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Regular article

Calculating the reflected radiation error between turbine blades and vanes based on double contour integral method

Chi Feng, Dong Li, Shan Gao *, Ketui Daniel

Harbin Engineering University, School of Information and Communication Engineering, No. 145-1, Nantong Street, Harbin 150001, China

HIGHLIGHTS

- A method to calculate the view factor between irregular surfaces is proposed.
- An accurate reflection model based on discrete irregular surfaces is established.
- The results showed significant reduction of the error.

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ABSTRACT

This paper presents a CFD (Computation Fluid Dynamic) simulation and experimental results for the reflected radiation error from turbine vanes when measuring turbine blade's temperature using a pyrometer. In the paper, an accurate reflection model based on discrete irregular surfaces is established. Double contour integral method is used to calculate view factor between the irregular surfaces. Calculated reflected radiation error was found to change with relative position between blades and vanes as temperature distribution of vanes and blades was simulated using CFD. Simulation results indicated that when the vanes suction surface temperature ranged from 860 K to 1060 K and the blades pressure surface average temperature is 805 K, pyrometer measurement error can reach up to 6.35%. Experimental results show that the maximum pyrometer absolute error of three different targets on the blade decreases from 6.52%, 4.15% and 1.35% to 0.89%, 0.82% and 0.69% respectively after error correction.

1. Introduction

Gas turbine is a powerful and efficient power plant having important applications in many industries. One of the methods of improving its efficiency has been to increase its turbine inlet temperature as high as possible. This has seen turbine inlet temperature of first generation gas turbines rose from 1073 K to 1873 K for the latest models of gas turbines [1]. Gas turbine blades as one of the most critical components of the gas turbines are exposed to high thermal and centrifugal loads, thus subjecting them to frequent repair or replacement. With regards to this, accurate blade temperature measurement for blade health monitoring is quite inevitable.

Due to high speed rotation of turbine blades, the traditional contact temperature measurement methods such as thermocouples are rarely used. However in place of this, radiation pyrometers are used. These types of thermometers have widely been applied in a variety of research and industrial fields [2–4]. They are widely preferred when contact with a hot target is not advisable or even possible. In addition, pyrometers have no upper limit of temperature measurement since the energy available for detection increases rapidly with temperature. However, since the target in a typical turbine is surrounded by a hemisphere of potentially higher or lower effective temperature than the target itself, the radiation from the surrounding environment will introduce a non-negligible error when measuring the temperature of the blade using this type of thermometer.

Problems of environmental reflected radiation have been studied in many aspects by many scholars. The study of Pratt and Whitney [5], on the test and production engines, in unfriendly status, indicated that as much as 70% of the radiant energy collected by the pyrometer between the wavelength 0.35 and 1.5 μm can be reflected radiation. Among the reflected radiation sources such as the combustion chamber, adjacent blades, etc. energy from the blade on the first stage of the high-pressure turbine could in some cases be over 75% [6]. For the detailed analysis of the vane reflected radiation on the blade, De Lucia and Lanfranhi [7] developed a

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* Corresponding author.
E-mail address: gaoshan6666@126.com (S. Gao).

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Nomenclature

CFD	Computation Fluid Dynamic
L	spectral emissive power ($w \cdot m^{-2} \cdot \mu m^{-1}$)
c	constant
T	temperature (K)
F	view factor
A	area (m^2)
R	distance (m)
C	contours bounding
S	suction surface
P	pressure surface
D	the distance from the blade leading edge to the tailing edge (mm)
d	the projected distance from a point on the blade pressure surface curve to the leading edge (mm)
ratio_d	the ratio of d and D
hz	moving distance of blade along the z axis (mm)

Subscripts

b	black body
ex	radiation exitance
py	pyrometer
sim	simulation
TC	thermocouple
cor	corrected
V	vane blade

Greek symbols

λ	wavelength (μm)
ε	emissivity
γ	angle (°)

computer modeling system for infrared pyrometry measurement of gas turbine blade temperature. Gao [8] improved the model based on the rotational angles and positions of the blades.

But the previous studies have several shortages that need to be improved. Firstly, all the aforementioned papers [7,8] predigest the blades as a simple stretching model with no twist. Secondly, when calculating the reflected radiation of vane on rotor blade, they assumed that both the surfaces of the vane and the blade are isothermal. However, the fact is that the blade temperature distribution is non-isothermal. Thirdly, the method used to calculate the view factor in the reflection model based on the simplified blade model with no twist is no longer useful for real irregular surfaces.

The main aim of the present study is therefore to improve the shortfalls of the above studies. In this paper, building accurate reflection model of radiation involved discretizing the surfaces of the blade and the vane using triangular panels; getting the complex temperature distribution of blade and vane surface by computation fluid dynamic; and calculating the view factor between arbitrary two triangular panels using double contour integral method. The new proposed method can thus be used to calculate the reflected radiation between the vane and the blade with complex surface temperature distribution and under different relative positions. Such calculations are quite important in estimating reflection error when measuring blade's temperature using a pyrometer.

