HTD-Vol. 226, Fundamental and Applied Heat Transfer Research
for Gas Turbine Engines
ASME 1992

THERMAL CHECK: A SIMPLE AND ACCURATE BENCH TEST FOR MEASURING THE AS-BUILT HEAT TRANSFER PERFORMANCE OF COOLING (OR HEATING) CIRCUITS IN GAS TURBINE COMPONENTS

Eugene F. Adiutori
Ventuno Press
West Chester, Ohio

ABSTRACT

"Thermal check" is a simple and accurate bench test for measuring the as-built heat transfer performance of cooling (or heating) circuits in gas turbine components. It involves measuring the temperature distribution which results when a uniform heat flux is applied to a component while air is flowing through the cooling circuit.

The particular advantage of thermal check is that it greatly shortens the design cycle, oftentimes making it possible to complete several design cycles on cooling circuits before the first engine is assembled.

NOMENCLATURE

h	heat transfer coefficient, W/m^2K
q	heat flux, W/m^2
R_{htr}	thermal resistance due to the heater filament and insulation, and the heater/component adhesive, m^2K/W
T	temperature, K

Subscripts

comp	component
htr	heater
i	ith location
t/c	thermocouple

INTRODUCTION

Internal cooling circuits are commonly used to cool gas turbine components. If the performance of a particular cooling circuit is critically important, its as-built performance is generally measured by testing an instrumented prototype engine. The component temperature distribution measured in the engine test is compared with temperatures calculated at the test conditions, using engine design h correlations and methodology. The comparison between measured and calculated temperature distribution is used to establish the as-built cooling performance of the circuit.

The major difficulties with measuring as-built cooling performance by testing an instrumented engine are:

- Data from engine tests is generally not available until long after the first components have been delivered, resulting in a design cycle measured in years.
- Boundary conditions on component surfaces are subject to large uncertainty during engine tests, and this causes large uncertainty in measured cooling performance.
- Engine tests are prohibitively expensive.

The design cycle would be greatly shortened if the as-built cooling performance of critical circuits were measured in component bench tests rather than engine tests. Moreover, bench tests are much less costly than engine tests, and they provide a more accurate measurement of cooling circuit performance because the boundary conditions in bench tests are not subject to the large uncertainty inherent in engine tests.

"Thermal check" is a component bench test for measuring the as-built performance of cooling or heating circuits. It is the subject of the patent noted in the Reference section. The manner in which thermal check is utilized in the design and manufacture of gas turbine components is described in this article.

THERMAL CHECK METHODOLOGY

Thermal check methodology involves applying a uniform heat flux to the EXternal surface of a cooled (or heated) component, and measuring the resultant steady-state temperature distribution. It is closely analogous to "flow check", a widely used bench test for measuring the as-built flow performance of gas turbine components.

In a thermal check, uniform heat flux is generated in thin film, electrical heaters glued to the external surface of the component. The heat flux is determined from the measured volts, amps, and heater area. The steady-state temperature distribution is measured either on the component surface with imbedded thermocouples, or on the heater surface with film thermocouples and/or infrared (IR) technology and/or liquid crystal (LC) technology.

If heat transfer in the component is essentially 1-dimensional, thermal check data are reduced directly to heat transfer coefficients, and h correlations used in engine analyses are modified to obtain agreement between calculated and measured h distribution. The modified h correlations describe the as-built heat transfer performance of the cooling circuit.

If heat transfer in the component is strongly multi-dimensional, the temperature distribution at thermal check conditions is calculated using the h correlations and the thermal conduction program used in engine analyses. The design h correlations are modified to obtain agreement between calculated and measured temperature distribution. The modified h correlations describe the as-built heat transfer performance of the cooling circuit.

Thermal check results may be used to accomplish the following:

- Demonstrate that the as-built performance of cooling (heating) circuits meets the design intent.

- Improve the accuracy of heat transfer analyses.

- Optimize the design of cooling (heating) circuits.

- Control the quality of cooling (heating) circuit heat transfer performance.

- Generate heat transfer data banks at low cost.

- Obtain off-design heat transfer data which can not be obtained from engine tests.

The details of thermal check, as they apply to gas turbine components, are described below.

HEATER DESIGN CONSIDERATIONS

The uniform heat flux required for thermal check is readily provided by thin film (approximately 0.01 cm thick) electrical heaters. These heaters are commercially available (for example, from the Minco Corporation). Although a wide variety of heaters are stock items, it is generally desirable to use custom heaters designed on the basis of the following criteria:

- The filament thickness and width must be uniform in order to generate a uniform heat flux. Filament aspect ratio should be 10 or more in order to minimize edge effects.

