Quantification of the Fire Thermal Boundary Condition

Thomas Vega

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Brian Y. Lattimer

Tom E. Diller

Scott T. Huxtable

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ABSTRACT

The thermal boundary condition to a fire exposed surface was quantified with a hybrid heat flux gage. Methods were developed to determine the net heat flux through the gage, incident heat flux, cold surface heat flux, convective heat transfer coefficient, adiabatic surface temperature, and the separated components of radiative and convective heat flux. Experiments were performed in a cone calorimeter with the hybrid gage flush mounted into UNIFRAX Duraboard LD ceramic board. The results were then compared to results obtained with a Schmidt-Boelter gage and a plate thermometer. The hybrid heat flux gage predicted a cold surface heat flux within 5% of cold surface heat fluxes measured with a Schmidt-Boelter gage. Adiabatic surface temperature measurements compared well with the plate thermometer measurements at steady state.

Hybrid gage measurements were performed on flat plate samples of Aluminum 5083, Marinite P, and UNIFRAX Duraboard LD ceramic board. The gage and sample assemblies were exposed to mixed-mode heat transfer conditions in a cone calorimeter. Temperature measurements were performed at the top, center, bottom surfaces of the marinite and ceramic board samples. A single midpoint temperature was performed on the aluminum. Boundary condition details obtained with the hybrid gage were then input to the commercial finite element analysis package Abaqus. Abaqus was used to create the flat plate geometries of the sample and variable temperature dependent material properties were used for each material. Measured temperatures were then compared to the model predicted temperatures with good results.

Hybrid gage measurements were verified using a new experimental apparatus. The apparatus consisted of an impinging jet assembly, a tungsten lamp, and a gage holster assembly. The impinging jet was used to expose the gage to isolated convection and the lamp was used to expose the gage to isolated radiation. The gage holster assembly was used to water cool the gage when desired. Measurements performed with the gage water cooled in isolated convection allowed for the convective heat transfer coefficient to be determined. Two methods were developed to determine the convective heat transfer coefficient in mixed-mode heat transfer conditions. These methods were then verified by comparison to the isolated heat transfer coefficient. Similarly, the incident radiation was isolated by water cooling the gage while only the lamp was on. The components of heat flux were then separated for mixed-mode comparisons and were verified against this isolated radiation. The hybrid gage predicted convective heat transfer coefficients within 10% of the isolated heat transfer coefficient and incident heat fluxes within 11% of the isolated radiation.
Dedication

This work is dedicated to my Aunt Terry Vega, my Grandparents, Ghislaine Cedeno, and to the friends who have supported me throughout the years. My Aunt and Grandparents have served as a constant source of inspiration and guidance. Ghislaine Cedeno has been a constant source of motivation and support. Without them none of this would have been possible.

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1.1 Motivation

The thermal boundary condition to a fire exposed surface is still not entirely understood. Quantification of this boundary condition is required to make accurate predictions of the temperature rise of materials exposed to mixed-mode heat transfer conditions. Knowledge of the net heat flux, incident heat flux, convective heat transfer coefficient, and separated convective and radiative heat flux components are necessary to better model this boundary condition.

The most popular method for measuring heat flux in fire environments are water cooled total heat flux gages such as the Schmidt-Boelter gage or the Gardon gage. These gages create a voltage, which can then be converted into a heat flux, based on the differential temperature through their thickness [1]. Water cooled total heat flux gages measure the total heat flux to a water cooled surface, which is known as a cold surface heat flux [2]. Furthermore, these gages cannot distinguish between convection and radiation to the sensor [2]. In order to separate the convective and radiative components of net heat flux, multiple sensors must be used. In these experiments two Schmidt-Boelter gages are used; one gage is fitted with a sapphire window of known transmittance [3,4]. The windowed gage directly measured the incident radiation, which is scaled by emissivity and window transmittance while the other gage measures the total convective and radiative cold surface heat flux. The cold surface convection is then obtained by subtracting the two. This method requires continuous purging of the sapphire window with compressed air, that the two gages are located near each other to maintain the assumption of equal incident radiations to each sensor, and that the transmittance is known. Furthermore, using multiple gages increases the intrusiveness of the measurement. These limitations severely limit the usefulness of water cooled total heat flux gages in mixed-mode heat transfer environments. In addition, these gages require water lines, which further restrict their utility. As a result of these limitations, water cooled total heat flux gages are most often used as radiometers in environments where convection is minimal.

Recent advancements have led to the development of a high temperature hybrid heat flux gage [5-7]. The hybrid heat flux gage is capable of withstanding temperatures above 1000°C without the need for water cooling under continuous operation [5]. Also, Diller and Hubble [6] have developed a hybrid methodology to determine the net heat flux through the gage based on the sum of the differential and slug heat flux terms. The focus of this research was to use the hybrid heat flux gage to quantify the fire thermal boundary condition, which was made possible because the gage did not require water cooling. This included measurements of the net heat flux through the sensor, the incident heat flux, the convective heat transfer coefficient, and the separate radiative and convective components of net heat flux. Knowledge of the thermal boundary condition was then used to predict the temperature rise of
three different materials exposed to mixed-mode heat transfer conditions. The methodologies developed to determine this thermal boundary condition were then validated.

1.2 Organization

This thesis is comprised of three different journal articles. Each journal article corresponds to a chapter of this thesis. Formatting changes have been made to the journal articles to maintain a logical flow. Each journal article has been titled with a Chapter number. Each chapter has its own separate set of references and the citations in text refer to the references found at the end of the chapter where they appear.

