent studies have displayed the spectral radiative properties of ceramic thermal barrier coatings which are finding applications in high performance turbine engines. As a function of temperature, a region in the long wavelength infrared spectrum exhibits properties which will minimize the classical errors associated with temperature measurement by radiometric detection. Hollow sapphire waveguides transmit the portion of the long wavelength infrared spectrum which is optimum for radiometric temperature measurement from these materials, while the physical properties of the sapphire can withstand the combustion conditions within the engine. A prototype long wavelength infrared radiation thermometer was constructed to obtain surface temperature measurements from coated turbine blades subjected to high temperature combustion conditions.

KEY WORDS: ceramics; infrared radiation; radiation thermometer; thermal barrier coatings; thermal radiative properties; turbine engines.

1. INTRODUCTION

Advanced thermal coating materials are being developed for use in the combustor section of high performance turbine engines [1]. Such coatings can provide a thermal barrier between metal components and hot gases, allowing higher operational gas temperatures for improved turbine performance without component degradation. To optimize coating use, accurate surface temperature measurements are required to understand their response to changes in the combustion environment.

Radiation thermometry combined with fiber optics provides powerful sensors for determining surface temperatures in otherwise inaccessible

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locations [2]. However, typical instruments operate in either the short-wavelength infrared (SWIR) or the visible portion of the electromagnetic spectrum to take advantage of the transmissive properties of widely used solid silica and sapphire fibers. Our laboratory [3] and others [4] have shown that ceramics which show promise as thermal barrier coatings (TBCs) in turbine engine applications have low, variable emissivities at short wavelengths, which lead to serious measurement inaccuracies. Combustion reflection has been shown to contribute up to 70% of the measured short-wavelength signal [5] when used on TBCs where emissivity is low. Temperature measurements would be more accurate in the long-wavelength infrared (LWIR), where ceramic TBC emissivities are typically high and stable (i.e., near-blackbody) [3,4].

Hollow sapphire waveguides have been employed for LWIR laser power delivery [6] and in LWIR remote spectroscopy [7]. Radiation is propagated in the air core of a hollow waveguide by total internal reflection and, due to optical properties, is limited in the case of sapphire to the delivery of LWIR. The spectral band is well suited to the region of near-blackbody radiative characteristics of TBCs, while the high melting point (2053°C) and durability of sapphire allows waveguides to be placed near and in combustion environments.

This paper presents a prototype LWIR radiation thermometer for temperature measurement of TBCs used in high-performance turbine engines. The sensor probe consists of a hollow sapphire waveguide to deliver the LWIR signal of the TBC to a detector. Temperature measurements from TBCs on substrates subjected to high-temperature combustion conditions were obtained.

2. MEASUREMENTS

2.1. Prototype LWIR Radiation Thermometer

Figure 1 is a schematic diagram of the hollow sapphire waveguide radiation thermometer. The durable hollow sapphire waveguide (25 cm long $\times$ 1450 μm in OD $\times$ 1070 μm in ID) was coupled to a hollow glass extension waveguide (2 m long). During measurements, the target LWIR radiance would enter the hollow sapphire waveguide and propagate through its length and through the length of the hollow glass waveguide, whence it would be launched through the remaining components of the optical system. The optical components include (a) a mechanical chopper to modulate the LWIR beam, (b) an aperture to limit the optical throughput of the system to the target signal, (c) a pair of planoconvex lenses to bring the LWIR beam to a focus on the detector, (d) a LWIR narrow-bandpass filter to limit further the spectral region passed by the hollow waveguides, and (e) a LWIR detector that is sensitive to modulated radiance. The LWIR narrow-bandpass filter exhibits a transmittance of 80% at the bandpass between 10 and 11.4 μm (1000 to 877 cm^{-1}). The filter is the most spectrally limiting component of the optical system and serves (a) to allow LWIR radiance to pass that corresponds to the spectral region of near-blackbody emissivity of the TBCs studied; (b) to eliminate spurious SWIR energy that can propagate within the sapphire and glass walls of the hollow waveguides; and (c) to eliminate significant LWIR interference from the large emission bands of hot, high-pressure H_2O vapor and CO_2 gas generated in turbine combustors. Gas spectra were generated from the HITRAN spectroscopic database [8] at temperatures and pressures in the range expected in advanced turbines [5] to confirm the third service of the filter.

