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Reflection error correction of gas turbine blade temperature

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HIGHLIGHTS

- Reflection error greatly affects radiation thermometer measurements.
- Correction of this error in gas turbine blades has been provided.
- The method was demonstrated through simulation and an experiment.
- Results achieved showed significant reduction of the error.

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ABSTRACT

Accurate measurement of gas turbine blades' temperature is one of the greatest challenges encountered in gas turbine temperature measurements. Within an enclosed gas turbine environment with surfaces of varying temperature and low emissivities, a new challenge is introduced into the use of radiation thermometers due to the problem of reflection error. A method for correcting this error has been proposed and demonstrated in this work through computer simulation and experiment. The method assumed that emissivities of all surfaces exchanging thermal radiation are known. Simulations were carried out considering targets with low and high emissivities of 0.3 and 0.8 respectively while experimental measurements were carried out on blades with emissivity of 0.76. Simulated results showed possibility of achieving error less than 1% while experimental result corrected the error to 1.1%. It was thus concluded that the method is appropriate for correcting reflection error commonly encountered in temperature measurement of gas turbine blades.

1. Introduction

Accurate temperature measurement of components operating in harsh environment such as gas turbines is quite essential as far as their life span is concerned. With the aim of boosting efficiency of gas turbines, high turbine inlet temperature has been one of the foreseen options which has seen it rise over 1773 K [1,2] over the years. At such extreme temperature, gas turbine components such as blades and vanes have become quite vulnerable to damage by excessive heat. Some of the methods that have been employed to protect these parts against the menace include coating the component surface with thermal barrier coatings (TBC) and using various cooling techniques that have enabled the components to operate at more than 200 K beyond the melting point of their superalloys [3–7]. It is however well known that due to the harsh condition under which turbine blades and vanes operate in, TBC coatings crack or erode over time exposing the superalloy material to the extreme temperatures. Furthermore, the internal cooling passages of blades or vanes can get blocked leading to uneven surface cooling. All these challenges combined can finally lead to component failure. As a result of this, temperature measurement of such critical components is quite inevitable in order to provide appropriate signal of its life deterioration [8].

The commonly used high temperature measurement methods are thermocouples and radiation thermometers (pyrometers). Each of the methods has its own advantages and disadvantages [9,10]; hence, one has to choose the most appropriate one. Unlike the contact type thermometers (thermocouples) that must come in contact with the target, pyrometers measure temperature remotely making it suitable for rotating parts such as blades. On the other hand, thermocouples can be used to measure temperature of the fixed vanes if their temperature range can allow. Despite pyrometer's ability to measure temperature remotely, reliability of its temperature cannot be guaranteed especially when the target has low emissivity coupled with high temperature of

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the surrounding surfaces. In such situations radiation received by pyrometer includes those emitted by the target and those from the surroundings that are reflected by the target. Under reflective gas turbine environment operating at very high temperature coupled with advanced cooling processes and the use of low emissivity TBC, greater challenge is introduced into radiation thermometry. Such environment can render pyrometer temperatures highly unreliable if they are not corrected before adapting them. Several attempts have been made by researchers to provide solutions to this problem. Some have advocated measuring all radiations from the surrounding surfaces that contribute to reflection error and offsetting them from the pyrometer measured thermal radiation [11,12] while others have advocated the use of multispectral pyrometers [13–17]. The latter being considered potential has not fully ventured into the wider market for being costly and being prone to uncertainties related to multiple variables from the optical measurement system for the uncertainty analysis [13].

Interested with the critical component – the turbine blade, we hereby present a more robust method for measuring its temperature within its operating environment using single wavelength pyrometer. Unlike the work of [11,12] that addressed reflection errors based on the assumption that temperature of all the surrounding surfaces could be measured using thermocouples, this work does not buy this assumption fully. Among the surfaces influencing pyrometer temperature measurement of a given blade is that of the adjacent blade viewed by the target. This blade being under high speed rotation becomes quite challenging to measure its temperature using a thermocouple for correction of reflection error as concluded by [11]. Our modeling therefore provides for correction of this error taking into consideration the mentioned challenge. The technique used combines the ideas of [11,12,18]. In this work, gray surface assumption has been made; that is, the surface emits and reflects diffusively and that surface emissivities are known.