The second chapter of this thesis is focused on developing methods to quantify the thermal boundary condition produced by a fire using the hybrid heat flux gage. Comparisons of the hybrid gage are made to the Schmidt-Boelter gage and the plate thermometer based on measurements taken in a cone calorimeter. Included in this chapter are methods to quantify the net heat flux through the gage, incident heat flux to the gage, cold surface heat flux, the convective heat transfer coefficient, the adiabatic surface temperature, and the radiative and convective components of heat flux.

The third chapter applies the methods developed in the second chapter to predicting the temperature rise of materials exposed to fire. The hybrid gage is surface mounted onto Aluminum 5083, Marinite P, and UNIFRAX Duraboard LD ceramic board, which were exposed to mixed-mode heat transfer in a cone calorimeter. Using the hybrid gage, exposure conditions to the different substrates were measured. Models were created in the finite element package Abaqus and boundary condition details such as convective heat transfer coefficients, gas temperatures, and incident source radiation were input. Model predicted temperature profiles were then compared to measured temperature profiles.

The fourth chapter validates the methods developed in the second chapter. A new experimental apparatus was designed to expose the hybrid gage to isolated and mixed convective and radiative heat fluxes. The hybrid gage was mounted into a holster where water cooling could be turned on and off. Measurements of the isolated convection while the gage was water cooled allowed for a direct measurement of the convective heat transfer coefficient. This convective heat transfer coefficient was then used to verify the heat transfer coefficients determined by the previously developed methods under mixed-mode conditions. Similarly, an isolated radiation measurement while the gage was water cooled allowed for a direct measurement of the incident radiation. This incident radiation was then used to verify the separation methods developed in Chapter 2.
1.3 References


CHAPTER 2

Fire Thermal Boundary Condition Measurement using a Hybrid Heat Flux Gage

Vega, T., Lattimer, B.Y., and Diller, T.E.

Virginia Tech

2.1 ABSTRACT

New experimental methods have been developed using a hybrid heat flux gage to quantify the thermal boundary condition to a surface that is exposed to fire. The hybrid heat flux gage is a novel heat flux gage, which can measure heat fluxes at temperatures greater than 1000°C without the need for water cooling. Methods have been developed to measure the net heat flux and incident heat flux and to determine the convective heat transfer coefficient and adiabatic surface temperature. Incident radiative and convective components of heat flux into the gage can be quantified when measurements are taken in conjunction with a gas temperature. Measurements were taken with a hybrid heat flux gage flush mounted onto ceramic board insulation in a cone calorimeter. The results of these experiments were then compared to both a Schmidt-Boelter total heat flux gage and a plate thermometer. The hybrid heat flux gage predicted a cold surface heat flux within 5% of cold surface heat fluxes measured with a Schmidt-Boelter gage. Using the hybrid heat flux measurements, time resolved measurements of heat transfer coefficient and adiabatic surface temperature were possible. Adiabatic surface temperature measurements compared well with the plate thermometer measurements at steady state.

NOMENCLATURE LISTING

- \( A_s \): area of exposed surface (m\(^2\))
- \( C \): specific heat capacity (kJ/kg-K)
- \( g \): gravitational constant (m/s\(^2\))
- \( h \): average heat transfer coefficient (W/m\(^2\)-K)
- \( k \): thermal conductivity (kW/m-K)
- \( L \): length scale of expose surface (m)
- \( Nu_L \): average Nusselt number (- -)
- \( P \): perimeter of sample (m)
- \( \beta \): thermal expansion coefficient (K\(^{-1}\))
- \( \delta \): gage thickness (m)
- \( \epsilon \): emissivity (- -)
- \( \nu \): Kinematic viscosity (m\(^2\)/s)
- \( \rho \): density (kg/m\(^3\))
- \( \sigma \): Stefan-Boltzman constant (5.67x10\(^{-11}\) kW/m\(^2\)-K\(^4\))

**Subscripts**

- \( P \): perimeter of sample (m)
- \( \text{Avg} \): average
2.2 INTRODUCTION

Knowledge of the thermal boundary condition for a material that is exposed to a fire is necessary to make accurate predictions of the temperature rise of that material. Currently, the mixed-mode convection-radiation boundary condition produced by a fire is still not entirely understood. New experimental methods are required to quantify this boundary condition, including measuring the net heat flux, heat transfer coefficient as well as the radiative and convective components.

The thermal boundary condition could be modeled if the net heat flux into a material were known. However, as Wickstrom and Wetterlund [1] discussed, measuring the net heat flux into a material is difficult for reasons such as temperature differences between the heat flux sensor and the surface temperature of the substrate, different surface emissivities for the sensor and the substrate and the different geometries of the sensor and substrate which leads to different heat transfer coefficients. Also, as Diller [2] points out, the physical presence of a heat flux gage alters the convection to the material by changing the air flow around the material.

The most common method for quantifying the thermal boundary condition of a fire exposed surface is to measure a cold surface heat flux and use a calculated surface temperature to determine the net heat flux into the material by
where, $q^*_{\text{net}}$ is the net heat flux through the gage, $q^*_{\text{cold}}$ is the net heat flux to a water cooled surface and $T_{\text{cold}}$ is the temperature of the water cooled surface. Equation (1) can be used if the surface emissivity of the gage is assumed equal to that of the material [3]. Inspection of Equation (1) exposes the primary drawbacks of this approach: the surface temperature is required and the heat transfer coefficient must be known.

In the absence of devices capable of directly measuring the net heat flux into a material, indirect methods have been developed for measuring net heat flux into a material. These methods require inverse heat transfer analysis and calibrations to account for conductive losses. A common method is to weld or solder thermocouples to steel plates that are insulated on one side to calculate the absorbed and cold surface heat fluxes based on a heat balance calculation. Examples of this type of analysis can be found in Refs. [4,6,26]. Ingason and Wickstrom [7] have used plate thermometers to predict radiant heat flux with some success; however, a correction factor is necessary to account for conductive losses through the device. Keltner [27] uses inverse analysis on plate temperature measurements separated by an insulation layer to determine heat flux using a directional flame thermometer.

