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ADVANCES IN TURBINE BLADE TEMPERATURE MEASUREMENTS

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ABSTRACT

Radiation pyrometry principles and imaging methods like photography and photoelectric scanning are combined to make accurate research quality temperature measurements on turbine airfoils. Two systems are described for obtaining detailed temperature distribution measurements: an infrared photographic system for stationary vanes and a photoelectric scanning system for rotating blades. An overview is presented outlining the design, calibration methods, and recent test results.

INTRODUCTION

Some operational jet engines use cooled turbine airfoils because they can operate with higher turbine inlet gas temperatures and thereby obtain higher engine efficiency. The upper limit on the turbine inlet gas temperature is strongly determined by the required turbine life which is a function of airfoil temperature and stress levels. The goal of turbine cooling design is to maintain the airfoils at the design temperature without producing any severe thermal gradients on the airfoil surface.

Surface temperature distributions are used to experimentally evaluate the performance of cooled turbine vanes and blades in ground based turbine test facilities. The temperature distribution measurement techniques described herein greatly assist in heat transfer, thermal stress, and blade life studies as well as provide correlation with analytical prediction methods. Because these studies require high resolution thermal maps of vanes and blades, non-contacting optical methods capable of obtaining such detail were investigated. An infrared (IR) photographic method was selected for temperature measurements of stationary vanes. This method uses conventional photographic equipment along with a densitometer and a computer for film data reduction. A photoelectric scanning system was developed for obtaining temperature distribution measurements on rotating turbine blades having blade tip speeds up to about 400 meters-per-second. This turbine blade pyrometer combines fiber optics with high speed electronics and also uses a computer for data reduction. An overview of each customized system design, calibration method, and recent test results are presented. Details of the systems have been reported in references 1, 2, and 3.

TEMPERATURE DISTRIBUTION MEASUREMENTS

Radiation pyrometry techniques presently in use for turbine cooling studies measure the intensity of a narrow bandwidth of near IR radiation emitted by the airfoil surface. Surface temperature is then calculated from the received radiation by using suitable calibration techniques. By combining radiation pyrometry principles with imaging methods, it is possible to obtain research quality temperature measurements over a considerable area of an airfoil with high spatial resolution.

The present approach followed at the Lewis Research Center is illustrated in figure 1. A suitable viewing system, interfaced with the test rig, gains viewing access to either the turbine vanes or blades. Surface radiance distribution is recorded using IR photography for stationary vanes, and photoelectric scanning for rotating blades. With the photographic method, a thermal image of a heated vane is first formed on film and later the film density distribution is converted into a surface temperature distribution. With the photoelectric method, the rotating blade is scanned and the detector output is converted into temperature in near real time.

Surfaces emit radiation as a function of their absolute temperature. The curves in the insert in figure 1 show the typical intensity variation with wavelength for several temperatures covering the range of interest for turbines. The shaded area in the near IR region indicates the general bandwidth measured with both systems. Sufficient power is radiated here to permit the measurement of temperatures (900 K to 1400 K) of interest. In addition, radiant emissions and absorptions from completely combusted jet fuels have negligible interfering line or band radiation in this interval. The wavelength interval is also within the optical region which permits the use of conventional optical techniques and equipment. Finally, the radiated energy in this interval increases rapidly with small increases in temperature, thereby inherently providing high sensitivity.

IR Photography Method

The IR Photographic method in use for stationary vane temperature measurements is shown in block diagram form in figure 2. This method is used to obtain a surface temperature map of a heated vane in hot gas test rig with an optical view port. The system consists of a remote-controlled camera (1) to image the vane radiation through an IR filter onto the IR sensitive film; a film processor (2); a microdensitometer (3) to measure and record film density information over the entire thermal image; and a computer (4) provided with calibration data to calculate the temperature distribution from the film density record. The final result is a turbine vane temperature record (5) consisting of temperature profiles and two-dimensional contour maps of temperature distribution.

