A SOFTWARE MODULE FOR CORRECTING PYROMETER MEASURED TEMPERATURES

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ABSTRACT

Knowing the turbine blade surface temperature of the first stage turbine blades is of major importance for reasons of turbine blade life. Various techniques have been developed to measure the turbine blade surface temperature, including pyrometer techniques. The temperature measured with these pyrometers, however, do not necessarily picturise the real metal surface temperature of the blade, due to the presence of gas layers and a thermal barrier coating (TBC), influencing the radiative intensity emitted by the metal of the turbine blade. A model was constructed to account for these layers and correct the measured temperature obtaining the real TBC temperature. The model is implemented in the PERCEPTION software tool. This paper shows how the temperature profiles obtained with two different pyrometers are corrected for the presence of these layers using the PERCEPTION software. Furthermore, some assumptions used in the model and possible extensions of the model are discussed.

INTRODUCTION

Gas turbines are commonly applied in power generation utilities and as propulsion engines in aviation. One of the major concerns in gas turbine technology is the efficiency of the installation. The efficiency is directly correlated to the combustion temperature inside the combustion chamber of the gas turbine. A higher combustion temperature increases the overall efficiency of the gas turbine. On the other hand, an increasing gas temperature increases the thermal load, and with gas temperatures well above the acceptable temperature of the metal of the turbine blade, uncontrolled heating of the turbine blade reduces the lifetime of the turbine blade significantly.

Various measurement techniques can be adopted for target temperature measurements, with varying accuracy. Many organizations have used pyrometers to determine the metal temperature of uncoated blade surfaces. Among others, KEMA has developed a high speed pyrometer that monitors the blade temperature at a relatively short wavelength of 1 μm (SW). However, when the blade is covered with a TBC layer, the measurements are complicated due to the fact that a clean TBC is reasonably transparent but this is not the case for a polluted TBC, see Zhu [1], Markham [2].

Therefore, an experimental study on the feasibility of radiation thermometry based on 10 μm long-wavelength infrared radiation (LWIR) technology has been performed by KEMA [3]. The pyrometer detector detects a radiative intensity and translates the intensity into a measured temperature. Different measurements have been performed with the LWIR and SW pyrometer, and the measured temperatures for the various experiments are shown in Fig. 1.

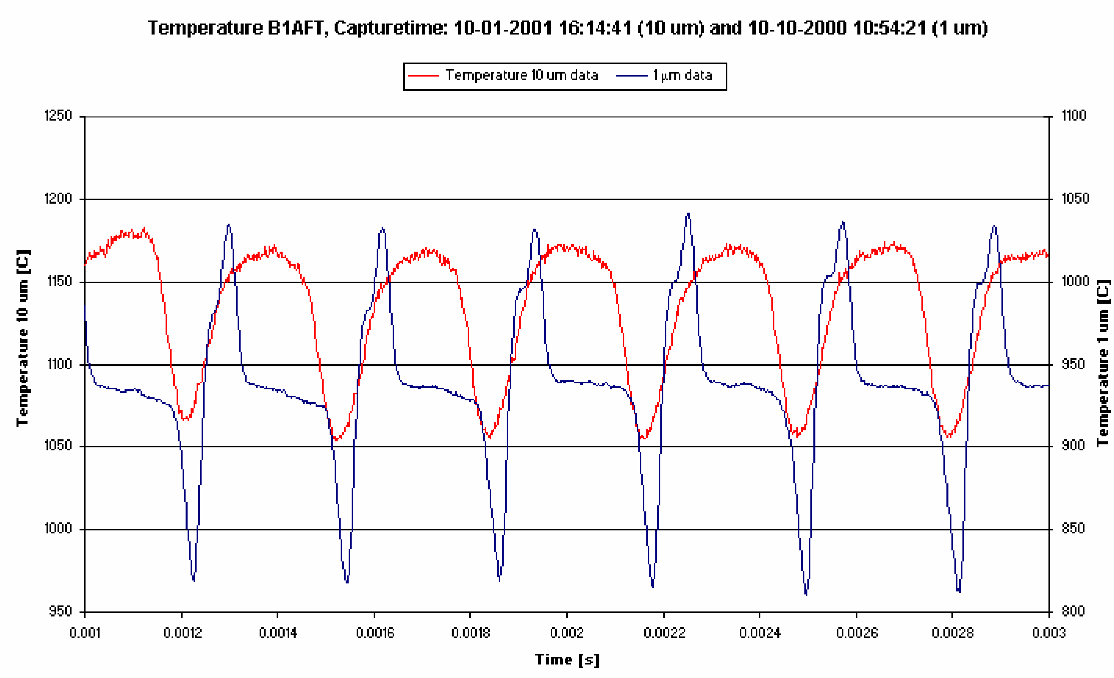

Fig. 1: Temperatures obtained from experiments with the LWIR and SW pyrometer.