The convective heat transfer coefficient used in analysis of fires is typically calculated based on a correlation for either forced or natural convection for simple geometries. Some studies have attempted to quantify the heat transfer coefficient under mixed-mode heat transfer conditions. Quintiere and Harkleroad [8] quantified the heat transfer coefficient in the ASTM E1321 LIFT apparatus using steady state surface temperatures on blackened calcium silicate board and water cooled heat flux gages to measure incident heat flux levels. Cain and Lattimer [25] and Lattimer et al. [24] used inverse heat transfer analysis and steady state surface temperatures to quantify heat transfer coefficients in mixed-mode environments. Staggs [6,9] also attempted to quantify the heat transfer coefficient at steady state inside of the cone calorimeter. In this study, a series of experiments was performed on steel plates where the steady state temperature of the plates was recorded over a range of incident heat fluxes. A correlation of the heat transfer coefficient as a function of temperature was derived. Staggs [6,9] proposed that the convective heat transfer coefficient was much higher than what was previously thought and speculated that this was primarily because of convective cooling due to a modified airflow caused by the hot conical heater of the cone calorimeter. Direct methods to determine the heat transfer coefficient with time in a mixed-mode environment have not been reported, but are required to determine coefficients in more complex flow situations.

The adiabatic surface temperature is the temperature that a surface would achieve if it was perfectly insulated. The adiabatic surface temperature has been proposed as a means of connecting fire models to structural models with plate thermometers in radiation dominated environments [10-13]. Experiments have been performed on structural steel where measurements were obtained using plate thermometers and the results were compared to FDS and ANSYS models by Wickstrom et al. [13] with good results. The plate thermometer directly measures the adiabatic surface temperature after the
device reaches steady state, which is approximately 3-5 minutes. Real time adiabatic surface temperatures have not been reported but would be needed if the exposure source varies with time.

Separation of convective and radiative components has been attempted in some studies, but no method has been established for use in fire. Water cooled radiometers and total heat flux gages are frequently used to determine radiation, convection, and total heat flux. However, this requires multiple gages and correction for optical window transmissivity is necessary. Separation using devices coated with different emissivities has also been reported [5,15]. Lattimer et al. [15] used two thermopile gages with different emissivity coatings to separate convection and radiation. Thin plates with different emissivities have also been used to separate the convective and radiative components using energy balances on these plates [5]. This approach produced acceptable results for mid and high level heat fluxes; however, it proved inaccurate for radiation at low heat fluxes and collection of soot on the low emissivity surface in fire tests resulted in issues for using this approach in fire environments. Also, Lam and Weckman [16] attempted to quantify the magnitudes of convection and radiation at steady state using several different heat flux gages, including Schmidt-Boelter and Gardon gages, by taking measurements in radiative, convective and mixed-mode environments. In their experiments, Gardon gage measurements were up to 18% lower than the Schmidt-Boelter gage measurements for mixed-mode environments. The Schmidt-Boelter gage provided good results; however, the measurements were sensitive to the selection of the natural convection coefficient correlation.

The research reported in this paper explores the use of a new heat flux gage that does not require water cooling to quantify boundary condition details for a surface that is exposed to a fire. Because the device is not water cooled, it is capable of measuring the net heat flux through its own surface using a hybrid methodology that was derived by Hubble and Diller [17]. With knowledge of the net heat flux through the gage, exposure conditions to the surface of the sample can be determined. Methods were developed to experimentally measure the convective heat transfer coefficient, incident heat flux, cold surface heat flux, and adiabatic surface temperature. When the gas temperature is measured, the hybrid gage measurements were used to separate the convective and radiative components of heat flux. These methods were demonstrated through experiments performed in a cone calorimeter with a range of mixed-mode heat transfer environments.

2.3 EXPERIMENTAL

Boundary condition details were measured through a series of experiments in an ASTM E1354 cone calorimeter set to cold surface total heat fluxes of 10, 20, and 40 kW/m². As shown in Figure 2.1, the cone was modified to include a swing arm assembly so that the measuring device could be exposed to the cone heater instantaneously. The swing arm assembly was composed of a 3.2 mm thick, 24.1 mm wide, and 305 mm long aluminum arm with a 101.6 mm x 101.6 mm, 1.02 mm thick sample holder plate on the end.

Experiments were performed with different devices on the swing arm platform. This included the hybrid gage inset and flush onto the surface of 25.4mm thick Superwool 607 ceramic board, Schmidt-Boelter gage mounted surface flush in a 25.4mm thick Superwool 607 ceramic board, hybrid
gage on the surface of the plate thermometer insulation board, and plate thermometer. These setups are shown in Figure 2.2. All setups were 101.6 mm x 101.6 mm in dimension. For experiments with the hybrid gage on the plate thermometer insulation, the insulation from the plate thermometer was removed and the hybrid gage was rigidly mounted onto the surface. In select experiments, gas temperature measurements were made above the devices described above. Results were used to compare heat fluxes and adiabatic surface temperatures measured with the different devices.

2.3.1 Hybrid Heat Flux Gage

The hybrid heat flux gage is a recently developed gage that is capable of withstanding temperatures that are in excess of 1000°C without the need for water cooling [19]. The gage uses a thermopile design made with Type K thermocouple materials and ceramic to quantify the heat flux through the gage [20]. The gage directly outputs a voltage signal, a top surface temperature, and a bottom surface temperature. The hybrid heat flux gage has four screw holes so that it can be mounted onto a given substrate.

