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Effect of pyrometer type and wavelength selection on temperature measurement errors for turbine blades

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ABSTRACT

Turbine blade temperature measurements are important for monitoring the working state of the blades. However, the reflected radiation from the high temperature surrounding environment leads to significant error in the optical pyrometer measurements. This study calculates and compares temperature error of single wavelength pyrometer, ratio pyrometer and multicolor pyrometer in measuring turbine rotor blade temperature. Emissivity of the blade was measured in the wavelength range of 1.2 μm to 2.5 μm. Temperature distribution of the rotor blade and the guide vane was simulated by CFD software. Additionally, temperature error was calculated based on - discretization of a three-dimensional blade model. The results show that from the leading edge to the trailing edge of the rotor blade pressure side, the variation trend of the three kinds of pyrometer temperature error is the same, first decreasing, then increasing before decreasing again. The maximum relative temperature error was found to be 7.5%, 4.9% and 2.6% when the wavelength of the pyrometer was 1.3 μm, 1.6 μm, 2.2 μm, respectively. The study also shows that wavelength selection has great influence on the ratio pyrometer. It was found that the maximum relative temperature error ranged from 2.6% to 15.7% based on the choice of the various wavelengths. On the other hand, the maximum relative temperature error of the multicolor pyrometer was 3.8%. The analysis presented in this work will be of importance in providing guidelines for choosing the optimum measurement wavelengths for optical pyrometers. Furthermore, the finding will also useful in the calculation and correction of the optical pyrometer error.

1. Introduction

On-line temperature measurement of turbine blades is of great importance as far as blade health monitoring is concerned. Due to high-speed rotation of turbine blades, traditional contact temperature measurement methods such as thermocouples are rarely used. This make, optical pyrometers the best option for temperature measurement. Other reasons that makes an optical pyrometer best suited for this purpose is the fact that it has quick response and can work in a wide range of temperature. Furthermore, it does not interfere with temperature distribution of the blade [1–11].

Various temperature measurement techniques have been developed based on thermal spectral radiation intensities of the hot components in turbine engines. They are basically based on single, ratio or multicolor measurement, short/long wavelength. Some of the sources of measurement error of these pyrometers are high-temperature gas absorption and radiation reflected from the high temperature surrounding environment, luminous transient interference and lens contamination [12,13]. For turbine blades working in confined spaces of turbine engines, the effect of the reflected radiation has the most significant effect on the optical pyrometer temperature measurement accuracy. Some scholars have calculated temperature error of the optical pyrometers induced by reflected radiation based on environment reflection model [14–19]. M.de Lucia et al. developed an environment reflection model by calculating the view factors of every element on the blade and environment surface after discretization [14]. Shan Gao et al. analyzed the characteristics of the reflected radiation when the rotor blade rotates to different positions [15]. Chi Feng et al. proposed the use of triangular surface units instead of rectangular surface units to build the reflection model [17]. Tairan Fu et al. used a reflection model to calculate the effective spectral emissivity of gas turbine blades for optical pyrometer [18].

The shortfalls in the above literature is the fact that they only focused on the method and accuracy of establishment of the reflection model. Temperature error characteristics of different kind of pyrometers or different wavelengths selection have however not been

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studied, although it is quite essential for use in optical pyrometry. Thus in this work, temperature error induced by the reflected radiation from the surrounding environment when measuring the gas turbine blade temperature with single wavelength pyrometer, ratio pyrometer or multicolor pyrometer were analyzed and compared. This analysis provides reference for choosing the optimum wavelengths for optical systems for turbine blade temperature measurements.

As a note to the reader, CFD framework for determining the temperature errors was used in this work, and further detail of which is found in Ref. [17].

2. Thermal radiation pyrometer theory

2.1. Single wavelength pyrometer

The law that gorverns the relationship between temperature and emitted thermal radiation is given by the Planck's equation [20].

$$I_{em}(\lambda, T) = \varepsilon_\lambda I_b(\lambda, T) = \varepsilon_\lambda C_1\lambda^{-5}[\exp\left(\frac{C_2}{\lambda T}\right) - 1]^{-1} \tag{1}$$

where $C_1 = 3.7418\cdot10^8$ W·μm^4/m^2 and $C_2 = 1.439\cdot10^4\,\mu$m·K are the first and second Planck radiation constant, respectively; $I_b(\lambda, T)$ is the blackbody radiation intensity at temperature T (K) and wavelength λ (μm); ε_λ is the surface emissivity which is equal to 1 for a blackbody and less than 1 for a non-blackbody.

An approximation often used to simplify the calculation of radiative heat transfer with radiance error of less than 1% is Wien's law, whose validity is limited by the condition $\lambda T < 3000\,\mu$m·K, such that

$$I_{em}(\lambda, T) = \varepsilon_\lambda C_1\lambda^{-5}\left[\exp\left(\frac{C_2}{\lambda T}\right)\right]^{-1} \tag{2}$$