- The filament pattern should be simple. A series of over-and-back straight filaments works quite well, and makes it possible to adjust the heater length by simply cutting the heater with household scissors, and soldering a lead to the cut off end of the filament.

- The gaps between the heater filaments should be as small as possible--of the order of 0.01 cm.

- The thermal resistance between the heater filament and the heater surface should be minimized. (Values as small as .00018 m^2K/W are readily attainable.)

- The heater resistance should match the heater power supply. For example, if the power supply can provide a maximum of 10 amps at 110 volts, the heater resistance should be approximately 11 ohms in order to attain the highest heat flux permitted by the power supply.

In order to simplify attachment of the heater to the component, a high temperature film adhesive with minimum thermal resistance should be applied to the heater. Film adhesives are commercially available with thermal resistance as low as .00044 m^2K/W and operating temperatures to 450 K.

THERMAL CHECK OF A COMPONENT IN WHICH HEAT TRANSFER IS 1-DIMENSIONAL, AND IMBEDDED THERMOCOUPLES ARE PERMITTED

If heat transfer in a component is essentially 1-dimensional, and if imbedded thermocouples are permitted in the component surface, thermal check data are reduced directly to h distribution. (Heat transfer is essentially 1-dimensional in regions in which the wall is thin and uniform and is not severely curved, and heat flux gradients are moderate.)

For example, heat transfer in an internally cooled turbine frame strut would normally be essentially 1-dimensional, and a thermal check would be performed on it in the following way if imbedded thermocouples were permitted:

- Connect the turbine frame to an an air supply so that air flows to the cooling circuit in essentially the same way it flows in the engine.

- Instrument the strut as shown in Figure 1.

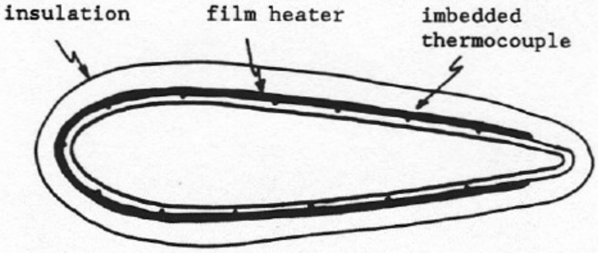

FIGURE 1 CROSS-SECTION OF A TURBINE FRAME STRUT CONFIGURED FOR THERMAL CHECK

Notice in Figure 1 that wire thermocouples are imbedded in EXternal surfaces. (Thermocouples are installed in external rather than internal surfaces because external installation is much simpler. This of course means that the data reduction must account for the ΔT through the wall. However, this generally introduces little error because the thermal resistance of the wall is usually much smaller than that of the boundary layer, and because wall thickness and thermal conductivity are usually known quite accurately.)

- Apply thin film heaters to the EXternal surface of the strut as shown in Figure 1. This is readily accomplished if a thin film adhesive is first applied to the heater surface. In order to avoid edge effects, the heaters should extend beyond the thermocouples by 3 or 4 times the filament width.
- Insulate the outer surface of the heaters.
- Provide means for measuring the inlet and outlet temperatures of the coolant, and the coolant flow rate.
- Obtain data at several heat flux levels and coolant flow rates. Record the electrical power to each heater, the area of each heater, the coolant flow rate, the temperature of the inlet and outlet coolant, and the temperature distribution in the test component.

The data are reduced to local values of heat flux (q) and boundary layer temperature difference (ΔT). Local values of h are determined by dividing q by ΔT.

The heat flux at each heater is determined by dividing heater electrical power by heater area, and analytically correcting for ambient heat loss. The boundary layer ΔT at each imbedded thermocouple location is obtained by subtracting the coolant inlet temperature from the thermocouple temperature, and analytically correcting for the following:

- Coolant temperature rise from the inlet to each thermocouple location (from a heat balance on the electrical heaters upstream of the thermocouple, and the calculated upstream ambient heat loss).
- Temperature drop through the wall at each thermocouple location (from the measured heat flux and design (or measured) values of local wall thickness and thermal conductivity).

Both corrections will generally be quite small.

The h correlations used in engine analyses are modified to obtain agreement between measured and calculated h distribution. The modified h correlations describe the as-built heat transfer performance of the internal cooling circuit.

THERMAL CHECK OF A COMPONENT IN WHICH HEAT TRANSFER IS MULTI-DIMENSIONAL, AND IMBEDDED THERMOCOUPLES ARE PERMITTED

If heat transfer within the component is strongly multi-dimensional, the thermal check is performed in the manner described above for a 1-dimensional case, but the data are not reduced directly to heat transfer coefficients.

Rather, the temperature data are compared with temperatures calculated at thermal check conditions using the h correlations and the thermal conduction program used in engine analyses. The h correlations are modified to obtain agreement between measured and calculated temperature distribution, and the modified h correlations describe the as-built thermal performance of the cooling circuit.