The hybrid heat flux gage derives its name from the methodology it employs to calculate heat flux. During a transient exposure, the gage functions as both a differential heat flux gage and as a slug calorimeter [17]. A differential heat flux gage is a type of gage that utilizes the one dimensional version of Fourier’s Law in order to calculate the net heat flux through the thickness of the gage,

\[ q_{diff} = \frac{k(T_S - T_b)}{\delta} \]  

(2)

A slug calorimeter measures the amount of thermal energy that is absorbed by the slug as a function of time with no heat loss from the back of the sensor. This type of device utilizes an energy balance,

\[ q_{slug} = \rho C \delta \frac{dT}{dt} \]  

(3)

where the derivative in Equation (3) is performed on the average of the front and back surface temperatures of the gage. Slug calorimeters have the drawback of not being able to record measurements at steady state, since the slug requires a temperature gradient with time and must not have heat losses from the back of the sensor. Hubble and Diller [17] developed a methodology that uses the slug and differential measurements to quantify the actual net heat flux measurement.

\[ q_{net} = q_{diff} + \frac{1}{2}(q_{slug}) \]  

(4)

The hybrid heat flux gage used in these experiments was coated with high emissivity (0.95) flat black paint.
The hybrid heat flux gage requires a calibration for differential heat flux sensitivity at room temperature and high temperature as well as a slug heat flux sensitivity calibration [19]. Calibrations were performed using a halogen lamp radiation source. A variable transformer was used to generate heat fluxes in the range of 5-35 kW/m². A reference Schmidt-Boelter water cooled gage was used to measure the heat flux produced at different lamp voltage levels. The lamp voltage levels were measured with a Fluke 177 True RMS Multimeter.

The results of the room temperature differential heat flux sensitivity calibration can be seen in Figure 2.3. The gage produces a voltage that varies linearly with the incident heat flux. The slope of this line represents the sensitivity at room temperature, which is equal to \( S_o = 0.0302 \text{mV/(kW/m}^2) \). An elevated temperature calibration was also performed because the response of the sensor changes as its temperature increases [19]. This resulted in the following correlation of sensitivity as a function of temperature

\[
S = S_o \left(1 + 3.4923 \times 10^{-4} T_{Avg}^2 + 1.0238 \times 10^{-6} T_{Avg}^3 - 3.5056 \times 10^{-9} T_{Avg}^4 + 1.9126 \times 10^{-12} T_{Avg}^5 \right)
\] (5)

where \( T_{Avg} \) is the average gage temperature in (°C). The high temperature sensitivity does not change from gage to gage, thus only a room temperature calibration is needed in order to determine \( S_o \) and Equation (5) can be used to determine the gage sensitivity at all temperatures.

The thermal mass of the gage, \( \rho C \delta \), which was used to determine the slug calorimeter portion of the heat flux, was measured by transient tests on the gage. For this calibration, the sensor was mounted on top of a thermal insulator and exposed to heat fluxes that ranged from 5-35 kW/m² for a 30 second time period. These calibration tests lead to the plot of average gage temperature divided by heat flux versus time shown in Figure 2.3b. The slope of this line was determined to be 10.4 kW-s/(m²-°C), which represents the thermal mass of the gage. The linearity of the signal confirms the no heat loss assumption for a slug calorimeter.

### 2.3.2 Schmidt-Boelter Heat Flux Gage

The Schmidt-Boelter gage that was used for this experiment was a water cooled, 12.5mm diameter gage that was made by Medtherm (model number GTW-7-32-485A). The Schmidt-Boelter gage was coated with high emissivity (0.95) flat black paint and it was calibrated with the same halogen lamp source as the hybrid gage. The results of this calibration can be found in Figure 2.4. The experimentally determined Schmidt-Boelter gage sensitivity was found to be 0.1795 mV/(kW/m²).

### 2.3.3 Plate Thermometer

The plate thermometer is a device that was designed by Wickstrom [21] for furnace control in fire resistance testing. The device has also been used to measure the adiabatic surface temperature for items exposed to fire conditions. The plate thermometer used for these experiments was purchased from Pentronic. The device is 100 mm by 100 mm composed of a 0.7 mm thick stainless steel covering on one side of a 10 mm thick insulation pad. The plate temperature is measured between the plate and
insulation using a Type K thermocouple welded to the center of the steel plate. A schematic of the plate thermometer is shown in Figure 2.2.

2.3.4 Gas Temperature

Gas temperature measurements were performed using two different types of devices, bare bead thermocouples and an aspirated thermocouple assembly. The aspirated probe tubing and its placement are shown in Figure 2.1. For the bare bead thermocouple experiments, one fine 0.254 mm butt-welded thermocouple was attached to the swing arm assembly and was approximately 6.35 mm above the exposed surface of the hybrid gage. The other 0.508 mm diameter butt-welded thermocouple was stationary and located under the cone heater for the entire experiment. When the assembly was rotated using the swing arm assembly, the stationary thermocouple was also 6.35 mm above the top surface of the hybrid gage, and approximately 25.4 mm away from the 0.254 mm diameter thermocouple attached to the swing arm. Gas temperatures were measured in separate experiments using an aspirated thermocouple assembly where air was drawn through 6.35 mm diameter stainless steel tubing over a 1.5 mm diameter bare bead thermocouple using a pump. The aspiration velocity was measured to be approximately 15 m/s. The 20 mm distance from the tube inlet to the bead and the 1.5 mm bead diameter for the aspirated thermocouple assembly were kept as close as possible to those used by Blevins and Pitts [18].

2.3.5 Test Procedure

Experiments were performed in a cone calorimeter with the exhaust fan off. Cold surface total heat fluxes used in the experiments included 10, 20, and 40 kW/m². All of the measurements were recorded using a National Instruments data acquisition system. Data was collected using LabView at a frequency of 1 Hz. Every test was run with a two minute baseline. After this two minute time period, the measuring device was rotated under the cone heater using the swing arm. Data was collected for 900 seconds so that the gage could reach steady state and then the device was rotated away from the cone heater.

