DEVELOPMENT AND EVALUATION OF THE TIME-RESOLVED HEAT AND TEMPERATURE ARRAY

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The development and evaluation of a differential style heat flux gauge is presented. The sensor is constructed from spot-welded foils of copper and constantan on either side of a thin Kapton® polyimide film and is capable of measuring the heat flux and surface temperature at ten locations simultaneously. Analytical modeling was performed to estimate the sensor’s sensitivity and time response. Calibrations were performed in conduction, convection, and radiation yielding an average heat flux sensitivity of 210 $\mu$V/(W/cm²). Time response measurements were also performed which gave an average first-order response of 169 milliseconds. The capabilities of the sensor are demonstrated by showing its use in on-going convection research.

I. Introduction

The accurate characterization of a thermal system requires the measurement of both temperatures and energy fluxes. While temperatures can be measured in a variety of ways, the accurate measurement of heat flux is still a challenge. This paper reports on the development and evaluation of a simple heat flux sensor capable of making multiple simultaneous, time-resolved heat flux and surface temperature measurements. This capability allows the sensor to measure the distribution of heat flux over a surface to better describe the physical phenomena. Examples of research areas where this sensor could be used include gas turbines, electronics cooling, and biological systems.

Heat transfer rates have been measured using a variety of sensors operating on different principles [1]. One popular type of heat flux sensor is called a differential sensor. By measuring the temperature drop across a known thermal resistance, the heat flux through the sensor is determined using Fourier’s Law which, at steady state, reduces to

$$q'' = \frac{k}{\delta} \Delta T$$  \hspace{1cm} (1)

where $k$ and $\delta$ are the thermal conductivity and thickness of the resistance layer. The temperature difference across the gage ($\Delta T$) can be measured using either thermocouples or resistance temperature detectors (RTDs).

Thin-film heat flux gages have certain advantages over other types of differential heat flux sensors. It is generally possible to place a number of sensors on a single film which allows the heat flux to a surface to be mapped. This is particularly important when investigating the effects of non-uniform boundary conditions on heat transfer, such as turbulence, jets, and transition. Another advantage is that thin-film gages can be made flexible, allowing them to be mounted to curved surfaces such as airfoils. Thinner sensors also have a frequency response that is faster than traditional designs such as the Schmidt-Boelter gage [2].

Several researchers have developed thin-film differential heat flux sensors. Ortolano and Hines [3] created a thermopile to measure the temperature drop across a thermal resistance layer. Their sensor was able to produce a large output at the expense of poor spatial resolution. Epstein et al. [4] used vapor deposition to deposit nickel RTDs on either side of a 25 micron polyimide (Kapton®) substrate. A similar sensor was developed by Piccini et al. [5] except RTDs were only deposited on one side of the polyimide. The sensor was then mounted on a test article which was manufactured from metal whose temperature was monitored using a thermocouple. Since the thermal conductivity of the model was high, it was assumed that the temperature measured by the thermocouple was the temperature of the backside of the heat flux gage. The heat flux at each RTD location was then determined by the temperature difference between the RTD and the thermocouple.

Recently, a new type of heat flux sensor was developed at Virginia Tech [6]. The Heat Flux Array (HFA) is a differential heat flux sensor which utilizes a pair of vapor deposited copper/nickel thermocouples to directly measure the temperature drop across the sensor.
Since the temperature drop is directly measured, the voltage generated is proportional to the heat flux through the gage. The principle problem with this sensor stemmed from the fragility of the thin-films produced by the vapor deposition process. The current paper reports on the development, fabrication, and calibration of an improved version of the HFA called the Time-Resolved Heat and Temperature Array (THeTA). The THeTA utilizes spot welded thermoelectric foils instead of deposited films which produces a more sensitive and robust sensor.

