DESIGN AND MANUFACTURE OF A NEW DOUBLE-SIDED KAPTON HEAT FLUX GAUGE

A Thesis

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ABSTRACT

The measurement of Heat flux, or the flow of thermal energy, is a critical measurement for heat transfer analysis. In the case of axial flow turbines, the measurement of heat-flux is complicated by the high speed at which the turbo-machinery rotates. Additionally, because turbo-machinery utilizes fluid flow over a shaped body, it is important to not disrupt the air flow and boundary layer in the region of measurement to preserve the integrity of measured results. Because of these complications, heat flux gauges utilized in heat transfer studies of turbo-machinery must be critically designed to limit any disruptions caused by the instrumentation.

Early heat flux gauges were placed inside a cavity machined into the airfoil in a way that made the edge flush so as not to disrupt the airflow. Today, however, with the advances in film-cooling now utilized in the gas-turbine industry, it is not possible to machine a pocket onto a shaped blade due to internal air passages which cool the blade from within before expelling the gas as a cooling jet around the outer surface of the blade. For this reason and because one needs both the front side and back side temperature history, the heat-flux gauge substrate must be incredibly thin and must have a carefully aligned sensor on each side. To this end, a series of double-sided heat flux gauges have been developed which satisfy the design criteria.

The double-sided Kapton heat-flux gauge has allowed The Ohio State University (OSU) Gas Turbine Laboratory (GTL) to conduct research related to film effectiveness within film-cooled full-stage rotating high-pressure turbines. The first generation of this device developed at the OSU GTL for this purpose in the 1990’s and while effective had several design characteristics which proved difficult to manufacture consistently, including a fragile set of three masks used for the gauge design and a requirement to puncture the insulating material on which the gauges were placed. In time these features made gauge manufacture difficult due to the requirement that the front and back gauges be located precisely in line with each other (top to bottom), and greatly contributed to large gauge-to-gauge variation.

A second-generation gauge was developed which would greatly decrease the variation among units. The new gauge incorporated a less fragile thermal resistor design to decrease destruction caused during cleaning, required only two masks, as well as a novel concept to complete the electrical circuit to the bottom gauge when it was not exposed, without requiring an altering of the insulating material integrity.

The development of a new heat flux gauge, which is less than 0.0011-inches thick, provides only an extreme minimum of flow disruption while additionally satisfying requirements of decreased complexity of construction and decreasing gauge-to-gauge variation and will be implemented on upcoming turbine experiments.

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NOMENCLATURE AND ABBREVIATIONS

OSU GTL	The Ohio State University Gas Turbine Laboratory
MIT GTL	Massachusetts Institute of Technology Gas Turbine Laboratory
Q	Heat Flux
k	Thermal Conductivity
d	Specimen Thickness
T1	Upper/Front Kapton Gauge Temperature
T2	Lower/Rear Kapton Gauge Temperature

CHAPTER 1

INTRODUCTION

The primary goal of this activity was to develop and manufacture an improved double-sided Kapton heat-flux gauge that could be used as part of the Tech 56 Build 2 film cooling measurement program. Jeff Barton was responsible for the previous development work at the OSU GTL involving these devices. The development and construction efforts of Mr. Barton formed the background for the development of the new gauge work described herein.

Epstein et al. at the MIT Gas Turbine Laboratory performed the initial development effort on the Kapton heat-flux gauge and that work is reported in Reference 1. The construction technique used at the OSU GTL is significantly different from that used in Reference 1, but the basic ideas related to the gauge are the same.

Because the airfoil upon which these heat-flux gauges are attached is internally and externally cooled, it is necessary to have both a front side and a backside temperature at the specific measurement location. Thus, the double-sided gauge is essential, but it does not necessarily have to be made using Kapton as the base material. In the first generation design, the four lead wires were deposited on one side of the Kapton film and a nickel heat flux gauge was deposited on each side. In order to obtain access to the underside gauge, feed through holes were placed in the Kapton. These feed through holes were a constant source of difficulty and were found to be the weak link in the previous gauge design. Thus, the primary intent of the new design was to eliminate the feed through holes but retain a nickel gauge on both sides of the Kapton. Manufacturing of the current gauge (first generation OSU GTL) design was initiated to provide experience in gauge manufacture during the development of the second-generation design.