1.1. Principles of thermal radiation

A body whose temperature is greater than absolute zero emits thermal radiation governed by the famous Planck's law [19]

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

where $B_{em}(\lambda,T)$ (measured in $\mathrm{W/m^2\,sr\,\mu m}$) is the radiance emitted by a surface and which is a function of wavelength λ and absolute temperature T. $C_1 = 1.191042 \times 10^8\ \mathrm{W/m^2\,sr\,\mu m^{-4}}$ and $C_2 = 14{,}388\ \mathrm{\mu m\,K}$ are the first and the second radiation constants respectively. ε is the surface emissivity which is equal to 1 for a blackbody and less than 1 for a non-blackbody [20]. For a very large exponential term in Eq. (1), Wien's law, Eq. (2) is obtained.

$$B_{em}(\lambda, T) = \varepsilon C_1 \lambda^{-5} \exp -\left(\frac{C_2}{\lambda T}\right). \tag{2}$$

This is the principle equation used by single wavelength pyrometers which can be used effectively with radiance error of less than 1% for value of $\lambda T < 3000\ \mathrm{\mu m\,K}$ [21]. Temperature measured by a single wavelength pyrometer can be obtained by finding the inverse of Eq. (1) or (2). This is only applicable to an isolated target. However, for target under the influence of external radiations, radiation measured by pyrometer detector is the sum of those emitted by the target and those from the surrounding surfaces that are reflected by the target. This can be expressed mathematically as [22]

$$B_{exi} = \varepsilon_{\lambda i} B_{emi} + (1 - \varepsilon_{\lambda i}) \sum_{j=1}^{n} F_{i\text{–}j} B_{exj}. \tag{3}$$

where the first term on the right hand side of the equation represents radiation emitted by a surface while the second part represents the reflected one. $F_{i\text{–}j}$ is the radiation view factor from surface i to surface j. From this equation, it can be seen that with low target emissivity and high surrounding surface temperatures, reflected radiation received by pyrometer detector can be quite significant leading to over estimation of target temperature. Correction of this error is therefore quite necessary for reliability of the measured temperature. Gas turbine blades being subjected to these external radiations are the subject of interest in this work and a technique that can be employed to measure its temperature is provided in the following sections in which Eqs. (2) and (3) have been applied rigorously to correct reflected radiation from those measured by the pyrometer in order to calculate the true target temperature.

1.2. View factor calculation

In order to calculate the view factor between any two interacting finite areas, A_1 and area A_2, the general formula given in Eq. (4) can be used [19].

$$F_{1-2} = \frac{1}{A_1} \int_{A_2} \int_{A_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA_1 dA_2, \tag{4}$$

where r is the length between differential areas dA_1 and dA_2 while θ_1 and θ_2 are the angles between r and the normal to dA_1 and dA_2 respectively. F_{1-2} is the fraction of energy from surface 2 that is intercepted by surface 1 and is usually read as view factor from surface 1 to surface 2. Evaluation of the double area integral in Eq. (4) can be quite cumbersome for relatively complex surfaces exchanging thermal radiation; hence, for faster computation of the view factors in our modeling, blades and vanes surfaces were divided into numerous discrete rectangular surfaces [11] with two discrete surfaces exchanging thermal radiation illustrated in Fig. 1. From this geometry, an analytical equation (5) [12] simplified from Eq. (4) based on Fig. 1 was used to calculate the view factors between the two discrete surfaces. By use of view factor summation principle, reciprocity relation and view factor algebra [19], view factors between all interacting surfaces were calculated. For more complex geometries, methods such as Nusselt Sphere technique, Hottel's Crossed-String method, Contour integration, Hemi-cube, Numerical integration, and Monte Carlo method among others [23–27] can be used.

$$\begin{aligned} F_{1-2} = \frac{b_1 b_2 \cos\theta_1 \cos\theta_2}{\pi A_1 s} \Bigg[& (z_1 + h_1 - z_2) \tan^{-1}\left(\frac{z_1 + h_1 - z_2}{s}\right) \Bigg] \\ & + (z_1 + h_2 - x_2) \tan^{-1}\left(\frac{z_1 - h_2 - z_2}{s}\right) \\ & - (z_1 - z_2) \tan^{-1}\left(\frac{z_1 - z_2}{s}\right) \\ & - (z_1 + h_1 - z_2 - h_2) \tan^{-1}\left(\frac{z_1 + h_1 - z_2 - h_2}{s}\right) \\ & + \frac{s}{2}(\ln((z_1 + h_1 - z_2 - h_2)^2 + s^2) + \ln((z_1 - z_2)^2 + s^2) \\ & - \ln((z_1 + h_1 - z_2)^2 + s^2) - \ln((z_1 - z_2 - h_2)^2 + s^2)) \end{aligned} \tag{5}$$

1.3. Pyrometer operating wavelength and other specifications

Another important factor that should be considered is the operating wavelength of the pyrometer detector. According to Planck's distribution function, measurement of high target temperatures can be achieved effectively at short wavelengths than long wavelengths due to the strength of the emitted thermal radiations [19]. However, in gas turbine environment the dominant combustion gas products such as water, Carbon Dioxide, Carbon Monoxide and unburned gases [19,28] are very active within some bands in these short infrared wavelengths and can significantly influence