2.4 RESULTS

Experimental data for the devices and setups shown in Figures 2.1 and 2.2 are provided in this section for total cold surface heat flux levels of 10, 20, and 40 kW/m². In select experiments, the gas temperatures were measured between the cone heater and the device to support the separation of radiation and convection heat fluxes.

2.4.1 Measured Heat Fluxes

The heat flux measurements taken with the water cooled Schmidt-Boelter gage are shown in Figure 2.5. The tests showed to be repeatable and the water cooled heat fluxes remained relatively constant, which one would expect since the cone calorimeter provides a constant source of radiation.
Figure 2.6 shows the net heat flux through the hybrid heat flux gage versus time. Performing a generalized energy balance at the surface of the hybrid gage gives,

\[ q_{\text{net}} = \varepsilon_S q_{\text{rad}} + h(T_{\infty} - T_S) - \varepsilon_S \sigma T_S^4 \]  

(6)

Where, \( q_{\text{rad}} \) is the incident radiant heat flux into the gage. Inspection of Equation (6) provides insight into the differences between Figures 2.5 and 2.6. Because the Schmidt-Boelter gage is water cooled, it has a nearly constant surface temperature. Thus, if the incident radiant heat flux and the gas temperature are constant, the Schmidt-Boelter gage will provide a constant heat flux. The Schmidt-Boelter gage provides the net heat flux to a water cooled surface. The value in a cold surface heat flux is that it approximates the incident radiation when radiation is dominant. Figure 2.6 provides the net heat flux through the gage, which is not the same as the net heat flux to the sample because the surface temperatures are different. The value in knowing the net heat flux to the gage is that if you know the convective heat transfer coefficient and you measure the gas temperature, you can determine the exposure conditions to the surface of the sample. Knowing the incident radiation and convection to the sample surface enables temperature predictions to be made. In addition, because the surface temperature of the gage is variable, the gage is capable of distinguishing between heat flux from radiation and convection. Water cooled heat flux gages simply provide the total heat flux to the cold surface. If a water cooled gage is used in a mixed-mode environment then a cold surface heat flux will be of little value.

2.4.2 Plate Thermometer

Plate thermometer measurements are provided in Figure 2.7. These temperature measurements have been reported by Wickstrom [11,13] to be related to the adiabatic surface temperature. From the results in Figure 2.7, the measured adiabatic surface temperature from the plate thermometer would correspond to the temperature reached by the plate thermometer at steady state, which occurs 200-400 seconds after exposure. The time required to reach the steady state under the constant exposure heat flux conditions was measured to decrease with an increase in heat flux.

2.4.3 Gas Temperature Measurements

Gas temperature measurements were taken in order to quantify the convection to the surface of the hybrid gage. Inspection of Equation (6) shows that there are three unknowns for a given hybrid gage measurement, the gas temperature, the convective heat transfer coefficient and the incident radiation. Thus, knowledge of the gas temperature is needed to quantify the radiation and to separate the convective and radiative heat transfer components.

Measuring gas temperature in radiation dominated environments, such as the cone calorimeter, is difficult because of the radiative error that is introduced by the source on the thermocouple beads [18,23]. This error can be very large for bare bead thermocouples at high heat flux levels, and while not entirely eliminated for aspirated thermocouples, it is significantly reduced. The bare bead gas
temperatures were taken solely for the purpose of showing the gas temperature trend throughout the experiments.

Measurements of the bare bead thermocouple gas temperatures and the aspirated thermocouple gas temperatures are shown in Figure 2.8. As expected, the aspirated thermocouple assembly predicted a lower gas temperature than the bare bead thermocouples because of the convective cooling produced by pulling air over the thermocouple bead inside of the stainless steel tubing. Also as expected, the larger diameter stationary bare bead thermocouple measured a higher temperature than the smaller diameter due to radiation effects. The magnitude of the difference between these measurements was similar to the difference observed in the literature [18].

2.5 ANALYSIS AND DISCUSSION

Analysis of the experimental data was performed to verify the measurements made using the hybrid heat flux gage and to develop new methods for quantifying the heat transfer boundary condition. A method for determining the heat transfer coefficient from the hybrid heat flux gage measurements is presented and used to predict cold surface heat flux as well as adiabatic surface temperature. Comparison of heat fluxes measured using the hybrid gage and Schmidt-Boelter gage were performed to demonstrate the measurement of the cold surface heat flux. Measurements of the adiabatic surface temperature taken with the plate thermometer were compared with the time dependent adiabatic surface temperatures determined using the hybrid gage. A comparison of the heat flux determined using the plate thermometer using the method presented by Ingason and Wickstrom [7] and the hybrid gage was also performed using hybrid gage measurements on the surface of the plate thermometer insulation board. Using gas temperature measurements, the hybrid gage measurements were used to determine the radiative and convective heat transfer components.