John Newkirk and Jeff Barton developed a prototype second-generation gauge that was eventually adopted as the final second-generation design.

CHAPTER 2

HEAT-FLUX GAUGES

Successful development of the double-sided heat flux gauge has upgraded the GTL capabilities to conduct film effectiveness measurement programs using a fully cooled high-pressure turbine stage [2]. The construction of the gauge is such that the lower gauge is immediately below the upper gauge and thus at the same relative location when mounted on an airfoil, allowing use of a one-dimensional semi-infinite heat-transfer analysis. The very early double-sided Kapton heat flux gauge development was done at the MIT GTL and is reported in Reference [1]. As noted earlier in this paper, the basic principal of a double-sided gauge on a polyimide material is the same as that developed at MIT, but the construction technique being used at the OSU GTL is significantly different from the MIT technique.

The basic concepts behind the heat-flux gauge are simple: temperature readings *(T[t])*, taken on each side of a material of known thermal conductivity *(k)*, and of thickness *(d)* will allow calculation of local heat-flux rate [*Q(t)*]. By allowing each temperature measurement to be taken in the identical span and chord location, a semi-infinite-sheet approximation will hold, permitting the simplified calculation of heat-flux through the following equation:

$$\dot{Q} = \frac{k}{d}\left[T_1\left(t_n\right) - T_2\left(t_n\right)\right]$$

The manufacture of the second generation heat-flux gauge follows closely that of the first generation GTL gauge, differing only in the geometric design and shape of the gauge pattern itself, as well as the method employed to complete the circuit of the rear gauge. All information presented below applies to both sets of gauges, with appropriate new vs. old qualities being addressed in the text.

For the temperature time history of the Kapton heat-flux gauge it is important to know the value *k/d* of the substrate material. The 0.001VN Kapton, a hydrocarbon polyimide film developed by DuPont, was selected as a material well suited to heat-flux gauge manufacture based on its low thermal conductivity and availability of film thickness down to 0.0005” [3]. DuPont publishes a thermal conductivity value of k = 0.12 W/m*K. In calibration measurements conducted by Scott Murphy at the OSU GTL a thermal conductivity of approximately twice the published value was determined experimentally [4]. Subsequent discussions with DuPont indicated that they measured thermal conductivity following ASTM F-433-77 (1987). Upon further inspection it was discovered that ASTM F-433-77 (1987) requires a sample to be a minimum of 0.090” thick while the published value is for a sample only 0.001”thick [5].

The OSU GTL has traditionally used platinum thin-film heat flux gauges painted onto a Pyrex substructure, which could have potentially been used for the film cooling measurement programs [2]. However, the use of the Pyrex gauge technique presented some problems not present with the Kapton substrate. The first of these was that the Pyrex gauge has a thickness significantly greater than the 0.001-inch thick Kapton and the wall thickness of the typical film cooled turbine airfoil is relatively thin compared to the normal thickness of the available Pyrex sheet material. The second difficulty with the Pyrex technique is that one would still have to develop a double-sided gauge technique because both temperatures are needed when doing film-cooling studies. The polyimide film has the advantage of being relatively thin, though still not zero thickness. Installation of the gauges onto the airfoil surfaces thus becomes an important consideration in order to minimize contour disruption. In order to maintain a minimal profile, and hence minimal flow interruption, the heat flux gauges were deposited directly onto the Kapton surface. Because adhesives or other forms of fasteners would interfere with the true transfer of thermal energy through the film, gauges were required to be placed onto the Kapton surface without the use of adhesives or mechanical fasteners. Placement of the gauge element (nickel in this case) was accomplished via Physical Vapor Deposition (PVD).

PVD technology has been available for over fifty years and has been employed in the manufacture of electronic circuitry and high-precision mirrors, as well as various other capacities. PVD begins with the placement of a target and source within a vacuum tank. For the purposes of heat flux gauge construction, the target is a single piece of Kapton, sandwiched between two “masks” or stencils, which are cut in a negative pattern of the gauge to be deposited on the Kapton sheet. The masks and sheet were in turn placed between two frames and secured to ensure proper alignment and prevent shifting of the Kapton relative to the masks. The source for heat-flux gauges is nickel powder and the source of the lead wires from the gauge to the outside is a copper pellet.