For example, heat transfer in cooled turbine blades is strongly multi-dimensional, and a thermal check of a turbine blade would be performed in the following way if imbedded thermocouples were permitted:

- Install the turbine blade in a flow stand--ie attach it to an air supply so that air flows to the cooling circuit in essentially the same way it flows in the engine.
- Instrument the turbine blade as shown in Fig 2.

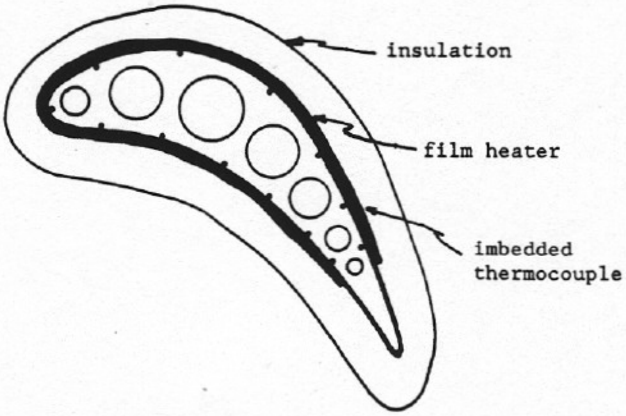

FIGURE 2 TURBINE BLADE CONFIGURED FOR THERMAL CHECK

Note that wire thermocouples are imbedded in the EXternal surface of the blade.

- Apply thin film heaters to the blade with a thin film adhesive applied to the heaters.
- Obtain data at several heat flux levels and coolant flow rates.
- Perform a heat transfer analysis of the component at thermal check conditions, using the h correlations and conduction program used in engine analyses.
- Compare the calculated temperature distribution with the measured distribution.
- Modify the h correlations so as to obtain agreement between measured and calculated temperature distribution.

The modified h correlations describe the as-built heat transfer performance of the cooling circuit.

THERMAL CHECK OF A COMPONENT IN WHICH IMBEDDED THERMOCOUPLES ARE NOT PERMITTED--METHOD 1 (FILM THERMOCOUPLES)

If imbedded thermocouples are not permitted in the test component (because of time/manpower/cost contraints, or because the integrity of the component would be compromised), thermal check can be used provided h values during thermal check are less than approximately 1700 W/m²K. The reason for this stipulation is described below.

When imbedded thermocouples are not permitted, the component temperature distribution is determined by measuring the temperature distribution on the EXternal surface of the HEATERS, and correcting for the temperature drop through the heater and adhesive. The temperature distribution on the external surface of the heaters can be determined with film thermocouples applied as shown in Fig. 3.

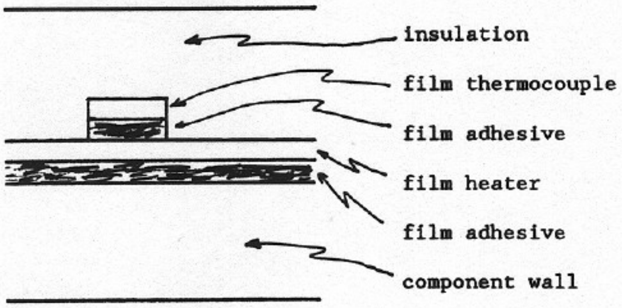

FIGURE 3 FILM THERMOCOUPLE APPLIED TO HEATER SURFACE

The component surface temperature at each film thermocouple location is determined from Eq. (1):

$$T_{comp,i} = T_{htr,i} - q_{htr}R_{htr} \qquad (1)$$

where R_{htr} is the thermal resistance due to the heater filament, the heater insulation, and the heater-to-wall adhesive.

With commercially available heaters and adhesives, the minimum value of R_{htr} is approximately 0.0006 m²K/W. Therefore, if the h values during thermal check are greater than 1700 W/m²K, the thermal resistance across the boundary layer will be smaller than R_{htr}, and the accuracy of the h results will suffer from the large relative correction. For this reason, temperature distribution should not be measured on the external surface of the heaters if h values during thermal check are more than approximately 1700 W/m²K.

The value of R_{htr} for a specific application can be determined from vendor specifications of the heater and the adhesive, but it is advisable to measure R_{htr} in the manner described below.

