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DESIGN AND UNCERTAINTY ANALYSIS OF A SECOND-GENERATION CONVECTIVE HEAT FLUX CALIBRATION FACILITY

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ABSTRACT

The National Institute of Standards and Technology has developed a convective heat flux facility to allow calibration of heat flux sensors. The facility consists of a small wind tunnel that produces a two-dimensional laminar boundary layer across a heated isothermal copper plate. Sensors are mounted flush in the copper plate alongside a reference to measure the heat leaving the plate. Convective calibrations up to 5 kW/m^2 are possible. Sensor output is compared with the reference value, and contrasted with a standard radiation calibration. Recognizing that many sensors are used in mixed radiation and convection environments, this facility provides a unique opportunity to assess a sensor's convective response. This report describes a second-generation heated plate and provides an analysis of the system uncertainty. Redundant references, improved sensor heating and mounting, improved reference isolation, and a minimized radiation component has reduced the combined relative expanded uncertainty of the reference to ±2.5 %. The benefits of an embedded temperature sensor in the heat flux sensor are described. The facility is available for comparative calibrations and for heat transfer studies by individual researchers.

INTRODUCTION

A convective heat flux calibration facility has been developed to assist U. S. heat flux sensor manufacturers and users in better understanding heat flux sensor calibration issues. Recognizing that some sensors perform differently in convection than conduction and radiation led to the goal of developing three separate facilities to allow comparative calibrations. Relative measurement uncertainties in application have been typically no more accurate than ±10 % which led to the goal of achieving a ±2 % uncertainty for the convection calibration facility.

In the current facility sensors are mounted flush in heated copper plate under a two-dimensional laminar boundary layer flow. Figure 1 shows how the reference area is mounted alongside the sensor and used to measure the undisturbed flux. The boundary layer is created by an open-loop wind tunnel with conditioned air entering a 300 mm x 300 mm contraction nozzle that produces a 300 mm wide by 10 mm slot flow entering the test section at a maximum velocity of 31 m/s (Re_h = 20,000). The calibration plate temperature is maintained at an isothermal condition by 10 power supplies independently heating different regions of the plate (Figs. 1 and 2). Plate temperature is controlled by PC-based software that monitors thermocouples embedded in the plate and optimizes the power output for the different regions of the plate. The boundary layer at the leading edge of the heated plate (nozzle exit) is laminar and 0.5 mm thick (measured at the maximum velocity condition). The boundary layer was found to exhibit transitional behavior at the sensor location (37 mm downstream; see Fig. 1) for velocities above 21 m/s. Testing has been performed at 21 m/s with a fully laminar boundary layer.

A guarded reference section is located at the same downstream position as a test sensor to be calibrated. The reference measures the heat flux by dividing the steady-state electrical power required to maintain the isothermal surface temperature, by the area of the reference section. The spanwise uniform boundary layer allows equating the reference heat flux to the undisturbed sensor-location heat flux. This is the flux that would pass through the plate if the sensor were not present. This definition was agreed upon at a 1995 workshop held at NIST (Moffat and Danek, 1995). The design, uncertainty

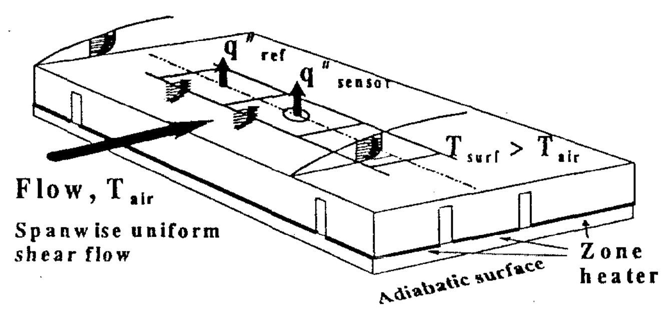

Figure 1: Heated constant temperature calibration plate beneath laminar boundary layer with reference heat flux used to calibrate heat flux sensor.