The calibration technique is detailed in reference 1. An area of each film is exposed with a calibrated relative energy scale (step tablet on grey scale). This exposure determines the film (detector) response curve. The film response curve is then correlated with a temperature distribution curve. This latter curve is the distribution of relative radiant energy with temperature and is a plot of Plancks equation integrated over the bandwidth of detection which is determined by the filter transmission function and the IR film spectral sensitivity. A thermocouple located on the vane surface in the field was used as a reference point. At this point, one known temperature and one known density are used to correlate the two curves. No correction for surface emittance is required with the relative method of temperature calibration.

The advantage of the IR Photographic method is that a thermal image of a vane can be recorded in a fraction of a second and can also be resolved into very small spot sizes with a microdensitometer. A thermal image for a particular camera exposure is limited to an average temperature span of about 200 K. However, this is more than is required for properly designed cooling schemes. A possible disadvantage of the method is that temperature data are not available during the time of the test. There is usually a delay of several hours up to a day because of the sequence of procedures required. In most cases, this is not a serious drawback, and the detailed information available from a thermal image analysis compensates for the delay in time.

An example of a recent image analysis is shown in figure 3. For these tests, a film-cooled turbine vane was heated in a 1530 K gas stream in a thermal stress rig. A conventional photograph of the test vane is included in the figure and is used for dimensional reference as well as to locate surface features. The thermal image of the heated vane was recorded on 35 mm high speed IR film at a magnification of 0.2. A microdensitometer with a small measuring aperature was used to scan the image in two modes. (The equivalent measuring spot size on the vane itself was 0.05 cm.) One mode recorded a density profile scan (10x size) across the image. In this example, it was at the mid span location. The other mode records a contour map (10x size) in equal density increments over the entire thermal image. The density scale on the profile scan was calibrated into a temperature scale using the reference thermocouple and the calibration technique previously described. The contours on the map were converted into temperature by projecting corresponding locations from the mid-span profile curve to the contour map at the mid span location. Generally, all contours can be calibrated from one or two profile scans. In similar tests, vanes were instrumented with an array of thermocouples. Using one thermocouple as a reference point, the photographically determined temperatures at all other thermocouple locations agreed to within 1% of the temperature (expressed in °C) measured by the thermocouples.

Photoelectric Scanning Method

The customized photoelectric system developed for temperature measurement on rotating blades is referred to as a turbine blade pyrometer (TBP). The optics together with the high speed electronics of the TBP are capable of resolving a spot diameter of 0.05 cm on a blade moving with speeds of the order of 300 to 400 meters-per-second. Near real time displays of temperature profile are generated for a single blade or for small groups of blades at steady state conditions.

A block diagram of the TBP interfaced with a test engine is shown in figure 4. The protected fiber-optic probe (1) is positioned within the engine by an actuator and the fiber is focused in the plane of the turbine blades. As the heated blades rotate, the emitted radiation from the spot location (0.05 cm dia. instantaneous field of view of the fiber) is transferred optically to a fast response silicon avalanche detector (2), thereby generating a continuous high resolution intensity profile which is monitored on an oscilloscope (3) during the entire test. The amplified detector output is digitized by an analog to digital (A/D) converter (4) at ranges up to 2 MHz rate. A blade position sensor (5) supplies a trigger signal when the first test blade enters the field of view. Starting with this trigger signal, a 200 point sample of the digitized detector output is stored in a high speed memory (6). This process may be repeated a number of times to average out random noise. The number of test blades (usually 1 to 8) scanned with a 200 point sample is determined by the digitizing frequency and the speed of the turbine. The 200 data points are transferred from the memory at a slower rate to the computer (7) where each point is converted into temperature from a "look-up" table.

Calibration information in the "look-up" table is obtained before a test by focusing the optical probe onto an accurately known temperature source, and relating the digital output of the A/D converter to the temperature. A blackbody oven is used as the temperature source. Therefore, a correction for the surface emittance of the blade is required with this absolute method of temperature calibration.

The timing and control logic circuit (8) provides interchange of control between the computer, the memory and the A/D converter. Through the logic circuit, the operator, via the computer, has control over the entire TBP system. The system performs all the required operations and presents data on a CRT display in the form of a temperature profile and a listing of the 200 calibrated points making up the profile. A hard copy of the turbine blade temperature record (9) is made in the test cell in about 3 seconds. In addition to generating a single temperature profile scan record, the system can also obtain a series of scans over a range of radial locations, using the probe actuator, and present them in an isometric view. These data can alternatively be presented as a two-dimensional contour map of temperature distribution with additional computer processing.