The real blade metal temperature differs from the temperature that would be expected from the detected radiative intensity, due to gas absorption and emission, reflected radiation, and TBC absorption, emission and scattering. as indicated in Fig. 2. As a result, the metal blade temperature is (mostly) underestimated.

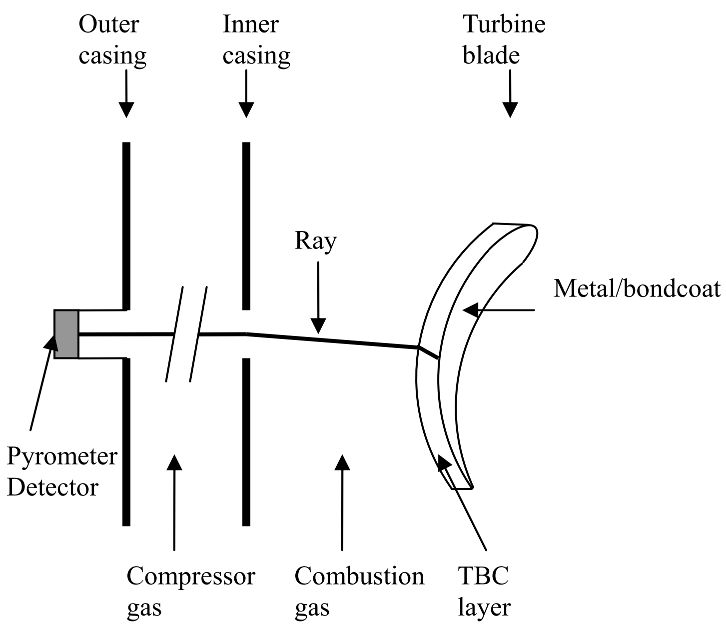

Fig. 2: Schematic overview.

To acquire the TBC and metal temperature more accurately, the measured temperature has to be corrected. A mathematical model is constructed to calculate the TBC and blade metal temperature from the measured temperature. The model is implemented in the PERCEPTION software module developed at KEMA.

RESULTS AND DISCUSSION

Figure 2 presents the schematic overview of radiation emitted by the metal or bondcoat layer of a turbine blade in the direction of the pyrometer inlet, and propagating through the TBC layer, a layer of hot combustion gas near the turbine inlet, and a layer of compressor gas for cooling the pyrometer. A mathematical model is constructed including the following assumptions,

- the pyrometer detects radiation with a wavelength dependent intensity within a certain spectral range,
- the signal (intensity) detected by the pyrometer detector is time dependent and is translated to a time dependent measured temperature,
- the emission coefficient of the metal or bond coat surface is wavelength independent within the spectral detection range of the pyrometer,
- the TBC layer has a wavelength independent absorption coefficient, scattering coefficient and refraction index within the spectral detection range of the pyrometer, which is verified for example by Bonanno [4],
- the thermal conductivity coefficient and heat flux from the hot combustion gas to the TBC layer are constants, and the temperature profile inside the TBC layer is assumed to be linear and derived from the conductive heat fluxes. The conductive fluxes are dominant above internal radiative heat fluxes as long as the absorption and/or scattering coefficient is large enough and the convective heat flux is high enough. For the practical case that the TBC-surface temperature is 1300 K, the absorption coefficient is 30000 m^{-1} and the convective heat flux is 400000 W/m^2, the radiative heat flux is approximately 1-2% of the conductive heat flux, which verifies the assumption of a linear temperature profile in the TBC,
- the TBC thickness may be non-uniform. Therefore, the TBC thickness is treated as a time dependent variable,
- the angle of incidence, which is the angle between the radiation leaving the TBC surface that is seen by the pyrometer and the TBC-surface normal, is due to the rotating blades a function of time.
- specular reflection is taken into account at the TBC-gas interface, and is calculated from the TBC refraction index,
- the refraction index of the gas layers is assumed to be equal to 1,
- the temperature of the compressor gas in the boroscope tube and the combustion gas at the turbine inlet is considered uniform in temperature and composition. However, the absorption and emission is spectrally dependent and the spectral absorption curves are determined with the HITRAN and HITEMP databases. The effects of radiation emission and absorption by H2O and CO2 must be taken into account and are predominant at a wavelength of 10 μm,
- due to the rotating motion of the rotor the distance from the turbine inner casing to the blade surfaces changes periodically in time. Along the line of sight of the pyrometer, the path length of the radiation through the layer of combustion gas is time dependent.