The vacuum chamber is evacuated to an ultra-low vacuum, on the order of 10^{-7} torr. When a solid is heated at extreme low pressures it can flash into a vaporous state, allowing the vapor to be physically deposited on any solid material the vapor encounters. Gauges and a primer coat for electrical leads were deposited using nickel, while leads were deposited using copper.

CHAPTER 3

GAUGE DESIGN CHANGES

Accurately observing resistive changes in the heat-flux gauge due to temperature effects required that the gauge have a significant resistance value. The resistance of the gauge is a clear function of the length, width, and thickness of the element. The length and width are both dictated by the desire to have as close to point measurement of heat flux as is possible, and the airfoils with which one is working are relatively small. To this end, the first generation GTL design consisted of 9 bends, creating a serpentine pattern across the gauge face and a deposition thickness designed to produce a gauge resistance on the order of 500 to 1000 ohms. In the second-generation gauge, the number of bends was reduced to three while decreasing the order of resistance, allowing construction of gauges which simplified the mask cleaning and manufacture. Figure 1 shows the second-generation gauge serpentine pattern design (top elements of figure) against that of the original gauge design (lower elements of figure). During cleaning of the masks of the first generation design, it was typical to bend one or more of the "fingers" which penetrated into the gauge region and provided regions where the gauge path would turn. The large number of fingers created difficulty during cleaning and handling as any bending of the fingers could result in unusable gauges due to electrical short circuits.

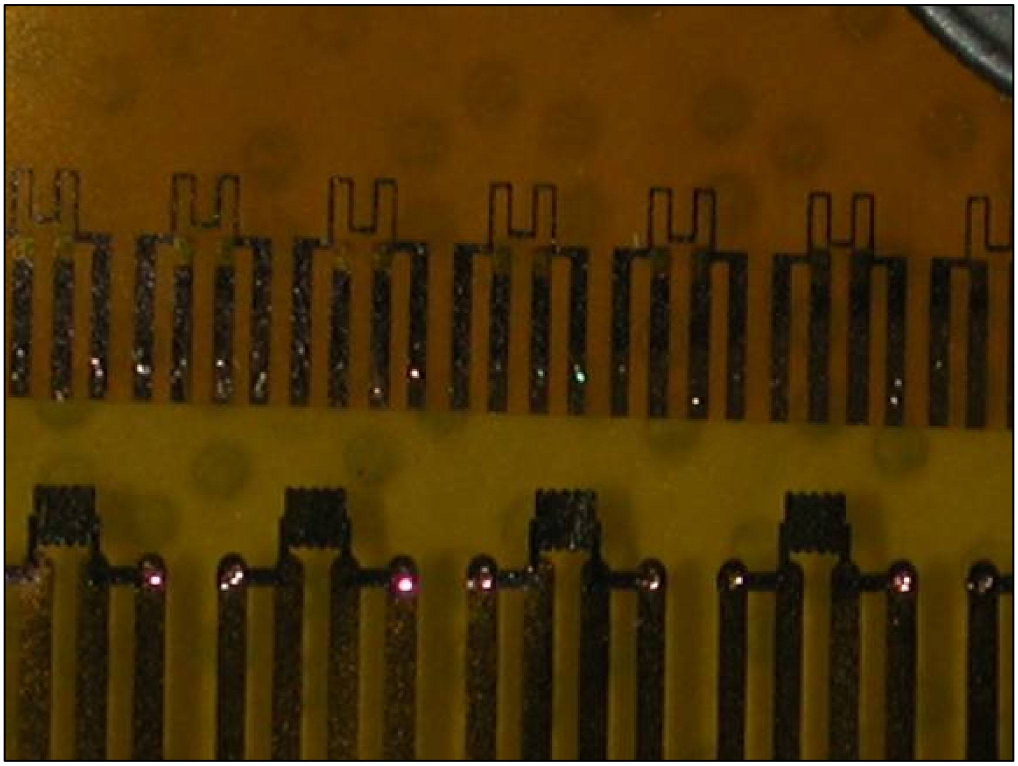

Figure 1 First (bottom) and Second (top) Generation OSU GTL Double Sided Kapton Heat-Flux Gauges

Also in an effort to simplify mask manufacture, gauge and lead masks were combined into a single mask for each of the top and bottom gauges, eliminating the need to disassemble the frame assembly and change masks in and out, potentially skewing the alignment of the top surface and bottom surface gauges and invalidating the critical 1-Dimensional assumptions. In order to allow for depositions of different thickness in specific regions, it was necessary to develop a system of plates, which could be interchanged to cover exposed regions.