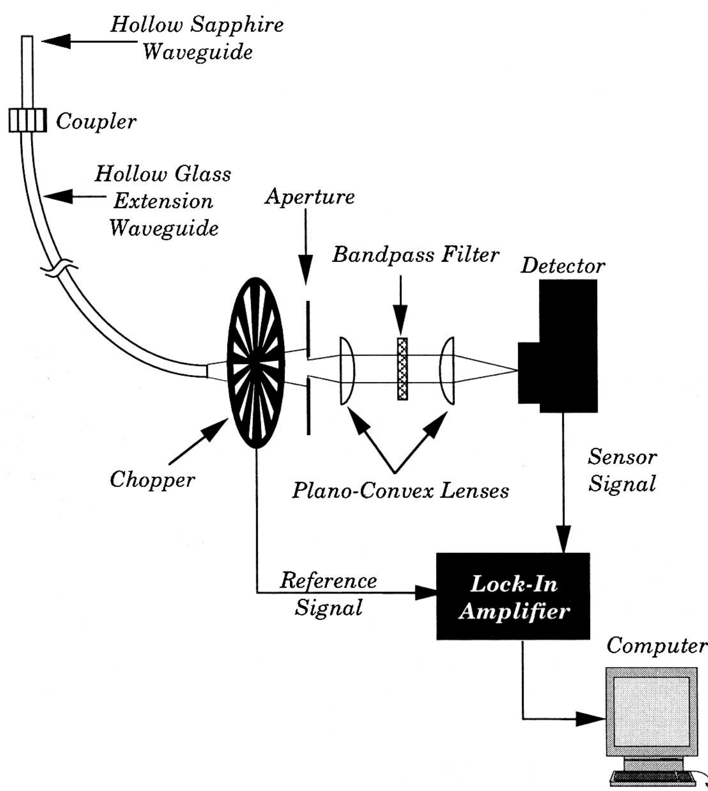

Fig. 1. Schematic of the prototype LWIR radiation thermometer.

The sensor was calibrated by placing a temperature controlled near-blackbody surface in view of the hollow sapphire waveguide. The calibration curve (response function) generated from 100 to 880°C agreed in shape with the curve generated from the theoretical Planck function radiant intensity at the center wavelength of the bandpass filter for the same temperature range. The agreement in shape for the low temperature region indicated that the detector was linear with intensity. Due to the lack of a high temperature blackbody source, the theoretical Planck curve was used to extend the sensor calibration to 1600°C. Analysis of calibration data at 820°C indicated the instrument stability to be within ± 2°C (± 0.25%). Slight temperature fluctuations in the calibration target may have been a contributing factor.

2.2. Specimens

Two specimens with proprietary yttria-stabilized zirconia TBCs were provided by United Technologies Pratt & Whitney. The spectral emissivities were measured with our Fourier transform infrared (FT-IR) benchtop emissometer [9] and were high (0.97) as a function of wavelength and stable as a function of temperature in the response region of the LWIR thermometer.

2.3. Procedure

The first measurements of TBC surface temperature by the LWIR thermometer were verified by measurements with an FT-IR emission spectrometer system [10]. Both instruments were arranged to measure simultaneously the temperature from the same 3 mm diameter spot on the TBC test blade surface. To heat the test blade, a propane torch flame was applied to the back surface. As shown in Fig. 2, agreement was observed between the two instruments for both the shape and the amplitude of the traces. The LWIR thermometer was measuring at a rate of 5 data points per s, while the FT-IR spectrometer was significantly slower, at 1 data point per 6 s. The FT-IR signal averaged several "scans" during the 6 s, so short-term temperature changes are not as well resolved by the FT-IR method.

Similar temperature trace comparisons were made between the LWIR thermometer and the fine wire thermocouples bonded adjacent to the 3-mm-diameter spot. Thermocouples provided temperature traces similar in shape to those of the radiation thermometer, but generally 20 to 100°C lower due to expected deficiencies related to surface attachment and contact.