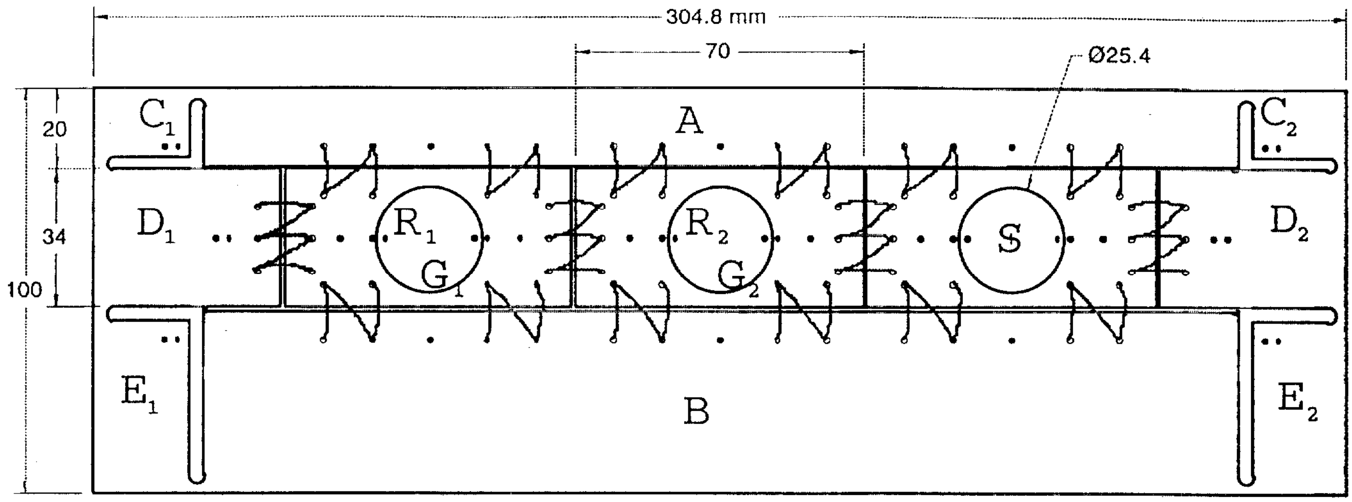

Figure 2: Bottom view of second-generation convection calibration plate, with differential thermocouple wiring, thermocouple locations, heater designations, and major dimensions shown. The reference section (R, with guard G)/ sensor (S) locations are interchangeable.

analysis, and testing of the first-generation calibration plate of the convection facility was reported in Holmberg, *et. al.* (1997) and Holmberg and Womeldorf (1998, 1999). This report addresses the design and analysis of the second-generation calibration plate. A workshop held July 1999 addressed the future direction of this facility, which will include comparative calibrations of different types of sensors and convective heat transfer studies by individual researchers.

Sources of error that will influence the accuracy of the reference-sensor comparison include control of lateral and vertical conduction around the reference, radiation, streamwise heat flux distribution, and experimental variability due to assembly variables and flow properties. Lateral and vertical conduction is minimized using guard heaters. These heaters maintain a constant temperature condition at the reference section boundaries. Designing for minimum radiation uncertainty can be done by minimizing radiation itself. Knowledge of residual radiation requires careful analysis of the test section. However, physical constraints, real properties, and measurement limitations result in some uncertainty. The streamwise heat flux distribution is found based on theory and numerical modeling, resulting in some uncertainty.

PLATE DESIGN AND UNCERTAINTY ANALYSIS

The second-generation plate reduces lateral conduction by using a low-conductivity epoxy bridge around the three sections that can hold the references and/or sensors. Differential temperature accuracy is improved by using multiple differential thermopiles around the reference perimeter across the epoxy bridge (see Fig. 2). A lower guard heater nulls vertical conduction, and the remaining uncertainty is minimized by insulation to improve temperature uniformity in the reference insert (see Fig. 3). Residual losses are estimated based on conduction modeling of the structure of the insert. Radiation is minimized by using a gold plated reference and an upper surface heated to the lower plate temperature.