An example of data obtained with the TBP system during an engine test is illustrated in figure 5. A group of convention cooled turbine test blades shown in the figure were instrumented with surface thermocouples. One blade contained a ceramic coating on the surface in the form of a chevron pattern to examine the spatial resolution of the system. Turbine inlet gas temperature was 1644 K while maximum blade temperature was limited to 1200 K by adjusting coolant flow. The tip speed of the blade was 366 meters-per-second. Typical temperature profiles are shown on the lower part of the figure. In the center is an isometric display of temperature profiles made across the chevron pattern at the scan line locations (1 thru 8) indicated on the blades. The origin is progressively offset with each scan. The isometric view is used to obtain a qualitative record of temperature distribution over the area bounded by the scans as well as to observe surface features like the chevron pattern. The apparent lower temperature of the chevron is due to its lower emittance. In the lower part of figure 5 is a quantitative temperature profile at scan location number three. The listing of the 200 calibrated point temperatures comprising the scan is available as another form of output presentation. Comparison of TBP and thermocouple measured temperatures agreed to within two percent of temperature (expressed in °C).

CONCLUDING REMARKS

At the Lewis Research Center IR photography has been used on several test rigs to investigate the effects of various cooling designs and for fundamental heat transfer studies. The turbine blade pyrometer was used to monitor and measure turbine blade temperature during uncoated and thermal barrier coated blade tests. Each technique has demonstrated the ability to produce research quality temperature distribution measurements.

Both techniques will be used in new test facilities. Updated and modified versions of the present systems are under development for use with higher temperature and pressure turbine test rigs.

REFERENCES

(1) Pollack, F. G. 1969. "Surface Temperature Mapping with Infrared Photographic Pyrometry for Turbine Cooling Investigations," National Aeronautics and Space Administration Tech Note D-5179.

(2) Buchele, D. R. and Lesco, D. J. 1972. "Pyrometer for Measuring Surface Temperature Distribution on a Rotating Turbine Blade," National Aeronautics and Space Administration Tech Memo X-68113.

(3) Uguccini, O. W.; Pollack, F. G.: High Resolution Surface Temperature Measurements on Rotating Turbine Blades with an Infrared Pyrometer. Proposed NASA Technical Note.

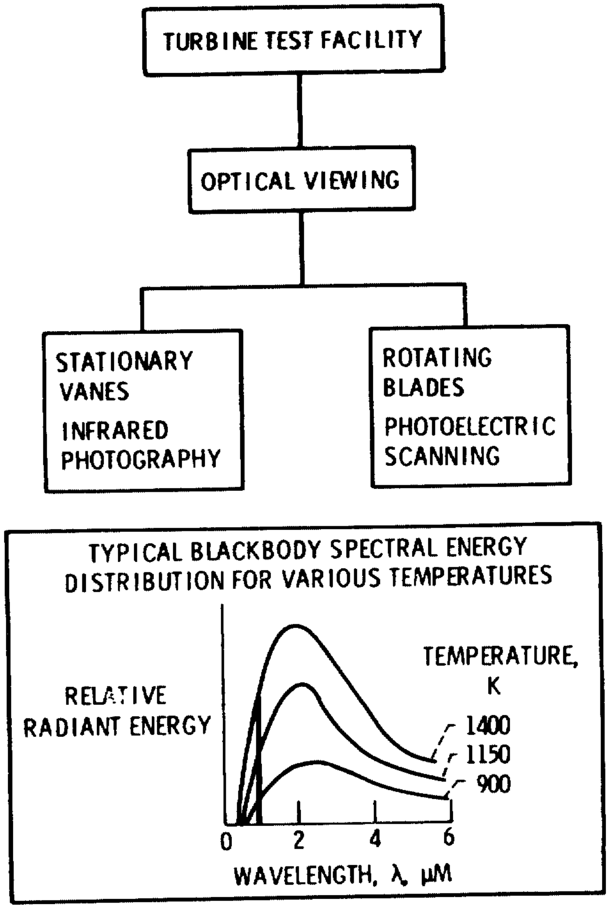


Figure 1. - Turbine temperature measurement with radiation pyrometry techniques.