II. Sensor Design

The THeTA is a differential heat flux sensor meaning it measures heat flux by measuring the temperature drop across a thermal resistance. The THeTA measures this temperature drop directly by a series of two thermocouples whose junctions are directly across from each other on opposite sides of the thermal resistance, Kapton® in this case. Using Kapton® as the thermal resistance sets the theoretical upper temperature limit of the THeTA at 300°C. The design concept of the THeTA is shown in Fig. 1. The voltage generated between the two positive thermoelectric alloys, \( \Delta V_1 \), is a measure of the temperature difference, \( T_1 - T_2 \). Also, the voltage generated between one of the positive thermoelectric alloys and the negative thermoelectric alloy, \( \Delta V_2 \), is a direct measure of the temperature where the two traces meet, \( T_1 \) in Fig. 1. The ability to measure both heat flux and surface temperature is vital in convection research since this allows the convective heat transfer coefficient to be directly measured in a time-resolved manner. Also, recent work has demonstrated that a sensor capable of measuring both the heat flux through the sensor as well as the temperature of the sensor can provide a more accurate measurement of the actual heat flux to the sensor [7].

![Fig. 1 Conceptual design of THeTA](image)

The thermoelectric alloys selected for the THeTA were copper and constantan, better known as type T thermocouple alloys. Type T was selected because it offers a number of advantages over other thermocouple types. First, since the positive metal is copper, copper wires can be used to carry the signal from the sensor to the data acquisition unit without creating any additional thermocouple junctions. Second, type T alloys offer a comparatively high sensitivity at 41\( \mu \text{V/°C} \) [8]. Finally, since constantan is commonly used in strain gages, it is widely available in thin sheets.

III. Sensor Fabrication

The THeTA reported on in this paper was equipped with ten measurement locations. Fig. 2 shows the THeTA during construction. The thermocouple pairs were formed by spot welding precision cut foils of type T thermocouple alloys which were 12.5 microns thick. At the weld location, the copper foil was 1.58mm (1/16”) wide and overlapped the constantan foil by 3.16mm (1/8”). The two foils were welded at many locations over this overlap area so the sensing area can be assumed to be 1.58mm by 3.16mm. Ten such pairs were placed on one THeTA at 6.35mm (1/4”) spacing along a line. The thermocouple pairs were connected from one side of the gage to the other by folding the constantan foil over the edge of the Kapton®. Note that only one piece of constantan foil was needed and that all the heat flux sensors were electrically connected. By measuring the signal generated between the constantan foil and any copper foil, the temperature at the location where those two metals were joined could be determined since the junction formed a type T thermocouple. Therefore one THeTA is able to measure the heat flux at ten locations as well as the surface temperature on either side of the sensor at all ten sensing locations. Typically, the THeTA is wired so that ten heat fluxes and ten surface temperature measurements are obtained.

![Fig. 2 THeTA during construction](image)
bonded to the Kapton using a thermally activated epoxy. The entire gage was also encapsulated in 3 micron thick Mylar using the same epoxy. These two processes were accomplished at the same time in a hot press with the gage between two sheets of Teflon. Encapsulating the gage serves multiple purposes. First, it protects the foils from oxidation. Second, the Mylar isolates the gage electrically which allows its use on conductive materials. Finally, encapsulating the gage waterproofs it which allows it to be used in research in water tunnels. Fig. 3 shows the gage after encapsulation. As a final step, the sensor was painted using Zynolyte flat black paint if it will be used to measure radiation heat flux. Since the sensor discussed in this paper was calibrated in radiation, it received the black coating.

\[ R'' = 2R_G + R_k \]  

(3)

Each individual resistance is simply the ratio of thickness to thermal conductivity. Based on the known thickness of the Mylar, Kapton, and welded foils, the thickness of the glue layer was estimated from measurements of the average completed gage thickness. By assuming that all four glue layers were the same thickness, the glue layer was determined to be approximately 20 microns thick. The thermal conductivity of the epoxy was assumed to be 0.20 W/(m-K) based on the measurements of Tanaeva and Evseeva [9]. The thickness of the Kapton® was measured to be 50 microns and the thermal conductivity has been measured to be 0.288 W/(m-K)[6]. Adding these individual resistances gave a total thermal resistance of 3.73 °C/(W/cm²). Multiplying the thermal resistance by the room temperature Seebeck coefficient (41 μV/°C) gave a theoretical sensitivity of 153 μV/(W/cm²).