2.5.1 Incident Heat Flux

The incident heat flux is comprised of both the incident radiation and convection due to the exposure. The net heat flux and surface temperature measurements of the gage were used to quantify the incident heat flux onto the gage. Rearranging Equation (6) leads to an expression for incident heat flux,

\[ q_{inc}^* = \varepsilon_s q_{rad}^* + h(T_\infty - T_S) = q_{net}^* + \varepsilon_s \sigma T_S^4 \]

where, \( q_{inc}^* \) is the total incident heat flux into the gage and \( q_{rad}^* \) is only the radiant component of incident heat flux. The variables on the right hand side of Equation (7) are direct outputs of the hybrid heat flux gage. The incident heat flux at the 10 kW/m\(^2\) cold surface heat flux level is shown in Figure 2.9a accompanied by the gage surface temperature for the same test shown in Figure 2.9b. Figure 2.9c and Figure 2.9d show the incident heat flux and gage surface temperature at the 40 kW/m\(^2\) cold surface heat flux level respectively.
Note that the incident heat fluxes shown in Figure 2.9 are different than the cold surface heat flux in Figure 2.11. From an energy balance at the surface, the cold surface heat flux is,

$$q_{\text{cold}}^* = \varepsilon_s q_{\text{rad}}^* + h(T_s - T_{\text{cold}}) - \varepsilon_s \sigma T_{\text{cold}}^4 = q_{\text{inc}}^* + h(T_s - T_{\text{cold}}) - \varepsilon_s \sigma T_{\text{cold}}^4$$  \hspace{1cm} (8)

Equation (8) also expresses the cold surface heat flux in terms of the incident heat flux defined by Equation (7). As seen in Equation (8), the cold surface heat flux is different than the incident heat flux due to the reradiation from the cold surface and the convection term. The cold surface reradiation term is typically small compared with other terms; therefore, the differences in the cold surface and incident heat fluxes is primarily due to the differences in convection. In these experiments, the convection with surrounding cases cools the surface causing the $q_{\text{inc}}^*$ to be less than $q_{\text{cold}}^*$.

### 2.5.2 Heat Transfer Coefficient

The heat transfer coefficient is needed to determine the cold surface heat flux, adiabatic surface temperature, and convective and radiative heat transfer components. A method for calculating the heat transfer coefficient using the hybrid gage was developed. The method is based on the surface energy balance that was performed to obtain Equation (1). Equation (1) can be rearranged to provide an expression for the heat transfer coefficient,

$$h = \frac{(q_{\text{cold}}^* - q_{\text{net}}^*) - \varepsilon_s \sigma (T_s^4 - T_{\text{cold}}^4)}{(T_s - T_{\text{cold}})}$$  \hspace{1cm} (9)

the $q_{\text{net}}^*$ and $T_s$ variables on the right hand side of Equation (9) are direct outputs of the hybrid gage. The $q_{\text{cold}}^*$ and $T_{\text{cold}}$ values can be obtained using a reference method approach. At the beginning of the exposure, the hybrid gage is cool and provides a direct measure of $q_{\text{cold}}^*$. Thus, $q_{\text{cold}}^*$ and the corresponding $T_{\text{cold}}$ can be determined by averaging the values of $q_{\text{net}}^*$ and $T_s$ from the hybrid gage during the initial part of the exposure while the gage is still cold. The results of performing this calculation can be seen in Figure 2.10. The $h$ values were plotted for several different averaging times to determine the $q_{\text{cold}}^*$ and $T_{\text{cold}}$ values to show that the results are insensitive to the selection of the reference time span.

The most commonly used method to calculate the heat transfer coefficient is to invoke a natural convection heat transfer coefficient correlation based on a known geometry. For cone calorimeter samples, a flat plate with a hot surface facing upward is typically used for natural convection, with the surface temperature assumed constant, as described in Ref. [22]. Tables for air properties in Ref. [22] were used to calculate the Nusselt number using,

$$Nu_L = \frac{hL}{k} = 0.54Ra_L^{1/4}$$  \hspace{1cm} (10)

where,
The surface area and perimeter of the sample was used to calculate the length scale,

$$L = \frac{A_S}{P}$$  \hspace{1cm} (12)

The properties of air were evaluated at the film temperature,

$$T_f = \frac{(T_S + T_\infty)}{2}$$ \hspace{1cm} (13)

where $T_\infty$ was measured with the aspirated thermocouple assembly. The results of this analysis are shown graphically in Figure 2.10 and steady state values for both the measured hybrid gage heat transfer coefficient and correlation calculated heat transfer coefficient are shown in Table 2.1. The percent difference for these steady state measurements ranged from 7.5 to 18.5 %. The differences in convective heat transfer coefficient values can be attributed to the more complex air flows seen in the cone calorimeter than the ideal laminar natural convection assumption invoked for the correlation calculations. Another contributing factor can be the uncertainty association with the correlation itself, which is not an exact value of the convective heat transfer coefficient.

### 2.5.3 Cold Surface Heat Flux

The hybrid heat flux gage can be used to calculate the cold surface heat flux that one would normally obtain using a Schmidt-Boelter gage. The calculations are based on the energy balance that was performed to obtain Equation (1). Rearranging Equation (1) and solving for $q_{\text{cold}}^*$ produces the following expression,

$$q_{\text{cold}}^* = q_{\text{net}}^* + \varepsilon_S \sigma (T_S^4 - T_{\text{cold}}^4) + h (T_S - T_{\text{cold}})$$ \hspace{1cm} (14)

where, $h$ is obtained from the heat transfer coefficient methodology described above and the $T_{\text{cold}}$ value was 297°K, which was the temperature of the water being used to cool the Schmidt-Boelter gage. The results of this analysis are shown in Figure 2.11. In Figure 2.11, the hybrid heat flux gage predicted $q_{\text{cold}}^*$ values are compared to the Schmidt-Boelter $q_{\text{cold}}^*$ from Figure 2.5. The percent difference between the hybrid gage measured cold surface heat fluxes and the Schmidt-Boelter measured cold surface heat fluxes ranged from 1.1 to 2.1 % at steady state. The agreement of these measurements verifies the ability of the hybrid gage to measure cold surface heat flux.