The prototype LWIR thermometer was also demonstrated for measurements at the atmospheric pressure combustion rig located at Pratt &

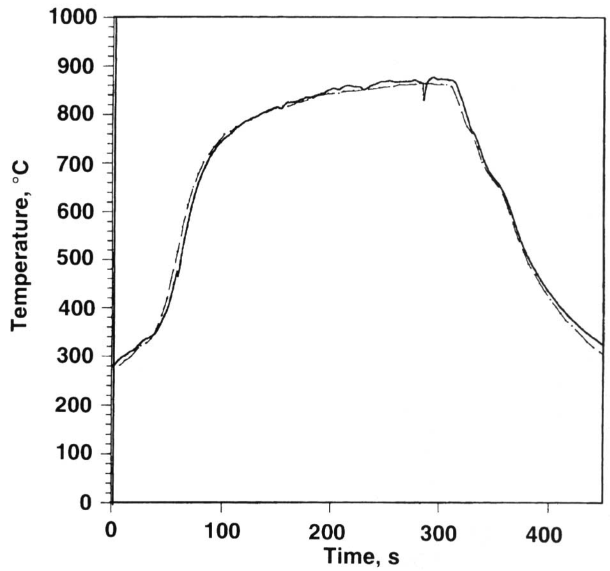

Fig. 2. LWIR radiation thermometer measurements (solid line) vs. FT-IR spectrometer measurements (dashed line). The target was a test turbine blade with TBC.

Whitney in East Hartford, Connecticut. The Becon Burner is designed to simulate the combustion processes that occur in large-scale engines. The rig is equipped with a 2-in.-diameter exhaust nozzle, and gas temperatures in the exhaust plume can reach 1500°C (2732°F). Figure 3 presents a photograph of the high-temperature, high-velocity exhaust of the Becon Burner with a test sample and the LWIR sensor mounted in position. Two configurations of the LWIR thermometer were utilized: (a) with the bare hollow sapphire waveguide exposed to the high-temperature exhaust plume and (b) with a water-cooled stainless-steel jacket around the sapphire waveguide in the exhaust plume. For both cases, successful temperature measurements were obtained with the receiving end of the sensor brought to 1 cm from the target surface.

Figure 4 presents two temperature traces obtained from a target spot 1.75 cm behind the leading edge of the test blade. In Fig. 4a, where a nominally constant burner condition was used, the blade surface temperature was maintained near 1220°C (2228°F). The temperature fluctuations (± 10°C or ± 18°F) were expected due to the "flame flicker" of the exhaust gas stream. No alternative temperature sensing methods were available to corroborate the temperature measurements obtained for the test blade. However, the leading edge of the blade lost its TBC and the