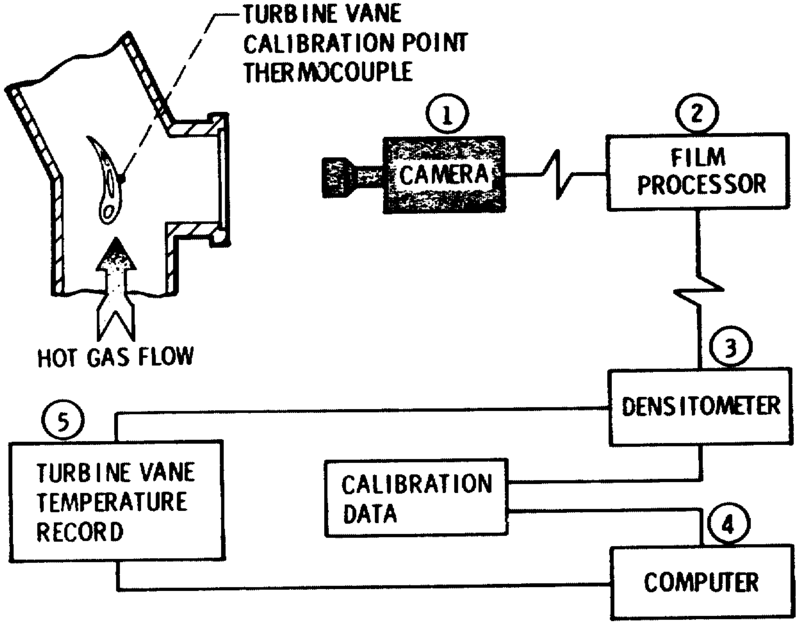
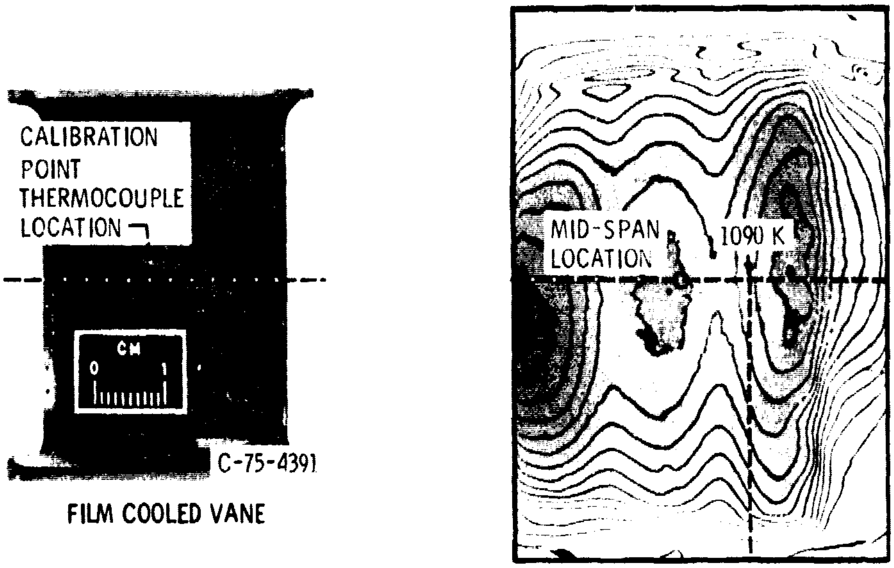
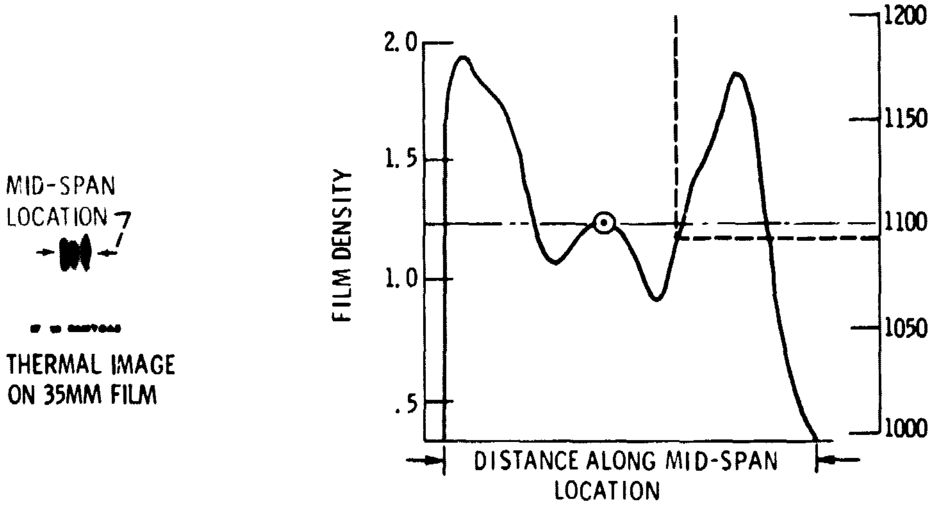