The necessity for having a heat-flux gauge on both sides of a film, with electrical connections on only the exposed surface of the film presents an interesting obstacle. The first-generation design required that a pair of “through holes” be punched at the base of the back gauges. These through holes aligned with a pair of leads for the rear gauges that were deposited on the front side of the polyimide sheet and are shown in figure 2. The holes were filled with an electrically conductive silver epoxy to provide circuit continuity through the hole.

Figure 2 - Through-Holes of Current GTL Double-Sided Kapton Heat-Flux Gauge

The existence of the through holes was the primary concern in the development of the second-generation design. Punching through holes is a delicate process and was a consistent source of gauge failure, requiring a sharp awl to be forced through the rather strong Kapton. The punching of holes could and did result in the destruction of mask sets. Additionally, there was concern that the resulting frayed material at the location of the through holes could result in slight, yet important disruption of the cooling flow over the gauge.

The most significant change in the second-generation gauge was the elimination of these through holes. The new design required a pair of leads be run down the length of the back side, in addition to the two pairs of leads running down the front side. The circuit of the back gauge was completed by a deposition of nickel and copper applied to the bottom edge of the gauge sheet to allow conduction around the sheet edge. For this to be successful, it was necessary to only place short leads (the previous 4” leads were frequently trimmed to be less than 0.5”) on the Kapton film; ensuring the leads did not terminate before the Kapton sheet edge. Small cuts made between each lead eliminate any short circuits via the sheet edge. This process proved extremely effective and reliable after some practice.

CHAPTER 4

RESULTS

All difficulties encountered during the production of the old gauge designs were minimal. Electrical resistance issues were clearly attributed to masks with bent gauge fingers or other clear physical defects. Adhesion issues were considerably more difficult to pinpoint, but did not occur consistently during production. For these reasons, development of the second gauge generation was conducted. It was believed that any resistive or adhesive issues would occur with an identical frequency as with the original design and be considered much more of a nuisance to production than truly problematic.

Initial manufacture of the second-generation gauges began in January of 2004. It was immediately apparent that the adhesive issues were significant and wide-spread. Adhesive issues were marked by failed tape tests; adhering scotch tape to the freshly deposited film and pealing the tape back at a 90^o angle. A second tell-tale indication of poor adhesion was “mud-flatting,” a cracking pattern observed on the fresh deposits which resembled the cracks made by large amounts of mud after drying in the sun. After substantial investigation of the adhesive problems it was discovered that the organic adhesive found on Kapton tape, which was being used to secure the Kapton film to the frames was “out-gassing” and releasing contaminants into the system which caused poor adhesion.

Following the time consuming solution of adhesion issues, development concentration shifted to the consistent deposition around the end of the film required to eliminate the use of through-holes. Various trials were conducted, varying target orientation within the vacuum chamber to improve the deposition procedure around the film edge. Initially the ability to successfully deposit around the film edge proved inconsistent, as some gauge sets showed a large number of successful gauges, with low resistance around the film edge deposits, while many others showed few to no successful around the film edge deposits.

The edge deposit procedure eventually developed entailed the sandwiching of an otherwise complete gauge set (fully completed front and rear gauges and leads) between two plates. The plate assembly also used two small sheets of Kapton placed on each side of the gauges to protect them from any damage caused by the plates. The Kapton gauge set was positioned such that only a very slight amount of the gauge sheet edge was exposed between the protective Kapton sheets and so the edge to be deposited on was approximately 1/16-inch above the bottom plate edge.

CHAPTER 5

CONCLUSIONS

The development effort put towards the second generation OSU GTL Kapton Heat-Flux gauge has yielded a new gauge and methods of production, which have greatly decreased the manufacturing difficulties associated with the previous design while maintaining the instrumentation capabilities of the OSU GTL. The new design which eliminates the necessity of puncturing the Kapton film to complete the thermal resistor circuit from the front to back surfaces greatly decreases gauge variation associated with the manufacturing process. Additionally, the improved design of the thermal resistor itself lends to increased mask durability and manufacturing simplifications.

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