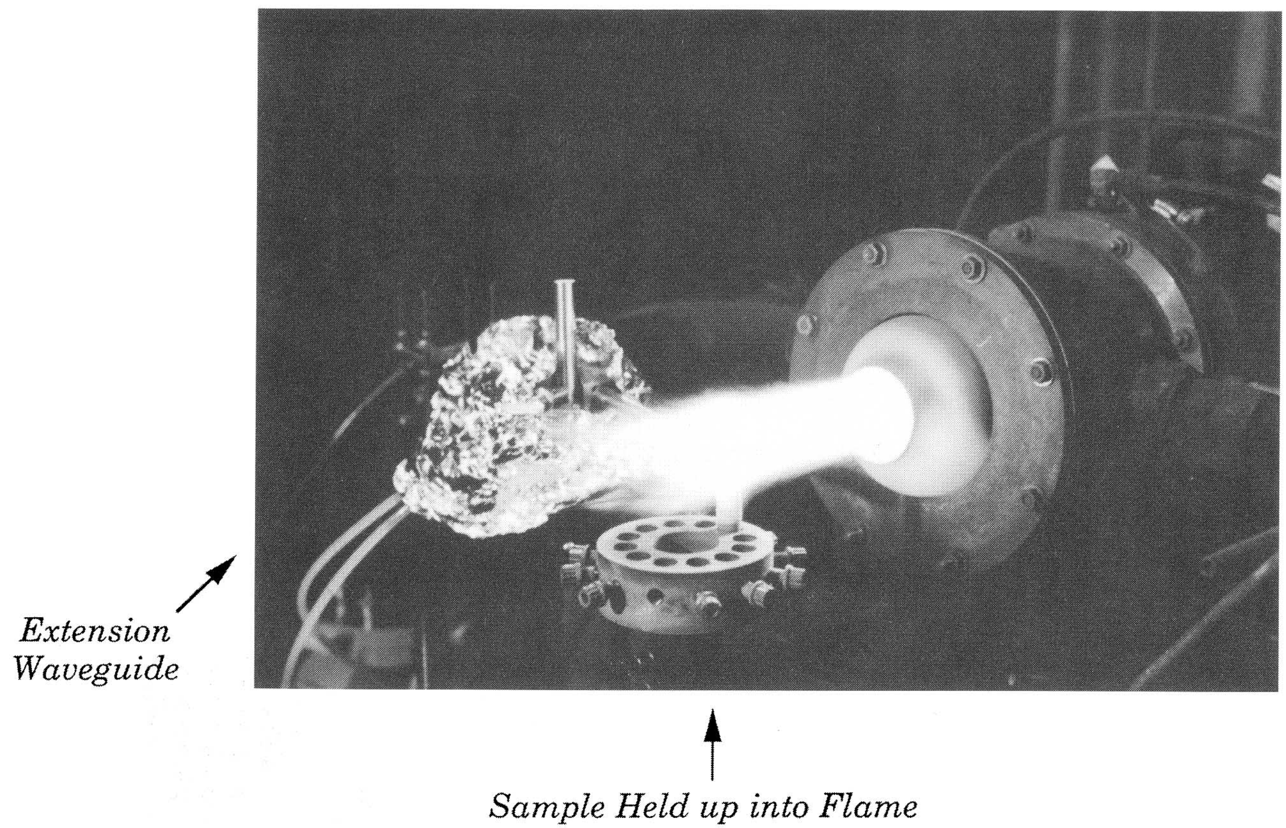

Fig. 3. Photograph of the Becon Burner. A sample is supported in the exhaust plume, and the LWIR sensor is inserted from the far side to 1 cm from the target. The extension waveguide carries the target signal to the remote detector.

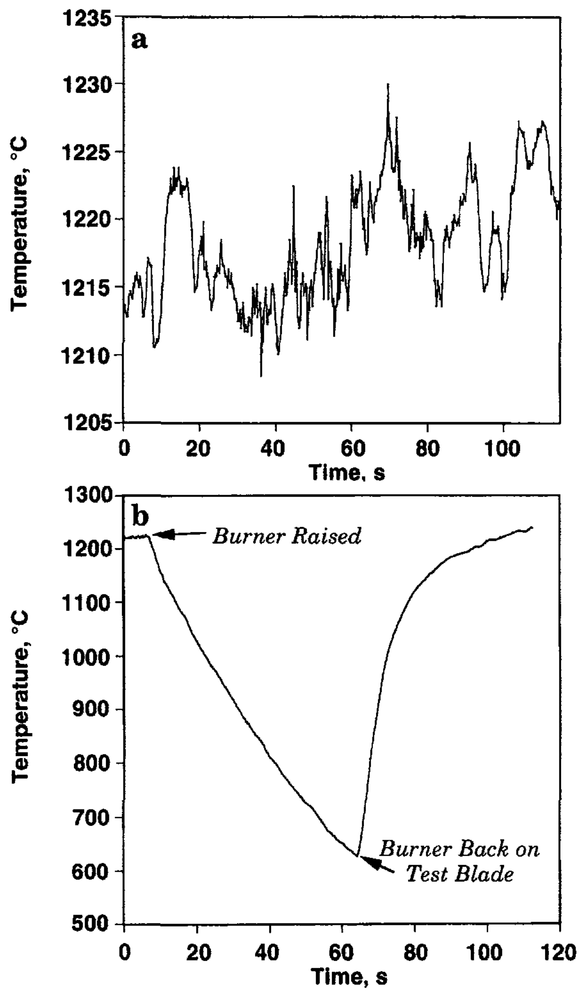

Fig. 4. LWIR thermometer temperature measurements from a turbine blade with TBC in the Becon Burner flame. (a) Constant burner setting; (b) trace obtained when the burner flame was purposely raised above the blade, then repositioned on the blade. Note the difference in temperature scales.

nickel alloy melted during the test. The melting point of this alloy is 1338°C (2440°F), so the readings obtained behind the leading edge were not unreasonable.