Figure 2. - Infrared photography method for stationary vanes.



FILM COOLED VANE

CONTOUR MAP



THERMAL IMAGE ON 35MM FILM

PROFILE SCAN

Figure 3. - Turbine vane temperature record.

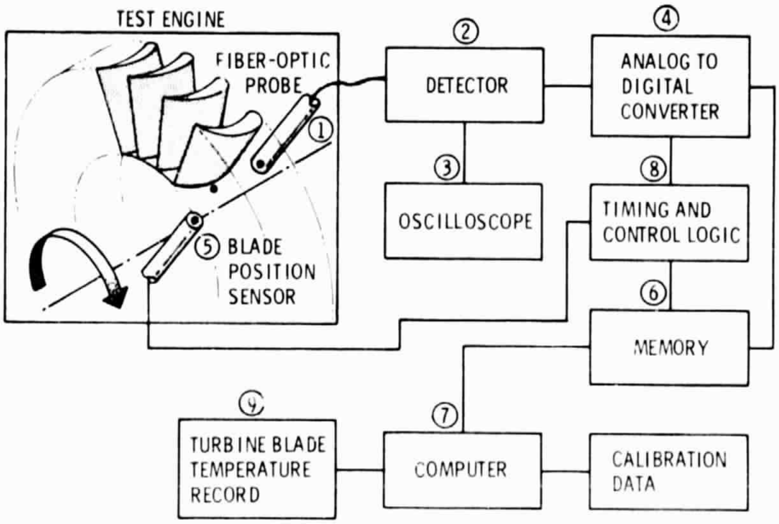
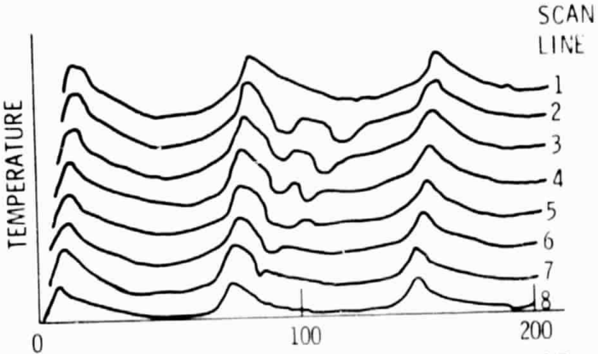
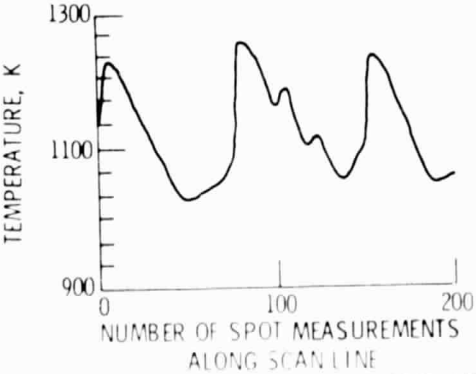


Figure 4. - Photoelectric scanning method for rotating blades.

CONVECTION COOLED
TURBINE BLADES



ISOMETRIC DISPLAY OF SCAN LINES 1 - 8



TEMPERATURE PROFILE ALONG SCAN LINE 3

Figure 5. - Turbine blade temperature record.