The mathematical model is implemented in the PERCEPTION software module, developed at KEMA. The program calculates (1) the time dependent temperature of the TBC at the TBC-combustion gas interface and (2) the temperature of the blade metal at the metal-TBC interface, using values for the variables mentioned above. Values for all input variables can be entered in the program or by means of a Microsoft Excel workbook. After the calculations are performed, the results can be studied in the program or can be exported to an Excel workbook. Figure 3 shows the interface of the PERCEPTION software.

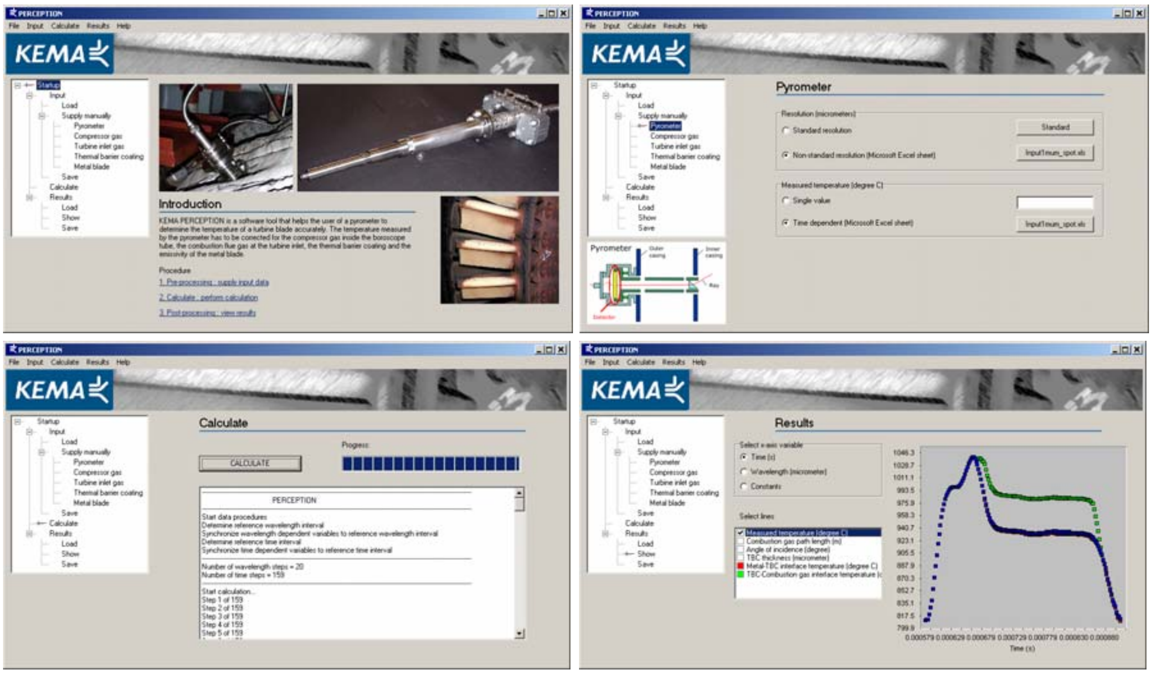

Fig. 3: interface of the PERCEPTION software, with the start up screen (top left), input screen (top right), calculation screen (bottom left) and results screen (bottom right).

The time dependent measured temperatures at detection wavelengths of 1 and 10 µm are presented in Fig. 1 and are corrected for the presence of the TBC coating and gas layers using the PERCEPTION software. Input data is supplied to the PERCEPTION software for the measured temperature, pyrometer detector resolution, compressor and combustion gas composition and temperature, TBC layer optical properties and metal or bondcoat radiation emissivity. The values for these parameters are discussed below.

Pyrometer

The measurements at 1 µm are normally performed with the commercially available TurboTherm system, which employs Si-detectors and conventional optical fibers. The wavelength range of the detection system is 0.30 - 1.05 µm [Rooth, 2003]. In the spectral range of 0.3-0.8 µm, the intensity of the emitted radiation is very small, and therefore the spectral range considered is 0.8-1.05 µm, as indicated in table 1.

For 10 µm pyrometry a cryogenically cooled HgCdTe infrared detector is used. A ZnSe-lens focuses the light that emerges from the Polymicro hollow waveguide fiber onto the detector [Rooth, 2003]. Before the light reaches the detector it is chopped and filtered by a Spectrogon bandpass filter with a central wavelength of 10.71 µm and 0.38 µm full width half maximum, resulting in the resolution presented in table 1.