The time response of differential heat flux sensors depends on how long it takes thermal energy to diffuse through the sensor and establish a linear temperature profile within the sensor. Hager [10] solved the one-dimensional heat equation for a step change in heat flux and calculated the time required for a differential temperature heat flux sensor to obtain 98% response on a perfect heat sink to be

\[ t = 1.5 \frac{δ^2}{α} \]  

(1)

where \( α \) is the thermal diffusivity of the thermal resistance layer. Unfortunately, due to the multiple different layers and the relatively thick metal foils used in the construction of the THETA, Hager’s analysis cannot be used. Instead, the RC network shown in Fig. 4 was used to approximate the time response. The capacitance of each layer is the product of the layer’s thickness, density, and specific heat. In the electrical analog circuit, each layer was treated as a lumped capacitance meaning that, as far as the thermal storage term was concerned, the entire layer was at a uniform temperature. A fourth order Runge-Kutta method was then used to solve the resulting set of eight coupled ordinary differential equations for a step input in heat flux.

Solving the coupled equations gave the temperature history at each node in the circuit. To determine the time response of the sensor, the ratio of

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IV. Theoretical Sensitivity and Time Response

The sensitivity of the THETA is dependent on three factors: the Seebeck coefficient of the thermoelectric materials used and the thermal conductivity and thickness of the thermal resistance. Multiplying the Seebeck coefficient by the thermal resistance gives the theoretical sensitivity of the sensor.

\[ S_{THETA} = \frac{δ}{k} S_t = R'' Se \]  

(2)

Fig. 4 shows a slice of the THETA along with a model of its electrical analog circuit. For the sensitivity calculations only the resistances are needed. The capacitances will be used to determine the theoretical time response of the sensor. For the THETA, the thermal resistance, \( R'' \), is the combined thermal resistance of the three layers between the two thermocouple layers. From Fig. 4, this total resistance is the resistance of the Kapton® plus the resistance of the glue layer on either side of the Kapton as shown in Eq. 3.
the temperature difference $T_1 - T_2$ to the steady state temperature difference was examined. At steady state, the temperature difference was the applied heat flux multiplied by $R^*$ from Eq. 3. The time required for this ratio to equal 0.632 (1-$e^{-1}$), and therefore the theoretical first-order exponential time constant, was found to be 124 milliseconds.

measure the heat transfer coefficient which was then compared to the analytical solution for Hiemenz flow. This test allowed the sensors performance to be evaluated without the need of a reference sensor. For each set of tests an uncertainty analysis is presented in the appendix.

B. Seebeck Coefficient Measurement

Since a traditional bulk wire thermocouple was not used in the manufacture of the THeTA, the Seebeck coefficient of the copper/constantan foils was measured. This measurement was made affixing the THeTA to an aluminum plate equipped with a resistance heater. A type E thermocouple was also imbedded in the aluminum plate and served as the temperature reference. The reference thermocouple came supplied with a voltage to temperature polynomial and an accuracy guarantee of 0.5°C. A 24-bit National Instruments (NI) USB-9161 thermocouple DAQ was used to measure the voltages from the THeTA as well as the type E standard at 1Hz. Since all temperature measurements were made relative to room temperature, no cold junction compensation was needed. Prior to running a test, the aluminum plate was wrapped in fiberglass insulation to eliminate heat losses to the surroundings. The plate was then heated to 10, 20, and 30 degrees above room temperature and allowed to reach steady-state. Once steady conditions were reached, the voltages produced between the constantan and copper foils were measured and averaged over 5 minutes (300 samples). The Seebeck coefficient was then determined by dividing this average voltage by the measured temperature rise. This calculation yielded a Seebeck coefficient of the copper/constantan foils of 34.29±0.64µV/°C which is somewhat lower than the value typically associated with type T thermocouples. Using this value in place of the 41µV/°C value from section IV decreased the predicted sensitivity to 127.6 µV/(W/cm²).

C. Conduction Calibration

The THeTA was calibrated in conduction using the conduction calibration facility located in the Advanced Experimental Thermo-Fluids Engineering Research (AETH) laboratory at Virginia Tech. This system is described in detail in [11] and is shown in Fig. 5. One-dimensional conduction is maintained between two aluminum plates, one heated and the other cooled. An RDF Corp. heat flux sensor was used as a reference as it has approximately the same thermal resistance as the THeTA. The RDF sensor and the THeTA were placed in a mask of Kapton® the size of the plates in the

![Diagram of THeTA and electrical analogy](image)