2. Numerical modeling

2.1. Fundamentals

Planck's law of radiation is the basic theory of non-contact temperature measurement. According to this law, radiation exitance of a given surface at different temperatures can be expressed according to equation [9]

$$L_b(\lambda, T) = c_1 \lambda^{-5} \left(e^{c_2/\lambda T} - 1\right)^{-1} \tag{1}$$

where $c_1 = 3.742 \times 10^4 \mathrm{W}\,\mu\mathrm{m}^4/\mathrm{cm}^2$ is the first radiation constant and $c_2 = 1.439 \times 10^4\ \mu\mathrm{mK}$ is the second radiation constant. $L_b(\lambda, T)$ is the spectral emissive power ($W \cdot \mathrm{m}^{-2} \cdot \mu\mathrm{m}^{-1}$) at temperature K and wavelength $\lambda(\mu\mathrm{m})$.

When considering the reflection of the surrounding environment, the real radiation exitance of a surface as recorded by a pyrometer can be expressed as [7]

$$L_{exi} = \varepsilon_i L_{bi} + (1 - \varepsilon_i) \sum_{j=1}^{m} L_{exij} \tag{2}$$

where ε_i is the emissivity of surface i, L_{bi} is the blackbody exitance from surface i, L_{exij} is the exitance from surface j reaching surface i, L_{exij} can be calculated based on view factor F_{ij}, The fraction of diffuse energy leaving a finite area j that arrives directly at a finite area i is defined as view factor F_{ij}, i.e.

$$F_{ij} = \frac{A_i L_{exij}}{A_j L_{exj}} \tag{3}$$

where A_i is the area of surface i, A_j is the area of surface j, L_{exj} is the exitance of surface j. Combining Eqs. (2) and (3) gives

$$L_{exi} = \varepsilon_i L_{bi} + \frac{(1 - \varepsilon_i)}{A_i} \sum_{j=1}^{m} A_j F_{ij} L_{exj} \tag{4}$$

View factor F_{ij} is an important factor in order to evaluate Eq. (4), the geometrical view factor between two isothermal, black, diffusely emitting and reflecting surfaces is defined as

$$F_{ij} = \frac{1}{A_j} \int_{A_i} \int_{A_j} \frac{\cos\gamma_i \cos\gamma_j}{\pi R^2} dA_i dA_j \tag{5}$$

where γ_i and γ_j are the angles between the surface normal and the line joining two infinitesimal areas dA_i and dA_j of respective surfaces. R is the distance between two areas. To simplify the analytical evaluation of Eq. (5), Sparrow [10] converted the double area integral into double contour integral by using Stokes' theorem. Applying Stokes' theorem twice, Eq. (5) can be reduced to Eq. (6).

$$F_{ij} = \frac{1}{2\pi A_j} \left\{ \int_{C_i} \int_{C_j} (lnR \cdot dx_i dx_j + lnR \cdot dy_i dy_j + lnR \cdot dz_i dz_j) \right\} \tag{6}$$

where C_i and C_j represent the contours bounding the view areas of surfaces i and j. dx, dy and dz are the elemental lengths in the respective directions and R is the distance between elements on the contours of respective surfaces.

An illustration for calculating the view factor F_{ij} between two triangular surfaces A_j and A_i with double contour integral method is shown in Fig. 1. From the figure, the contour of the triangular surface A_j consist of three vectors $\overrightarrow{DE}$, $\overrightarrow{EF}$ and $\overrightarrow{FD}$ while the contour of the triangular surface A_i consist of three vectors $\overrightarrow{AB}$, $\overrightarrow{BC}$ and $\overrightarrow{CA}$.

By considering the two interacting surfaces of the figure, Eq. (6) can be converted to Eq. (7)

$$\begin{aligned} F_{ij} &= \frac{1}{2\pi A_j} \left\{ \int_{\overrightarrow{AB}+\overrightarrow{BC}+\overrightarrow{CA}} \int_{\overrightarrow{DE}+\overrightarrow{EF}+\overrightarrow{FD}} (lnR \cdot dx_i dx_j + lnR \cdot dy_i dy_j + lnR \cdot dz_i dz_j) \right\} \\ &= f_{\overrightarrow{AB},\overrightarrow{DE}} + f_{\overrightarrow{AB},\overrightarrow{EF}} + f_{\overrightarrow{AB},\overrightarrow{FD}} + f_{\overrightarrow{BC},\overrightarrow{DE}} + f_{\overrightarrow{BC},\overrightarrow{EF}} + f_{\overrightarrow{BC},\overrightarrow{FD}} + f_{\overrightarrow{CA},\overrightarrow{DE}} + f_{\overrightarrow{CA},\overrightarrow{EF}} + f_{\overrightarrow{CA},\overrightarrow{FD}} \end{aligned} \tag{7}$$