The second-generation plate design adds functionality not present in the first-generation plate. Three locations (seen in Figs. 1 and 2) are available to allow interchange and comparison of references and sensors. The reference/ sensor assemblies (Fig. 3) are inserted into the holes machined into the heated plate; the top layer in the reference and sensor assemblies of Fig. 3 is actually the copper plate with hole seen in Fig. 2 and fixed in place with epoxy. The differential thermocouples seen in Fig. 2 are embedded in the top fixed plate. The second layer (Fig. 3) with protruding cylinder is inserted into the hole. This copper layer is heated from below by the reference heater. The guard heater serves to null the heat flux downward and force all energy from the reference heater upward to the top surface. In between the reference and guard heaters is a nulling heat flux sensor (a thin differential thermopile) that serves to indicate a no-flux condition. The sensor holder design (Fig. 3) allows easy alignment and installation as well as good thermal contact between the test sensor and the sensor heater. A heated test section top surface allows accurate control of radiation from the reference and sensor.

The analysis which follows examines major sources of uncertainty in the second-generation convection calibration plate beginning with conduction (lateral and vertical) and then radiation. Radiant flux from the reference is found to be negligible. The radiation balance is also presented for a sensor, as this is useful in analyzing sensor performance. While in the first generation plate the largest uncertainties were radiation from the reference and lateral conduction to the surrounding plate, now the main sources of uncertainty are conduction within the removable reference section and facility experimental variability.

REFERENCE UNCERTAINTIES

Lateral conduction: The reference region is 34 mm x 70 mm, plus a surrounding epoxy gap 1.0 mm in width. The area heated by the reference heater, including half of the epoxy gap, equals 2.485×10^{-3} m^2. Uncertainty calculations have been performed for a plate temperature to flow temperature difference, ΔT_{flow}, equal to 80 K. The convective heat transfer from the plate, q''_{conv}, at the sensor location, based on heat flux measurements and numerical calculations at the 21 m/s mean flow velocity condition, is 3630 W/m^2. The power input to the reference region, q_{conv}, is this times the reference area, 9.0 W.

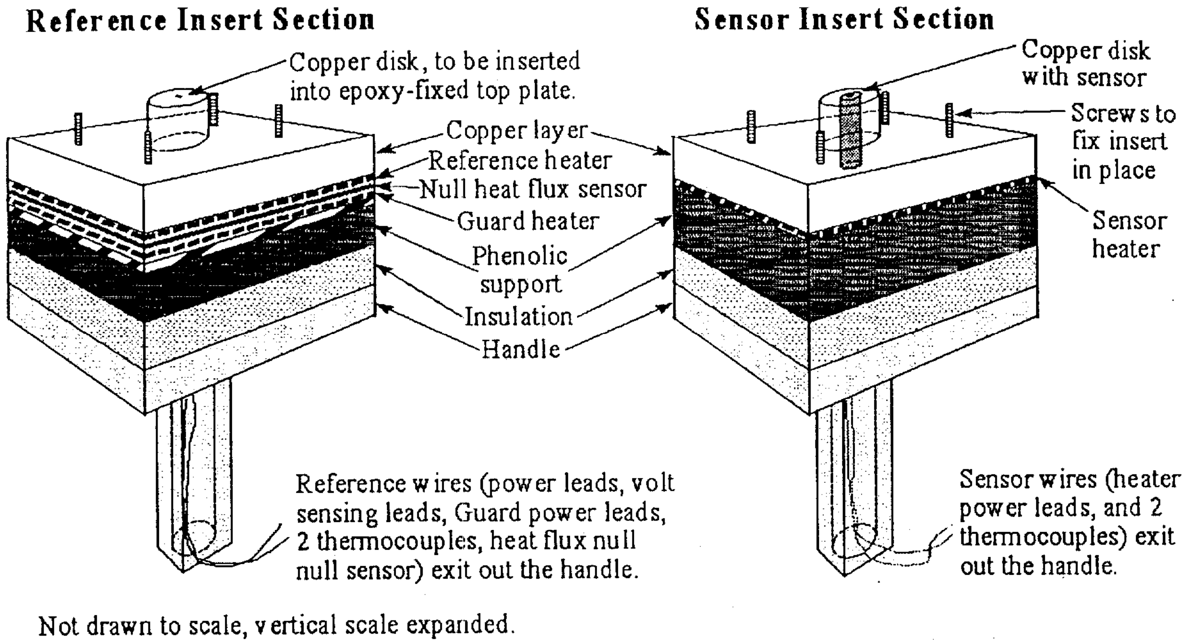

Figure 3: Reference section and sensor section.