Fig. 4 Side view of THeTA and electrical analogy

V. Sensor Calibration

A. Introduction

In order to confidently use a heat flux sensor, it must first be accurately and thoroughly calibrated. As a first calibration, the Seebeck coefficient of the thermoelectric alloys used was determined experimentally. Next, the THeTA was calibrated in both conduction and radiation using RDF and Schmidt-Boelter reference sensors respectively. The radiation calibrations were further used to experimentally determine the time response of the sensor. Finally, the THeTA was calibrated in convection by affixing it to a plate which experienced Hiemenz stagnation flow in a low speed water tunnel. Since the THeTA measured both heat flux and surface temperature, it was used to
Conduction calibration facility as shown in Fig. 5. Masking the two sensors helped ensure that the heat conduction was uniform over the area of the plates. Therefore, it was assumed that the heat flux through the RDF sensor was the same as the heat flux through the THeTA. Contact resistance between the two aluminum plates and the Kapton layer was minimized and made uniform using conformable layers of Gap Pad©. Once the stack was assembled, it was insulated to help ensure that only conduction from the hot plate to the cold plate occurred.

Conduction calibrations were performed at three levels of heat flux, 0.5, 1.0, and 1.5 W/cm². This was controlled by varying the voltage to the resistance heater on the hot plate. The ten heat flux signals from the THeTA were amplified using custom amplifier boards whose design is described by Ewing [12]. These amplified signals were then recorded at 10Hz using a 16-bit NI USB 6226 DAQ connected to a PC. A 24-bit NI USB-9161 thermocouple DAQ was used to record the RDF output as well as the type T thermocouple built into the RDF. Both RDF signals were sampled at 1Hz.

Fig. 5 Conduction calibration facility

To determine the sensitivity of the ten sensors on the THeTA, each sensor’s output was divided by the calibrated output of the reference sensor.

\[ S_{\text{THeTA}} = \frac{V_{\text{THeTA}}}{V_{\text{ref}}} \frac{1}{S_{\text{ref}}} \]  

(2)

\( S_{\text{HFA}} \) was averaged over 5 minutes (300 samples) after the measured heat flux and RDF temperature had reached steady state.

To demonstrate the repeatability of the conduction calibrations, the THeTA was calibrated at three heat flux levels, removed from the calibration stand, the Gap Pad© replaced, and the three tests repeated giving 6 total measurements of the sensitivity of the ten sensors. Fig. 6 shows the measured sensitivities, the 95% confidence uncertainty estimates, and the theoretical sensitivity calculated using Eq. 2. Most values are above the theoretical prediction of 139.4 µV/(W/cm²). This discrepancy is likely due to uncertainty in the thermal conductivity and thickness of the epoxy layer. Sensor to sensor variation is probably due to the non-uniform thickness of the glue since the sensitivity of the sensor is very dependent on this parameter. Fig. 7 demonstrates the dependence of the sensors on glue layer thickness by plotting the sensitivity of the sensors versus the thickness of the completed sensor as measured by a micrometer with an accuracy of ±5 microns. With the exception of one outlier, the data shows a strong positive correlation between sensor thickness and sensitivity.

Fig. 6 Conduction calibration results

Fig. 7 Sensitivity dependence on sensor thickness
D. Radiation Calibration

Calibrating the THeTA in radiation served two purposes. First, it is important to show that the sensitivity of a heat flux sensor is insensitive to the mode of applied heat flux. Second, the radiation calibrations were used to experimentally determine the time response of the sensors.

Radiation calibrations were performed using a halogen lamp as a radiation source. Equipped with a 600 watt halogen lamp, the radiation facility focuses the radiant energy using an elliptical reflector which was machined from aluminum. The reflector was turned on a lathe and designed to have a focal point 31.7mm (1.25 inches) from its end. Heat fluxes at the focal point of up to 20W/cm² are obtainable. The radial heat flux distribution of the lamp at an axial location corresponding to the ellipses focal point was characterized using a Vatell Corp. Heat Flux Microsensor (HFM) mounted on a 2-D traverse. The HFM reference sensor averages the heat flux over an area approximately 3mm in diameter. Fig. 8 shows the measured heat flux distribution and demonstrates that the heat flux is uniform to within 5% as long as the sensor is not more than 5mm from the centerline of the reflector. As previously stated, the sensing area of the THeTA is about 1.5mm by 3mm so the heat flux produced by the lamp can be assumed uniform over the THeTA sensing area.