Table 1: Detector resolution characteristics.

	1 µm	10 µm
Minimum wavelength (nm)	800	10456
Maximum wavelength (nm)	1050	10881
Resolution (nm)	12.5	30.3

Compressor gas

The boroscope tube is filled with compressor gas. The main components of the compressor gas, i.e. CO_2 and H_2O, alter the radiation intensity. In table 2 the physical and chemical properties of CO_2 and H_2O in the compressor gas are given. Using the HITRAN and HITEMP databases the absorption curves of H_2O and CO_2 are determined, resulting in an overall gas absorption curve. The data of this absorption curve is imported in the PERCEPTION software by means of an Excel worksheet.

Table 2: compressor gas properties for determining the gas absorption curves.

	CO2	H2O

Temperature (ºC)	377	377
Pressure (bar)	14.6	14.6
Content (%)	0.03	0.7

However, in the set-up considered, the compressor gas layer is very thin, and the compressor gas will not influence the radiation intensity significantly. Therefore, the compressor gas layer thickness is assumed to be zero.

Combustion gas

The main components in the hot combustion flue gas at the turbine inlet that may alter the radiation intensity are CO_2 and H_2O. In table 3 the physical and chemical properties of CO_2 and H_2O in the combustion flue gas are given. Using the HITRAN and HITEMP databases the absorption curves of H_2O and CO_2 are determined, resulting in an overall gas absorption curve, and is imported in the PERCEPTION software by means of an Excel worksheet. The combustion flue gas contains a considerable amount of CO_2 and H_2O. In the near-infrared region the combustion products have no significant absorption bands. However, at 10 µm radiation absorption of these combustion products alters the radiation signal significantly.

Table 3: combustion flue gas properties for determining the gas absorption curves.

	CO2	H2O
Temperature (ºC)	1059	1059
Pressure (bar)	9.9	9.9
Content (%)	3.24	7.1

Radiation emitted by the turbine blade propagates through a layer of hot combustion flue gas, as indicated schematically in Fig. 2. With the rotor blades moving, this path length changes periodically in time. Figure 4 presents the assumed path length for the measurements at 1 and 10 µm for a single period of a blade passing by. Note that although the measurements at 1 and 10 µm are performed at the same machine the assumed path length is somewhat different at the transitions at t = 0.66 ms and at t = 0.87 ms. At these instants the pyrometer views at the edges of the turbine blade. As a result the gradients in path length (and also in TBC thickness and angle of incidence) are very large. Furthermore, the beam that is captured by the detector has a finite thickness. Averaging of the path length is necessary. The beam width as observed with the pyrometer measuring at 1 µm is somewhat narrower than the beam width as observed at 10 µm. Therefore, the averaging is over a shorter time span at 1 µm than it is at 10 µm, resulting in a steeper gradient of the average path length.

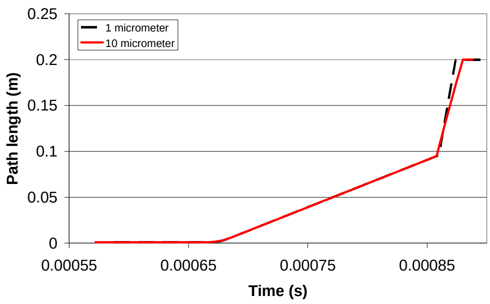

Fig. 4: Assumed distance from the outer surface of a turbine blade to the inner casing along the line of sight of the detected radiation as seen by detectors at 1 µm (black dashed line) and 10 µm (red solid line).

Thermal barrier coating

Values for the absorption coefficient, scattering coefficient and refraction index have been described by Siegel [5] and Makino [6] and have been checked by Rooth [3]. Antunovic [7] reports also values for various parameters at the wavelength intervals of interest. The absorption coefficient varies with temperature, especially at 10 µm wavelength. It is assumed that the TBC layer has a temperature of the order of 1000 ºC, corresponding to an absorption coefficient of approximately 70 mm^{-1}. At 1 µm the absorption coefficient is low, and at 10 µm the scattering coefficient is low. The upper values presented in the paper of Rooth [3] are presented in table 4, and are used for the calculations.

Table 4: Optical properties of the TBC layer.