### 2.5.4 Adiabatic Surface Temperature
The adiabatic surface temperature is the temperature that a surface would achieve if it was perfectly insulated. This quantity has been proposed as a convenient way to model the thermal boundary conditions in fires and link fire models to structural models [10-13]. Part of the appeal of this method is that the adiabatic surface temperature is the direct output of the plate thermometer at steady state. However, the hybrid gage can also be used to calculate the time varying adiabatic surface temperature using the energy balance that was performed to obtain Equation (6) and setting $q^{''\text{net}}$ to zero,

$$0 = \varepsilon_S q^{\star \text{rad}} - \varepsilon_S \sigma T_{S,ad}^4 + h(T_\infty - T_{S,ad})$$

Subtracting Equation (6) from Equation (15) cancels out the radiation terms and the convective gas temperature resulting in,

$$q^{\star \text{net}} = \varepsilon_S \sigma (T_{S,ad}^4 - T_S^4) + h(T_{S,ad} - T_S)$$

The only variable in Equation (16) that is unknown is the adiabatic surface temperature. A MATLAB script was written that used an internal non-linear equation solver based on Newton’s Method to solve Equation (16) for the adiabatic surface temperature using the $q^{''\text{net}}$ and $h$ for all times. The adiabatic surface temperatures predicted by the hybrid gage and measured by the plate thermometer are shown in Figure 2.12 for the 10, 20, and 40 kW/m$^2$ cold surface heat flux levels. The hybrid gage and the plate thermometer consistently converge to within less than 2.5% of each other. The primary difference between the hybrid gage and the plate thermometer for the results shown in Figure 2.12 is that the hybrid gage provides an adiabatic surface temperature for all exposure times while the plate thermometer only measures the adiabatic surface temperature at steady state. The plate thermometer reached steady state after approximately 500, 350 and 150 seconds for the 10, 20, and 40 kW/m$^2$ cold surface heat fluxes respectively. The hybrid gage measurement can be used to determine a real time adiabatic surface temperature using a transient $q^{''\text{net}}$ and $h$.

### 2.5.5 Separated Heat Flux Components

The hybrid gage is capable of determining the separate components of heat flux, when the measurement is taken in conjunction with a gas temperature measurement. Using the aspirated gas temperature data, Equation (6) becomes completely posed. Rearranging variables and solving for the incident source radiation results in,

$$q^{\star \text{rad}} = \frac{q^{\star \text{net}} - h(T_\infty - T_S) + \varepsilon_S \sigma T_S^4}{\varepsilon_S} = \frac{q^{\star \text{net}} - q^{\star \text{conv}} - q^{\star \text{rr}}}{\varepsilon_S}$$

The convective heat flux is quantified using the heat transfer coefficient that was measured experimentally with the hybrid gage,

$$q^{\star \text{conv}} = h(T_\infty - T_S)$$
With the gage temperature measured, the surface reradiation can be calculated from the hybrid gage output using

\[ q_{rr}^* = -\varepsilon s \sigma T_s^4 \]  

(19)

where, the negative sign indicates that heat is transferred out of the gage.

Figure 2.13a and Figure 2.13b contain plots of these different components for an experiment performed at 10 kW/m². Figure 2.13c shows the separate components of heat flux measured at the 40 kW/m² cold surface heat flux level. The incident radiation was nearly constant and similar to the cold surface heat flux. According to Equation (8) the cold surface heat flux and the incident source radiation should be different because of the convection term and the cold surface reradiation term. Incident radiation and cold surface heat flux are similar because convection was low. Had a comparison been made between the hybrid gage and a water cooled gage in mixed-mode heat transfer conditions the cold surface heat flux would have been different than the incident radiation.

The convection result can then be used to explain the shape of the total incident heat flux shown in Figure 2.9. From Equation (7) one can see that the total incident heat flux is composed of incident radiation and incident convection. The cone calorimeter provides a constant source of incident radiation, which is also observed in Figure 2.13. Thus, the shape of the total incident heat flux is controlled by the incident convection. The convective heat flux was negative and thus was a source of cooling to the hybrid gage. This was expected because the surface temperature of the hybrid gage is larger than the gas temperature measured inside of the cone.

The reradiation heat flux and the convection heat flux shown in Figure 2.13b can be used to explain the shape of the net heat flux measured with the hybrid gage. When the hybrid gage is cool, convection and reradiation have a minimal impact on the net heat flux, thus the hybrid gage measurement starts near the source radiation value. Initially the convection is a source of heating to the gage because the gas temperature is greater than the surface temperature of the gage. However, with time the hybrid gage heats up. After approximately 30 seconds the surface temperature exceeds the gas temperature and convection becomes a source of cooling. The surface temperature of the gage rises much faster than the gas temperature, thus convection increases with time until both surface temperature and gas temperature reach a steady state.

2.5.6 Plate Thermometer Comparisons

Ingason and Wickstrom [7] use the plate thermometer to calculate incident radiant heat flux and formulate the net heat flux to the plate thermometer at steady state. Ingason and Wickstrom’s [7] experiments were also performed inside of a cone calorimeter and for their analysis they assumed an ambient gas temperature. To directly compare the hybrid gage and plate thermometer, the insulation from the plate thermometer was removed and hybrid gage was mounted on top of it. Relationships in Ref. [7] were used to compute the incident radiant heat flux totals and the net heat transfer for the plate thermometer. The incident radiant heat flux and the net heat flux for the plate thermometer were
calculated using both the ambient assumption for gas temperature invoked in Ref. [7] and for measured aspirated gas temperature values. Figure 2.14a shows the incident radiant heat flux measurements for both devices at the 10 kW/m² cold surface heat flux level. Figure 2.14b shows the net heat flux totals for both the hybrid gage and the plate thermometer.

The plate thermometer and the hybrid gage give similar predictions for the incident radiant flux when an ambient gas temperature is assumed for the plate thermometer measurement. This is primarily due to how Ref. [7] derived their expression for incident radiant flux. Embedded into their equation is a conduction correction factor. This correction factor was used to make the plate thermometer results match the results of the Schmidt-Boelter gage. This relationship only remains true when an ambient gas temperature is assumed. If a more realistic measured gas temperature is used, then the plate thermometer will predict a lower and incorrect incident radiant flux, as seen in Figure 2.14a.