![Fig. 8 Lamp radiation intensity as function of radial distance](image)

A variable transformer was used to control the AC voltage to the halogen lamp and allowed the level of heat flux produced to be varied. The RMS voltage supplied to the lamp was measured using a Fluke 177 True RMS Multimeter with a quoted accuracy of 1% of reading. A Schmidt-Boelter water-cooled heat flux reference was used to calibrate the lamp and produce a curve which related the heat flux produced to the voltage supplied. The reference sensor was painted using the same Zynolyte flat black paint as was the THeTA for testing so there was no need to correct for emissivity mismatches. It was found that if the lamp was left on for more than about thirty seconds the reflector heated up enough to begin emitting additional radiation which caused the incident radiation to the sensor to increase slightly with time. This problem was negated by placing a piece of standard plate glass between the lamp and the test sensor. Since the glass was nearly opaque in the far infrared, it blocked most of the radiation emitted by the reflector while still passing a large portion of the radiation from the much hotter lamp. Tests showed that with the glass in place, the incident radiation increased by less than 1% during the first 30 seconds of a test.

Before the THeTA was calibrated in radiation, it was heat sunk by adhering it to an aluminum plate using the same thermally activated epoxy used in its construction. The calibrations were then completed by positioning the halogen lamp on a 2-D traverse in front of the sensor so that its position could be accurately controlled. A jig was constructed to aid in the positioning of the lamp and allowed the lamp’s position relative to the sensor to be accurate to within 0.25mm.

A shutter system was designed to subject the sensor to a step change of heat flux and consisted of a pneumatic cylinder which quickly removed a piece of sheet metal from between the lamp and the sensor. Once the lamp had been turned on and allowed to reach steady state (1-2 seconds), the cylinder removed the shutter. Two photodiodes were used to determine the speed of the shutter as it passed the sensor. These tests showed that the shutter was traveling at approximately 150 inches per second and therefore uncovered the sensor in about 400 microseconds which is more than two orders of magnitude faster than the predicted response of the sensor. Therefore, the incident radiation can be treated as a perfect step input for analysis. Fig. 9 is a depiction of the radiation calibration facility.

![Fig. 9 Radiation calibration setup](image)
Each individual sensor on the THETA was calibrated at heat fluxes of approximately 1, 1.5, and 2 W/cm². The signals from the THETA were recorded using the same hardware used in the conduction calibrations except this time the signals were sampled at 1kHz. It was necessary to sample at a higher rate to determine the time response and to acquire enough data for averaging since the total test time was approximately ten seconds. The data recorded during the first 500 milliseconds of the test was used to determine the sensor’s time response while the last 5 seconds was used to determine the sensitivity of the sensors. The sensitivities were determined by dividing the sensor’s output averaged over 5 seconds (5000 samples) by the heat flux absorbed by the Schmidt-Boelter with the lamp set at the same voltage. Fig. 10 shows the measured sensitivities, the 95% confidence uncertainty estimates, and the theoretical sensitivity calculated using Eq. 2. These sensitivities compare well to the conduction sensitivities with the exception of sensor 5 which is 33% lower. Incidentally, sensor 5 was the outlier in Fig. 7.

To determine the time response of the THETA, the method outlined by Doebelin [13] was used. This method utilizes the mathematical first-order exponential response to a step change input.

\[
\ln \left( 1 - \frac{q_{\text{out}}}{q_{\text{in}}} \right) = \ln \left( e^{-t/\tau} \right) = -\frac{1}{\tau} t \quad (3)
\]

If the left hand side is then plotted as a function of t, the curve produced should be linear with a slope of -1/\(\tau\) if the sensor is behaving as a first order system. Fig. 11 and Fig. 12 show the sensor response as well as \(\ln(1-q_{\text{out}}/q_{\text{in}})\) vs. t. The near linear behavior of the line in Fig. 12 is an indication that the sensor is indeed behaving as a first-order type. To determine the slope of the curve in Fig. 12, a line was fit to the data using least squares. Using the slope from the linear regression, the time constant for each sensor was determined. Fig. 13 shows the measured time constant for each sensor along with the predicted value of 124 milliseconds. Most of the sensors were slightly slower than the predicted value. There are several possible explanations for this discrepancy. First, the electrical analogy assumes that the sensor is mounted on a perfect heat sink. In the radiation test, the sensor was mounted on a piece of aluminum which will not behave as a perfect heat sink and will therefore tend to increase the measured time response. Second, there is uncertainty in the thermal properties of the Kapton, epoxy, and the paint. Finally, an additional layer of epoxy was used to bond the sensor to the aluminum plate. This layer will also add to the overall capacitance of the system and increase the sensor’s time response.
E. Convection Calibration