Lateral conduction is affected by several parameters (Fig. 4). The epoxy that fixes the reference region in place also conducts thermal energy to surrounding regions. Lateral conduction across this epoxy bridge increases with epoxy thermal conductivity and depth, but decreases with gap width (see Eq. 1 below). The first generation plate had a continuous copper surface with a thin bridge across a 3.2 mm gap. Epoxy's lower conductivity allows the gap to be narrowed, while still decreasing conduction throughout.

Temperature measurement uncertainties have been determined experimentally (type A) as well as through experience with the system (type B). Thermocouples were calibrated at 273.15 K using crushed ice made from distilled water. The resulting expanded system uncertainty, two standard deviations of measurements from thermocouples installed in the calibration plate at room temperature, is 0.03 K, and approximately twice this at elevated temperatures due to amplifier gain error. System resolution and zero calibration of differential thermocouples have demonstrated measurement uncertainties of 0.01 K (Holmberg and Womeldorf 1998), where this is the temperature between the two thermocouple beads. However, because of small thermal gradients in the copper plate, reported differential temperature values may not exactly represent the temperature difference across the bridge. To compensate for gradients in the plate, six differential thermopiles (Fig. 2), installed across the reference boundaries, are averaged around the active reference location to minimize the uncertainty. For this analysis, the estimated standard deviation for the temperature difference across the gap is taken conservatively as ΔT_{gap} = 0.05 K based on comparison of the differential thermopiles and the thermocouples and modeling of the thermal gradients in the plate (Holmberg and Womeldorf 1998, 1999).

The conduction across the epoxy gap around the reference is

$$q_{gap} = kPd\frac{\Delta T_{gap}}{w} \qquad (1)$$

where $k = k_{epoxy}$ = 0.2 ± 0.1 W/mK (as provided by the manufacturer) and P is the perimeter measured at the gap center. The amount of energy transferred across the gap is q_{gap}. If there is an undetected 0.05 K temperature difference randomly distributed between the reference and the four heated zones of the surrounding regions, the uncertainty on the lateral conduction is the square root of the sum of squares of the q_{gap} for each of the four sides, 6 mW. This amount of heat transfer cannot be reduced with the present plate because it is derived from the physical system and the accuracy of temperature measurement. Taking 6 mW as the uncertainty due to uncontrollable conductive heat transfer to surrounding regions, the *lateral conduction uncertainty* (i.e. the estimated standard deviation on lateral conduction) at ΔT_{flow} = 80 K is q_{gap}/q_{conv} = 0.06 %. Since the 0.5 K is not affected by the flux level of the system, q_{gap} is constant and this percentage will change inversely with q_{conv}.

Conduction along thermocouple wiring that crosses the epoxy bridge has also been considered. Teflon coated 36 awg wire thermocouple leads cross the gap from the reference region to neighboring regions and are routed within the plate and out through the insulation to room air. The length of wire in the isothermal plate environment is typically several thousand diameters so that conduction along the wire to room temperature can be regarded as negligible. The thermocouple wire cross-section area bridging the 1 mm gap is approximately 0.1 mm^2. The resulting conduction across the gap assuming the same 0.05 K temperature differential everywhere is approximately 1 mW, or 0.01 % of q_{conv}. Again, it is expected that 1 mW will be constant regardless of the system flux level.

Vertical conduction: The goal of the reference design is to have all power from the reference heater exit the top of the reference assembly (Fig. 3). Simply, the reference heater flux goes up, and the guard heater flux goes down. The null sensor sandwiched between the

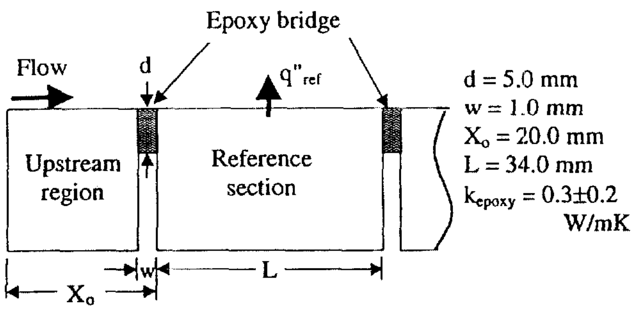

Figure 4: Side view of reference section and upstream region showing epoxy in gap and plate dimensions.

reference and guard heaters enforces this by providing feedback to the computer until the heaters are balanced, i.e. flux through the null sensor is zero. There are, however, thermal shunts in the system that bypass the null sensor. These include internal bolts; the power leads to the reference heater; and sensing leads (from the null sensor, two thermocouples, and reference heater). It is possible to estimate their effect and make a correction to the reported reference heat flux.