	1 µm	10 µm
Absorption coefficient (1/mm)	0.03	70
Scattering coefficient (1/mm)	13	0.1
Refraction index (-)	2.2	1.4

Furthermore, it is assumed that the thermal conductivity coefficient is equal to 2 W/mK, and the heat flux of the hot combustion gas to the TBC surface is taken 400 kW/m^2. This equals to a conductive heat flux of 400 kW/m^2, and a temperature gradient of $dT/dx = 200$ K/mm. The path length of radiation propagating through a layer of TBC is dependent of the propagation direction of the ray and thickness of the TBC layer. Figure 5 and 6 present respectively the local TBC thickness and the angle a ray makes with the TBC surface normal.

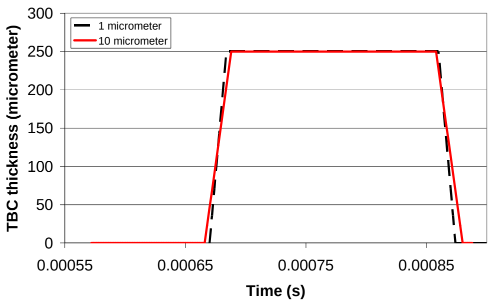

Fig. 5: Assumed thickness of the TBC layer as seen by detectors at 1 µm (black dashed line) and 10 µm (red solid line).

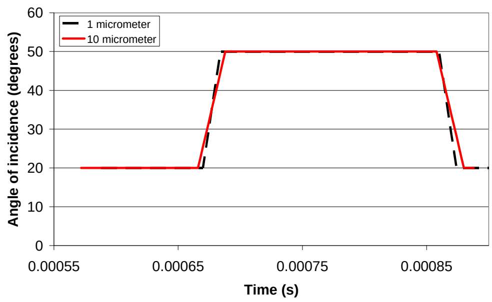

Fig. 6: Assumed angle of incidence between the direction of radiation leaving the turbine blade and the blade surface normal as seen by detectors at 1 µm (black dashed line) and 10 µm (red solid line).

Metal emissivity

The emission coefficient of the blade metal is taken equal to 1, i.e. the blade metal is considered as a blackbody.

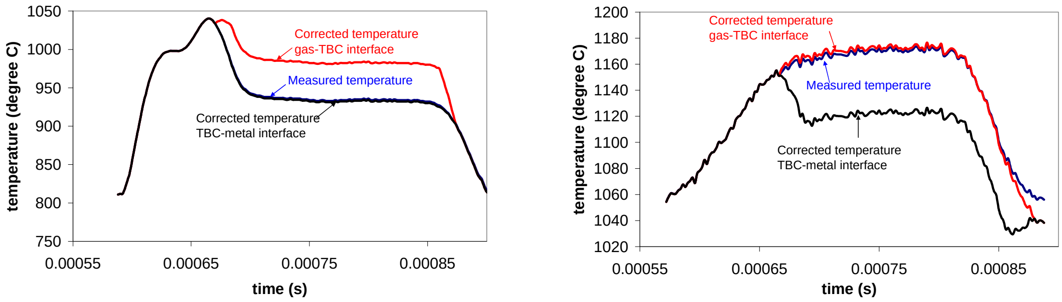

Fig. 7: Measured and corrected temperatures at 1 (left) and 10 µm (right).

These values are entered in the KEMA PERCEPTION software module, and the calculation is performed. The original measured temperature profile and calculated temperature profiles of the TBC-gas interface and metal-TBC interface are presented in Fig. 7. A number of conclusions are drawn:

- The measured temperature profiles at 1 and 10 µm, also presented in Fig. 1, have a very different trend. However, with the correction applied, the trend is more similar.
- The effect of the TBC layer on the measured temperature is significant. In case the TBC layer is approximately transparent, i.e. at 1 µm wavelength, the measured temperature corresponds well with the calculated temperature of the metal surface. In case the TBC layer is fully absorbing, i.e. at 10 µm wavelength, the measured temperature corresponds well with the temperature of the TBC surface.
- Knowing how to perform the temperature correction at the edges of the turbine blade is very difficult, due to the instant change in TBC thickness and angle of incidence at the edges.

Elements of further research:

1. The optical properties of the TBC layer have a large influence on the radiation signal. It is difficult to determine the absorption and scattering coefficients. Moreover, it is most likely that the coefficients are not uniform in the TBC layer. Obtaining the appropriate values is a time-consuming and difficult task, and the question remains how to obtain accurate estimates of these properties.
2. In the model specular reflection at the TBC interfaces is assumed. However, the bondcoat layer and TBC surface are also often regarded as diffusely reflecting. Research has to be adopted how interchanging between specular and diffusion reflection influences the radiation intensity.
3. In the model zero radiative exchange with the surroundings is assumed. This has only limited validity near the edges of the blades.

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