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Application of multispectral radiation thermometry in temperature measurement of thermal barrier coated surfaces

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ABSTRACT

Ceramics coatings are materials widely used in gas turbines to provide thermal shielding of superalloy materials against excessive turbine temperatures. However, measurement of their surface temperatures using conventional radiation thermometers, more so in the presence of high ambient radiation and low emissivity is quite challenging. A multispectral method employing curve fitting technique to measure the temperature of such targets in the range of 800–1200 K and ambient temperature of 1273 K is implemented in this paper through simulation. Several simulated experiments were carried out to identify emissivity models best suited for multispectral radiation thermometry applicable to ceramic coatings. The best emissivity model applicable to yttria-stabilized zirconia of coating thickness of 330 μm in the wavelength range of 3.5–3.9 μm was found to predict temperature with an error of less than 1.5% in the presence and absence of background noise.

1. Introduction

Radiation thermometers commonly known as pyrometers are instruments used to measure the temperature of surfaces non-intrusively. They include single wavelength, dual wavelength and multispectral pyrometers. These instruments infer temperature from infrared radiation emitted by the target surface. They can measure the temperature of high speed rotating parts such as those of turbine blades without interfering with the smooth flow of gas and other parameters of the gas turbine compared to contact type thermometers. In addition, they have fast response and their measurement is free from electromagnetic interference from the environment [1,2]. Their operating principles however require the knowledge of spectral emissivity of the material under investigation. Materials with high emissivity can be measured by these instruments with high degree of accuracy. However, temperature measurements of surfaces with low emissivity subject the measurements to errors due to reflection of environmental radiation by the target into the detectors of radiation thermometers. High ambient radiation can cause radiation thermometers to be very unreliable due to false overestimated temperatures.

With the aim of boosting efficiency of modern gas turbines, the solution has been to increase turbine inlet temperature without compromising the lifespan of the components. This calls for use of coating materials to protect the superalloy against turbine's high operating temperature that can go beyond their melting point. Yttria-stabilized zirconia (YSZ) is one of the most widely used and studied thermal barrier coating material (TBC) for this purpose due to it best performance in high temperature applications [3,4] and is widely used as a coating in turbine blades and vanes. It is quite unfortunate that despite its good thermal shielding properties, it exhibits low emissivity at short wavelength which also varies significantly with wavelength and coating thickness, though minimally with temperature [1,5–9]. This dynamic behavior of spectral emissivity poses a great challenge in the use of radiation thermometers. Multispectral radiation thermometry (MRT) can be used to address the above challenges and has widely been used in many applications [10–25] to measure temperature, mainly targeting metallic surfaces. Effectiveness of this technique is greatly dependent on emissivity model used. Currently, there are numerous emissivity models but no universally accepted model applicable to all types of surfaces has been found. A robust emissivity model well suited for metallic surfaces may not be appropriate for use in ceramic materials. Interested with ceramic materials, specifically YSZ, we hereby present a multispectral technique for measuring temperature of their surfaces. Several emissivity models have been tested for possibility of using them in MRT technique. The proposed MRT technique involves fitting of total spectral radiance from the target to multispectral model to yield

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the target temperature and coefficient of emissivity parameters. Non- linear least square technique employing Levenberg–Marquardt [26,27] algorithm is used in the fitting process.

2. Thermal radiation measurement principles

All bodies whose temperature is greater than absolute zero emits thermal radiation that can be detected by radiation thermometers. Radiation emitted by black bodies obeys the famous Plank law given as

$$B_{\lambda,b}(\lambda,T) = C_1\lambda^{-5}\left[\exp\left(\frac{C_2}{\lambda T}\right)-1\right]^{-1} \tag{1}$$

where $B_{\lambda,b}(\lambda,T)$, measured in W/m^2 sr µm is the radiance emitted by the surface at wavelength λ and absolute surface temperature T. C_1 is the first radiation constant with a value of 1.191042×10^8 W/m^2 sr µm^{-4} while C_2 is the second radiation constant with a value of 14,388 µm K. The spectral radiance emitted by a real body is usually less than that of a black body when both are measured at the same temperature. This is described by spectral emissivity, ε_λ, defined as the ratio between the spectral radiance emitted by a real body to that emitted by a black body at the same temperature; that is

$$\varepsilon_\lambda = \frac{B_{\lambda,real}(\lambda,T)}{B_{\lambda,b}(\lambda,T)} \tag{2}$$

or,

$$B_{\lambda,real}(\lambda,T) = \varepsilon_\lambda B_{\lambda,b}(\lambda,T) \tag{3}$$

Monochromatic radiation thermometers utilize Eq. (3) to infer temperature of the target when its spectral emissivity is known and environmental influences such as ambient temperature and atmospheric scattering and absorption are negligible. However, if environmental temperature is far much higher than that of the target and the target emissivity is low, the pyrometer measured radiance will majorly be composed of ambient radiation that is reflected by the target (see Fig. 1) which leads to overestimated temperature inferred by the radiation thermometer. This can have far much impact in the accuracy of the measured temperature as described by [28].