2.2. Ratio pyrometer

The ratio Pyrometer technique takes the ratio of two signals obtained from different wavelengths. This method is thought to be independent of emissivity by assuming that the measured targets are gray surfaces, such that the emissivities of the targets at the two wavelengths are equal, i.e. $\varepsilon_{\lambda_1} = \varepsilon_{\lambda_2}$. Assuming the wavelengths λ_1 and λ_2 are selected for a ratio pyrometer, Eq. (2) can be modified to give the two spectral radiance of each of its channels as

$$I_{em}(\lambda_1, T) = \varepsilon_{\lambda_1} C_1\lambda_1^{-5}\left[\exp\left(\frac{C_2}{\lambda_1 T}\right)\right]^{-1} \tag{3}$$

$$I_{em}(\lambda_2, T) = \varepsilon_{\lambda_2} C_1\lambda_2^{-5}\left[\exp\left(\frac{C_2}{\lambda_2 T}\right)\right]^{-1} \tag{4}$$

where $I_{em}(\lambda_1, T)$ and $I_{em}(\lambda_2, T)$ are the output radiance of the two channels of the ratio pyrometer respectively. The ratio of Eqs. (4) and (3) gives

$$R = \frac{I_{em}(\lambda_2, T)}{I_{em}(\lambda_1, T)} = \left(\frac{\varepsilon_{\lambda_2}}{\varepsilon_{\lambda_1}}\right)\left(\frac{\lambda_1}{\lambda_2}\right)^5\exp\left[\frac{C_2}{T}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\right] \tag{5}$$

and thus, temperature T can be obtained as

$$T = \frac{C_2(\lambda_1^{-1} - \lambda_2^{-1})}{\ln\left[R\left(\frac{\lambda_2}{\lambda_1}\right)^5\right]} \tag{6}$$

2.3. Multicolor pyrometer

Assuming the wavelengths $\lambda_1, \lambda_2. ..\lambda_n$ are selected for a multicolor pyrometer, Eq. (2) can be modified to give the n spectral radiance of each of its channels as

$$\begin{aligned} I_{em}(\lambda_1, T) &= \varepsilon_{\lambda_1} I_b(\lambda_1, T)\\ I_{em}(\lambda_2, T) &= \varepsilon_{\lambda_2} I_b(\lambda_2, T)\\ &\cdots\\ I_{em}(\lambda_n, T) &= \varepsilon_{\lambda_n} I_b(\lambda_n, T) \end{aligned} \tag{7}$$

In this case, the number of measurement equations is n with n + 1 unknown parameters, which are n emissivity ($\varepsilon_{\lambda_1}, \varepsilon_{\lambda_2}. ..\varepsilon_{\lambda_n}$) and temperature ($T$). One of the emissivity models for this type of pyrometer, and adopted in this research, is shown in Eq. (8). In this equation, n is the number of multicolor pyrometer wavelengths while a_i and m are parameters and the number of the parameters respectively.

$$\ln\varepsilon(\lambda, T) = \sum_{i=0}^{m} a_i\lambda^i (m < n-2) \tag{8}$$

Combining Eqs. (7) and (8), for n wavelength ranges for the multicolor measurements, the error function, F, to be minimized using the least squares algorithm or iterative calculations to determine the temperatures and spectral emissivities is given by the following equation [21]

$$F = \sum_{i=1}^{n} [\left(I_{\lambda_i,meas} - \varepsilon_{\lambda_i} I_{\lambda_i,b}\right)/I_{\lambda_i,meas}]^2 \tag{9}$$

where $I_{\lambda_i,meas}$ is the measured spectral directional radiation intensity distribution from the object.

3. Methodology

3.1. Temperature measurements in high-temperature environment

When temperature of a turbine blade is measured by an optical pyrometer, the reflected radiation from the surrounding environment will also be captured by the pyrometer. In literature, the proportion of such radiation could in some cases be over 75% [22].

Fig. 1(a) shows a three dimensional setup of the guide vanes and the rotor blades while Fig. 1(b) shows a two dimensional setup of the 1st stage guide vanes (1V) and the 1st stage rotor blades (1B) respectively, together with pyrometer position. From the figure, reflected radiation captured by the pyrometer is mainly coming from the first stage of guide vanes and adjacent blades. Futher detail can be found in Ref. [17].

When the reflection radiation exists, the general equation that takes into account the total spectral radiance measured by a pyrometer can therefore be expressed as shown in Eq. (10) [14,15,17,18]

$$I_{meas}(\lambda, T) = \varepsilon_\lambda I_b(\lambda, T) + (1-\varepsilon_\lambda)I_{ref}(\lambda, T_{amb}) \tag{10}$$

The second term of this equation represents the fraction of environmental irradiance reflected by the target. T_{amb} is the ambient temperature of the surroundings.

In this paper, the reflection model is established by dividing the rotor blade and the guide vane surfaces into many small triangular surface units [17], and the measured radiance exitance from the rotor blade surface unit i calculated using Eq. (11),

$$I_{measi} = \varepsilon_\lambda I_{bi} + \frac{(1-\varepsilon_\lambda)}{A_i}\sum_{j=1}^{n} A_j F_{j-i} I_{exj} \tag{11}$$

where A_i is the area of the measured target surface unit i, A_j is the area of the surface unit j, F_{j-i} is the view factor between i and j which is the fraction of diffuse energy leaving surface unit j that arrives directly at the surface unit i, I_{exj} is the exitance from j. To calculate I_{measi}, emissivity $\varepsilon_\lambda$and temperature distribution of the guide vane and the rotor blade should be known. In this work, emissivity ε_λ was obtained experimentally as described in Section 3.2 and the temperature distribution of the rotor blade and the guide vane were obtained from CFD simulation in Section 3.3.

Absolute temperature error and the relative temperature error was