In Fig. 4b, the burner was quickly raised off the test blade (in less than 0.5 s) early in the trace, and the sensor recorded the blade cooling. Then the burner was repositioned on the test blade (in less than 0.5 s), and the temperature rise was recorded. Important to note from this experiment is that there was no significant evidence of extraneous radiance contributing to the temperature measurement. If radiance originating from, for example, the glowing burner nozzle or from inside the burner was reflecting into the field of view of the sensor, a more abrupt change in signal would occur when drastically shifting the burner position [11].

3. CONCLUSIONS

The LWIR radiation thermometer is well suited to application to advanced high-performance turbine engines since (a) the operational wavelengths are optimized for the radiative properties of TBCs and (b) the sapphire probe is optimized to survive the high-temperature/pressure environment. HITRAN-generated gas spectra as well as measurements of the Becon Burner exhaust in the absence of a test blade indicated minimal interference from combustion products. Temperature measurements in our laboratory were confirmed by the FT-IR optical method and thermocouples. The radiation thermometer survived the combustion conditions of Pratt & Whitney's Becon Burner facility and recorded target temperatures. Development of a fast response system to target first stage rotor blades is the next step.

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REFERENCES

1. H. A. Webb and W. P. Parks, presentation at Air and Waste Management Association Annual Meeting, Cincinnati, OH (June 19–24, 1994), Conf. 940632-21.
2. R. Vanzetti and A. C. Traub, in *Theory and Practice of Radiation Thermometry*, D. P. DeWitt and G. P. Nutter, eds. (Wiley, New York, 1988), Chap. 11.
3. A. S. Bonanno, M. A. Serio, and J. R. Markham, in *Proceedings of the NASA Remote Temperature Sensing Workshop, NASA Lewis Research Center*, NASA Conf. Publ. 10167 (Oct. 27–28, 1994).

4. W. H. Atkinson and M. E. Cyr, in *Proceedings of the 3rd Annual HITEMP Review*, NASA Conf. Publ., 10051 (1990).
5. E. Suarez, in *Proceedings of the NASA Remote Temperature Sensing Workshop, NASA Lewis Research Center*, NASA Conf. Publ. 10167 (Oct. 27–28, 1994).
6. J. A. Harrington and C. Gregory, *Opt. Lett.* **15**:541 (1990).
7. S. J. Saggese, J. A. Harrington, and G. H. Sigel, Jr., *Opt. Lett.* **16**:27 (1991).
8. L. S. Rothman, R. Gamache, R. Tipping, C. Rinsland, M. Smith, D. Benner, V. Devi Malathy, J. M. Flaud, C. Camry-Reyret, A. Perrin, A. Goldman, S. Massie, L. Brown, and R. J. Toth, *Quant. Spectrosc. Radiat. Transfer* **48**:469 (1992).
9. J. R. Markham, K. Kinsella, R. M. Carangelo, C .R. Brouillette, M. D. Carangelo, P. E. Best, and P. R. Solomon, *Rev. Sci. Instrum.* **64**:2515 (1993).
10. P. W. Morrison, Jr., P. R. Solomon, M. A. Serio, R. M. Carangelo, and J. R. Markham, *Sensors* **8**(12):32 (1991); **8**(13):26 (1991).
11. J. R. Markham, W. W. Smith, J. R. Haigis, M. D. Carangelo, J. E. Cosgrove, K. Kinsella, P. R. Solomon, P. E. Best, A. Lewandowski, C. E. Bingham, and J. R. Pitts, *ASME J. Solar Energy Eng.* **118**:20 (1996).