In such situation therefore, the correction of reflection error is quite necessary. The general equation that take into account the total spectral radiance measured by a radiation thermometer can therefore be given as

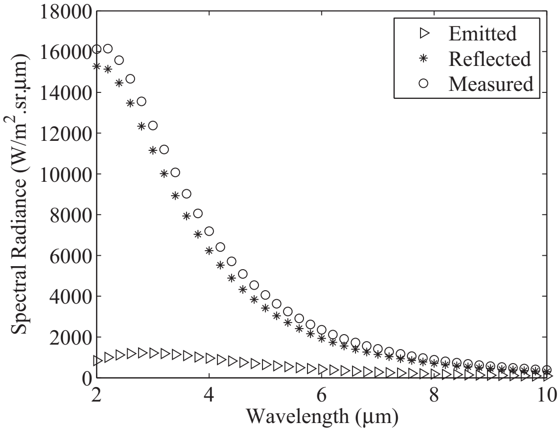

Fig. 1. Effect of reflected radiation on the measured radiation for target at T = 1000 K and ambient temperature of 1500 K in the spectral range 2–10 µm and a constant emissivity of 0.3.

$$B_{\lambda,meas}(\lambda,T) = \varepsilon_\lambda B_{\lambda,b}(\lambda,T) + \rho_\lambda B_{\lambda,b}(\lambda,T_{amb}) \tag{4}$$

The second term of this equation represents the fraction of environmental irradiance reflected by the target. T_{amb} and ρ_λ are the ambient temperature of the surroundings and spectral reflectance of the target surface respectively. For opaque and diffuse surfaces, Kirchhoff's law and energy conservation requires that the sum of absorbed and reflected radiance be equal to 1, that is $\alpha_\lambda + \rho_\lambda = 1$. Since $\alpha_\lambda = \varepsilon_\lambda$, then $\rho_\lambda = 1 - \varepsilon_\lambda$, hence Eq. (4) can be written as

$$B_{\lambda,meas}(\lambda,T) = \varepsilon_\lambda B_{\lambda,b}(\lambda,T) + (1-\varepsilon_\lambda)B_{\lambda,b}(\lambda,T_{amb}) \tag{5}$$

This is the equation which should be solved for the true surface temperature, T, of the target, a case not achievable directly using monochromatic and dual wavelength pyrometers [1]. However if spectral emissivity is known and constant, and that ambient temperature, T_{amb}, can be obtained, correction of the measured temperature can be achieved.

2.1. Multispectral radiation thermometry (MRT)

Unlike the use of single or two wavelengths in monochromatic and dual wavelength pyrometry, MRT utilizes multiple wavelengths to infer temperature of the target. In order to use this technique to determine surface temperature of a target, emissivity model, appropriate for the target surface has to be identified. Several mathematical models of spectral emissivity which can be employed in this technique have been proposed [10,19–24,29] and mainly tested for use in metallic surfaces with minimal consideration of the influence of ambient radiation. In this work, 10 emissivity models listed below were tested for possible application in ceramic thermal barrier coatings of different thickness.

Model 1 [22]:	$\varepsilon_\lambda = \exp(a/\sqrt{\lambda})$
Model 2:	$\varepsilon_\lambda = a + b\lambda^3$
Model 3:	$\varepsilon_\lambda = 1/(a + b\ln(\lambda)/\lambda)$
Model 4 [22]:	$\varepsilon_\lambda = \exp(a\sqrt{\lambda})$
Model 5 [22]:	$\varepsilon_\lambda = \exp(a + b\sqrt{\lambda})$
Model 6 [22]:	$\varepsilon_\lambda = \exp(a + b/\sqrt{\lambda})$
Model 7 [30,31]:	$\varepsilon_\lambda = \exp(-a - b\lambda)$
Model 8 [30,31]:	$\varepsilon_\lambda = \exp(-a\lambda)$
Model 9 [30,31]:	$\varepsilon_\lambda = a + b\lambda + c\lambda^3$
Model 10 [10]:	$\varepsilon_\lambda = 1/(1 + a\lambda^2)$

One of the best methods, commonly used in evaluating temperature and spectral emissivity in MRT technique is the least squares method [24]. The rationale of this technique is to fit experimental measured data to a given model equation with unknown parameters. The fitting results are the unknown parameters of the model. For an emissivity model with n unknown coefficients, this technique requires that $n+2$ wavelengths be used [19]. In this work, non-linear least square curve fitting technique, an iterative approach using Levenberg–Marquardt algorithm, was used to calculate the unknown parameters of emissivity and the predicted temperature by minimizing sum of squares of the residuals. In non-linear least squares technique, initial values of the unknown parameters are required for the first iteration. Using these parameters, the experimental data is fitted to the model equation to obtain a new set of parameters for use in the subsequent iterations. Iteration is terminated when sets of convergence criteria are attained. The unknown parameters that give the least sum of square errors (sse), least root mean square error (rmse) and the adjusted root square (adrsquare) closer to 1 thus become the best estimates of unknown parameters. By observing the goodness of the fitted curves and these statistical outputs, acceptance or rejection of the