Four small internal stainless steel bolts fix the insert (Fig. 3) to the plate, with their heads in the phenolic support layer. They surround the null sensor and pass by the guard and reference heater. Though poorly conductive compared to the copper, any flux through them cannot be accounted for by the null sensor. The present configuration was modeled numerically to estimate the flux from the guard heater to the upper plate, with a resulting flux of 0.1 % of the reference flux.

Larger errors are produced by thermal leakage from the power and signal sensing leads. These leads conduct thermal energy from the reference heater to the back of the support layer (Fig. 3). At this location they are coiled in contact with the back of the support layer to ensure that energy loss out the leads is supplied by the guard heater. The cumulative loss out the leads from the reference heater is equal to approximately 1.5 % of the reference flux, with an estimated relative uncertainty (type B) on this bias correction of 0.7 % of the reference flux. This correction has been estimated for the current wire arrangement based on known wire diameters and wire thermal conductivities and estimated thermal gradients within the system across the insert layers (phenolic, tape, wire insulation, insulation) from modeling. The large uncertainty on the correction is due to the spatial non-uniformity of the wire routing and the larger fraction being conducted out the leads rather than through the insulation. This uncertainty percentage does not change with flux level (temperature of plate).

Heat flux distribution: The heat flux as a function of downstream distance along the plate must be known accurately in order to determine the relationship between the sensor flux and the reference flux. The measured reference power is an average value over the heated area. With a non-linear streamwise heat flux distribution, due to natural boundary layer growth, the average heat flux over the sensor area will be different from that over the reference area.

The heat flux distribution can be estimated from the theoretical relation for laminar flow over an isothermal flat plate for which heat transfer varies as $x^{-1/2}$, where x is the distance from the plate leading edge. Integration of this profile across the reference area produces an average heat flux proportional to the measured reference heat flux. The flux at the sensor is then taken as the integral across the sensor area. The ratio of these two fluxes for a point sensor is $q''_{sens}/q''_{ref} = 0.969$. Numerical modeling results (Holmberg and Womeldorf, 1998) confirm this ratio. The difference between reference and sensor fluxes translates to a 3.1 % correction to the reference flux. The relative standard uncertainty on this correction is estimated to be less than 0.2 % of the reference flux based on agreement of analytical and numerical results. This value should be insensitive to the flux level.

Operational repeatability: The experimental variation in measured heat flux levels at different spanwise locations and times on the plate is estimated to be 1 % (type B estimated standard uncertainty based on system experience and limited test data). This variation is due to several factors. The inlet boundary layer is very thin (0.5 mm) and sensitive to calibration plate leading edge alignment; misalignment could lead to spanwise aerodynamic non-uniformity and thus convective heat flux variation. In addition, experimental test data has demonstrated 0.5 % variation due to reference and sensor insert installation differences from test to test, with values sensitive to the contact between the insert and upper fixed copper plate surfaces. Finally, test section dis-assembly and re-assembly will require careful monitoring to ensure that current conditions are maintained. The 1 % is a type B best estimate of these factors combined.

RADIATION ANALYSIS

The reference section has been gold plated to limit the sensitivity of the reference to radiation by minimizing the emissivity and eliminating the oxidation effects affecting copper. This combined with a heated upper test section surface nearly eliminates radiation from the reference. In contrast, the typical test sensor is covered with black paint and has a high emissivity and a surface temperature below the surrounding plate temperature. Whereas the net radiative flux from the reference is negligible, a painted test sensor will have a non-negligible net radiative flux with a higher uncertainty due to uncertainties in the sensor surface temperature and emissivity. Estimating the radiation from the sensor does not influence the facility accuracy, but may explain some of the difference between a sensor calibration and the reference value.