Convection calibrations were performed in a low-speed, low-turbulence (Tu < 1%) closed loop water tunnel. The aluminum plate was attached to a stagnation model which spanned the width of the water tunnel’s 61cm by 61cm test section. The bluff body measured 15.25cm square by 61cm wide and was equipped with an aft splitter plate to prevent vortex shedding interactions with the stagnation region. The THeTA was positioned horizontally such that all 10 sensors fell along the stagnation line. The aluminum plate was heated from behind using the resistance heater adhered to the back of the aluminum plate. Flow measurements were made along the stagnation line directly upstream of the THeTA using Time-Resolved Digital Particle Image Velocimetry (TRDPIV)[14]. The test setup is shown in Fig. 14.

Calibrations were performed by allowing the heated aluminum plate to reach steady state conditions while the tunnel was run at \( U = 10 \text{cm/s} \). The heat flux through the gage was then determined using Newton’s Law of Cooling.

\[
q'' = h\Delta T
\]  (4)

\( \Delta T \) was measured using the surface thermocouples on the sensor and \( h \) is the convective heat transfer coefficient. For stagnating flows, Goldstein [15] gives a solution for the heat transfer coefficient

\[
h = 0.5421k\Pr^{0.42}\sqrt{\frac{a}{\nu}}
\]  (5)

where \( k \), \( \nu \), and \( \Pr \) are the thermal conductivity, kinematic viscosity, and Prandtl number of the fluid, water in this case. The parameter \( a \) is the spatial acceleration constant and was found experimentally from the TRDPIV measurements to be \( a = 0.98 \) (1/s). This agrees well to the correlation given by White [16] for a square body in cross flow which relates the parameter \( a \) to the freestream velocity \( U \) and the body height \( L \).

\[
a \approx \frac{\pi}{2} \frac{U}{L} = 1.03
\]  (6)

Using Eq. 8 with the fluid properties at the film temperature, the heat transfer coefficient was estimated to be 757 W/m\(^2\)C. The sensitivity was then found by dividing the sensor’s output by the heat flux found using Eq. 7. Fig. 15 shows the measured sensitivities and their associated 95% confidence uncertainties. These again compare well with the sensitivities found in conduction and radiation.
Table 1 summarizes the results of the sensor calibration.

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VI. Example of Sensor Application

One of the purposes for the development of the THETA was to study the interaction of vortices with a boundary layer and their subsequent transient affect on the convective heat transfer coefficient. To study this phenomena, a vortex ring [17] was generated in water and allowed to impinge normally on the heated plate to which the THETA was mounted. TRDPIV was used to measure the flow field directly in front of the sensor while the THETA simultaneously measured the heat flux and surface temperature at ten points. Combining these two measurements (Eq. 7) allowed the time-resolved heat transfer coefficient to be determined. Fig. 16 shows the results obtained from the experiment. On the left is the flow field as measured by the TRDPIV just as the vortex ring impacts the plate after propagating from the left.

The plot on the right is the heat transfer coefficient measured by the THETA at the ten locations indicated by the dots at the right edge of the TRDPIV region of interest. The vertical line indicates the time corresponding to the instantaneous TRDPIV field shown. Before the arrival of the vortex ring (left of vertical line), the sensor measured a heat transfer coefficient of approximately 510 W/(m²°C) due to natural convection. When the vortex ring arrives, the heat transfer coefficient increased to about 2000 W/(m²°C).

VII. Conclusions

The THETA offers improved performance compared to currently available heat flux sensors. The use of thermoelectric foils results in a durable, sensitive transducer. In addition to measuring heat flux, the THETA is capable of measuring simultaneous surface temperatures which allows it to more completely describe the thermal system. This ability makes the THETA very useful in a variety of research applications. Calibrations performed in three different modes of heat transfer showed very good agreement. The time-resolved capabilities of the THETA were demonstrated by transient radiation calibrations as well as an example of the THETA...
measuring the time-resolved heat transfer coefficient resulting from a complex flow-field.

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