A SIMPLE METHOD FOR MEASURING R_{htr}

Figure (4) describes a simple apparatus which can be used to measure the value of R_{htr} with good accuracy. The value of R_{htr} is obtained from Eq. (2):

$$R_{htr} = (T_{film\ t/c} - T_{imbedded\ t/c})/q_{htr} \qquad (2)$$

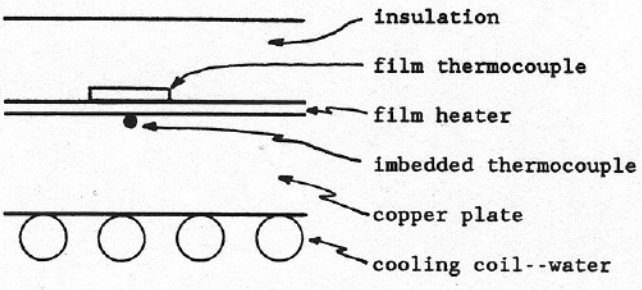

FIGURE 4 APPARATUS FOR MEASURING R_{htr}

THERMAL CHECK OF A COMPONENT IN WHICH IMBEDDED THERMOCOUPLES ARE NOT PERMITTED--METHOD 2 (IR) AND METHOD 3 (LC)

If h values during thermal check are less than 1700 W/m²K, thermal check may be performed by utilizing infrared (IR) or liquid crystal (LC) technology to measure the temperature distribution on the external surface of the heaters. The particular advantage of these technologies over thermocouple technology is that the data they provide can be used to generate temperature maps of high resolution. (It is generally impractical to install enough thermcouples to provide even moderate resolution.)

When IR technology is used, the heaters are applied in the normal manner, and are given a coat of high emissivity paint which provides a uniform emissivity. An IR recording is made of the surface of the heaters during the thermal check. Software reduces the IR recording to digital temperature distribution, and the temperature distribution is utilized in the manner described above.

When LC technology is used, the heaters are applied in the normal manner, and are given a coat of black paint, followed by a coat of liquid crystal paint. A video recording is made of the external surface of the heaters as the heater power is increased stepwise. The color lines in the liquid crystal are reduced to isotherms, and the isotherms are utilized in the manner described above.

USING THERMAL CHECK TO OPTIMIZE THE DESIGN OF INTERNAL COOLING CIRCUITS

Thermal check may be used to optimize the heat transfer design of internal cooling circuits. For example, optimum heat transfer design of a turbine nozzle airfoil generally requires a specific h distribution on the internal surface.

If the airfoil is cooled by an impingement insert, the h distribution is designer controlled by the size and distribution of holes in the insert. The desired optimum h distribution could be attained by performing a thermal check of the airfoil, then modifying the insert on the basis of the thermal check, and repeating the thermal check.

This trial-and-error process would continue until a thermal check indicated that the desired optimum h distribution had been attained.

USING THERMAL CHECK FOR QUALITY CONTROL

Thermal check may be used to control the heat transfer quality of internal cooling circuits.

If the performance of a particular cooling circuit were critically important, a non-destructive thermal check could be performed on 100% of the components which contain the circuit.

If the primary purpose of the thermal check were to verify that the manufacturing process was within control limits, a destructive or non-destructive thermal check would likely be performed on a sample basis.

If a component is normally flow checked during the manufacturing process, it would be cost effective to perform the thermal check in conjunction with the flow check.

("Flow check" is a bench test in which the flow characteristics of a component are measured, and the results are compared with flow characteristics calculated using the flow correlations and methodology used to design and analyze the component.

The comparison is used to modify the design flow correlations so as to obtain agreement between measured and calculated flow performance. The modified flow correlations describe the as-built flow performance of the component. Note the close analogy between flow check and thermal check.)

A non-destructive thermal check of a turbine blade would be accomplished in the following way:

- Apply a thin film electrical heater to the external surface of the blade.

- Use film thermocouples or IR or LC technology to measure the temperature distribution on the external surface of the heater.

- Obtain data at specified values of heater power level and cooling circuit flow rate or pressure ratio.

- Base the acceptance/rejection of the airfoil on a comparison of the thermal check data with an acceptable temperature distribution (or liquid crystal color pattern) determined by analysis, or preferably on a comparison with thermal check data obtained periodically on a master part known to be marginally acceptable.

CONCLUSIONS

Thermal check is a simple and accurate bench test for measuring the as-built heat transfer performance of cooling circuits in components such as those used in gas turbines. It is an inexpensive procedure which may be used to:

- Demonstrate that the as-built heat transfer performance of cooling (or heating) circuits meets the design intent.

- Improve the accuracy of heat transfer analyses.

- Optimize heat transfer design.

- Control the heat transfer quality of production parts.

The particular advantage of thermal check is that it greatly shortens the design cycle, oftentimes making it possible to complete several design cycles on cooling circuits *before the first engine is assembled*.

REFERENCES

U.S. Patent 4,902,139, "Apparatus and Method for Measuring the Thermal Performance of a Heated or Cooled Component", issued Feb. 20, 1990, Assignee General Electric Company, Inventor Eugene F. Adiutori