The test section top surface is aluminum maintained at the reference temperature ±2 K and painted flat black with an emissivity of 0.94, as provided by the paint manufacturer. The gold-plated lower surface has a measured emissivity of 0.01 ± 0.005. The effect of radiation on the sensor can be estimated from the geometry of the test section as shown in Fig. 5. A sensor is shown in the center position and off-center position, as are two references shown in the center and off-center. Configuration factors were determined for each surface combination using a commercially available software package. Using the temperatures, areas, and emissivities shown in Table I (representative of the test section and calibration plate with a plate to flow temperature difference of 80 K), one can calculate the radiosity of each surface of the enclosure, J_i, and the total radiant flux from both the sensor and the reference, A•q". The uncertainty of the upper plate temperature has been propagated through the calculation (shown in right-hand column).

The net radiation from the reference surface is 0.7 ± 0.5 mW, or 0.3 ± 0.2 W/m^2, which is 0.008 ± 0.006 % of the convective flux (3630 W/m^2), with uncertainty based on the 2 K temperature variation in upper plate temperature. Therefore, radiation from the reference is insignificant relative to the convective flux. Calculating for the higher

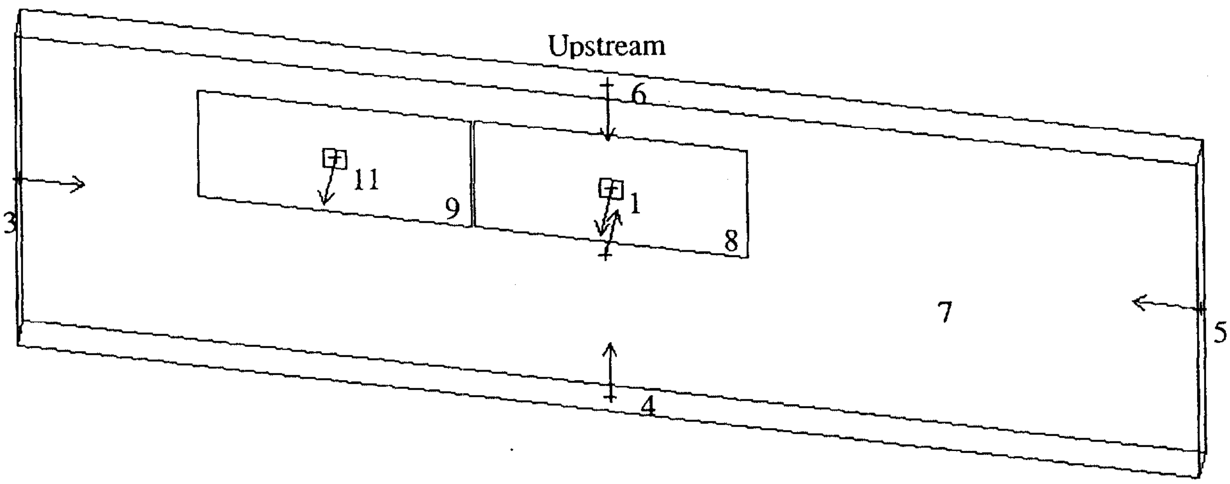

Figure 5: Test section surfaces for radiation analysis. Surface 10, not shown, represents the lower plate surrounding either a sensor (1 or 11) or a reference section (9 or 8). Configuration factors calculated were $F_{1\text{-}S}$=0.024, $F_{11\text{-}S}$=0.026, $F_{8\text{-}S}$=0.028, and $F_{9\text{-}S}$=0.030.

emissivity sensor, the net radiant flux leaving a black sensor would be 25 ± 22 W/m^2, or 0.7 ± 0.6 % of the convective flux. In summary, the radiant flux from the reference is about 0.01 % of the total flux leaving the reference and roughly 1 % of the total flux leaving the sensor.

Table 1: Radiation parameters of test section (both sensor and reference) and results.

Surface name	Index	ε	Temp (K)	Area (mm^2)	J_i (W)
Sensor	1	0.95	375	31.36	0.035
Lower plate - around the sensor	10	0.01	375	30,449	31.4 ± 0.6
Sides (3,4,5,6)	S	1.00	295	8,096	3.48
Top Plate	7	0.94	375 ± 2	30,480	33.9 ± 0.7
Reference section	8	0.01	375	2,380	2.60 ± 0.05

Determination of the precise radiant and convective fluxes at the sensor is impossible without an accurate measure of the surface temperature of the sensor. In fact, a small change in sensor surface temperature will have more of an effect on the convective flux than on the radiant flux. As seen above, a 2 K change in the upper plate temperature will result in a 0.6 % change in radiant flux from a black sensor, and thus 0.6 % increase in the total flux. However, if a sensor surface temperature is unknown and actually 2 K below the surrounding plate temperature, which is perhaps normal, then the resulting difference in the sensor convective flux relative to the reference flux will be proportional to the difference in ΔT_{flow} at the reference (2 degrees out of 80) resulting in a 2.5 % change in the convective flux.

A summary of calibration reference uncertainties is presented in Table 2. The combined relative expanded uncertainty based on these estimated standard uncertainties, with k, the coverage factor, equal to 2, is ±2.5 %.

SENSOR CONDUCTION ISSUES

In the new plate, the sensor is mounted so that the sensor heater is attached directly to the sensor holder (Fig. 3). This assures minimal contact resistance between the heater and the sensor, with the actual mounting of the sensor in the holder dictated by the manufacturer. Good thermal contact is required to heat the sensor and thus provide a flux through the sensor to the flow that is comparable to the flux through the reference to the flow. Ideally, one can follow the sensor manufacturer's mounting configuration that would also be used by the end user. Also ideally, one would have some means of measuring T_{sensor} accurately in order to better estimate the actual flux through the sensor relative to the undisturbed surface flux. Given some contact resistance, the relative conductivity of the sensor to the surface material and the direction of the flux determine whether the sensor temperature is below or above that of the surrounding plate. The "temperature deficit" (or surplus) created affects both the radiation estimate as well as the local convective flux due to the lower ΔT_{flow} at the sensor. The installation method and sensor internal construction are the concern of the manufacturer and user. However, the presence of a temperature sensor on the heat flux sensor surface allows more accurate analysis of sensor performance.

SUMMARY

The second-generation calibration plate design has been described and an uncertainty analysis presented to demonstrate that the NIST facility measures the heat flux at the reference to a relative expanded uncertainty (95 % level of confidence) better than ±3 %. Significant uncertainties present in the first-generation plate have been reduced. In addition, the new plate has increased redundancy, improved radiation characteristics, and sensor mounting arrangement that allow for more accurate knowledge of the flux through the sensor. A summary of reference uncertainties discussed in this report is presented in Table 2.

Table 2: **Summary of uncertainty in heat flux reference, with uncertainties given relative to the reference convective flux of 3630 W/m^2, (mean velocity = 21 m/s and at ΔT_{flow} = 80 K).**

Sources of uncertainty	*Standard relative uncertainty*	*Variables affecting magnitude of uncertainty*
Lateral conduction in/out reference section side	0.06 %	Uncertainty of differential thermocouple measurement across epoxy bridge separating reference from surrounding material; conduction of bridge; conduction along thermocouple wires leaving reference section.
Vertical conduction in/out reference section bottom	0.7 %	Uncertainty on correction due to thermal shunts due to internal structural design of reference (e.g. bolts); power and sensor wire conduction losses; accuracy of null sensor due to non-uniformity.
Heat Flux Distribution	0.2 %	Uncertainty of comparison of reference flux to the sensor flux is affected by the non-linear heat flux distribution due to boundary layer growth; inlet air flow measurements.
Experimental variation	1.0 %	Installation of reference inserts (contact resistance variability) and test section assembly variation. Flow variables: plate alignment and flatness affecting spanwise uniformity of boundary layer.
Radiation to/from reference surface	0.01 %	Emissivity of plate and of test section top surface; temperature difference between top surface and plate; view factors and radiation properties of other test section surfaces.
Total	**±2.5 %**	**Combined relative expanded uncertainty, coverage factor =2**

The facility is available for calibration and testing of sensors and for use as a research facility for interested individuals.

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