The net heat flux shown in Figure 2.14b was calculated for the plate thermometer using Equation (6), where the incident radiant flux was calculated using the expression from Ref. [7] that is shown in Figure 2.14a. The net heat flux from the plate thermometer when the gas temperature is assumed to be ambient predicts a higher net heat flux than the hybrid gage. From Equation (6) the incident radiation and reradiation terms for the hybrid gage and plate thermometer are similar at steady state; however, the convection is different. The hybrid gage uses a measured gas temperature and it uses a measured heat transfer coefficient. The $q''_{\text{net}}$ that the plate thermometer predicts using an aspirated gas temperature is closer to the hybrid gage. However, this is simply coincidental because this net heat flux was determined with the fictitious radiant flux shown in Figure 2.14a.

2.6 CONCLUSIONS

It has been proven that the hybrid heat flux gage is capable of measuring the net heat flux through its thickness and incident heat flux onto its surface when exposed to mixed-mode heat transfer. A method was developed to successfully determine the heat transfer coefficient during the exposure. Using the heat transfer coefficient, the hybrid gage output was used to determine cold surface heat flux and time dependent adiabatic surface temperature. Cold surface heat flux values compared well with Schmidt-Boelter measurements. The time varying adiabatic surface temperature was relatively constant during the cone calorimeter exposure and consistent with plate thermometer measurements after the plate thermometer reached steady state (200-500 seconds). The incident radiant heat fluxes determined using the plate thermometer using the method described elsewhere in the literature were low compared with the hybrid gage measurements. The differences were attributed to inaccuracies in accounting for heat losses in the plate thermometer. When heat flux measurements were taken in conjunction with a gas temperature measurement, the hybrid gage was used to separate the radiative and convective heat flux components. These showed that the radiation in the cone calorimeter was relatively constant and convection cools samples in the cone calorimeter, which results in a time varying incident heat flux.
Figure 2.1. A schematic of a) the hybrid gage flush mounted into the ceramic board and the aspirated thermocouple probe under the cone heater, and b) the relative motion of the hybrid gage, sample, and swing arm assembly from its initial position to its position under the cone calorimeter.
Figure 2.2. Schematics of select experimental setups, a) The hybrid gage flush inset to ceramic board, b) The Schmidt-Boelter gage flush inset to ceramic board, c) the hybrid gage mounted onto the insulation removed from the plate thermometer, and d) the plate thermometer.
Figure 2.3. Hybrid heat flux gage a) differential and b) slug calibration results.
Figure 2.4. Calibration results for the Schmidt-Boelter heat flux gage.
Figure 2.5. Cold surface heat fluxes measured using a Schmidt-Boelter gage at cold surface heat fluxes of a) 10kW/m$^2$, b) 20kW/m$^2$, and c) 40kW/m$^2$. 

(a) 10kW/m$^2$
(b) 20kW/m$^2$
(c) 40kW/m$^2$
Figure 2.6. Net heat flux values measured with the hybrid heat flux gage at cold surface heat flux values of a) 10kW/m², b) 20kW/m², and c) 40kW/m².
Figure 2.7. Plate thermometer surface temperature measurements at cold surface heat flux values of a) 10kW/m², b) 20kW/m², and c) 40kW/m².
Figure 2.8. Bare bead and aspirated gas temperature measurements at cold surface heat fluxes of a) 10kW/m\(^2\) and b) 40kW/m\(^2\). The stationary bare bead was 0.508 mm in diameter and the relative (attached to swing arm) bare bead was 0.254 mm in diameter.
Figure 2.9. The a) incident heat flux, and b) gage surface temperature at 10kW/m$^2$, c) incident heat flux at 40kW/m$^2$, and d) gage surface temperature at 40kW/m$^2$. 
Figure 2.10. Heat transfer coefficients measured with the hybrid gage at cold surface heat fluxes of a) 10kW/m$^2$, b) 20kW/m$^2$, and c) 40kW/m$^2$ and correlation calculated heat transfer coefficients.
Table 2.1. The steady state (final 120 seconds) averaged heat transfer coefficient values for both the hybrid gage measured and correlation calculated methods.

<table>
<thead>
<tr>
<th>Cold Surface Heat Flux (kW/m²)</th>
<th>Average Heat Transfer Coefficient (W/m²-K)</th>
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<tbody>
<tr>
<td></td>
<td>Method</td>
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<tr>
<td>10</td>
<td>Hybrid</td>
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<td></td>
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<td>40</td>
<td>Hybrid</td>
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</table>
Figure 2.11. The cold surface heat flux values measured by the Schmidt-Boelter gage and the hybrid gage at cold surface heat fluxes of a) 10kW/m², b) 20kW/m², and c) 40kW/m².
Figure 2.12. The hybrid gage and plate thermometer measured adiabatic surface temperatures at cold surface heat fluxes of a) 10kW/m², b) 20kW/m², and c) 40kW/m².
Figure 2.13. The separate components of a) incident heat flux and b) net heat flux measured by the hybrid gage at the 10kW/m² cold surface heat flux level and the separate components of c) net heat flux measured by the hybrid gage at the 40kW/m² cold surface heat flux level.
Figure 2.14. Comparisons of the a) incident radiant heat flux and b) net heat flux for the hybrid gage and the plate thermometer using both an aspirated thermocouple measured and ambient assumed gas temperatures for the plate thermometer.
2.7 REFERENCES


CHAPTER 3

Temperature Predictions using Hybrid Heat Flux Measured Boundary Conditions

Vega, T., Lattimer, B.Y., and Diller, T.E.
Virginia Tech

3.1 ABSTRACT

The hybrid heat flux gage is a high temperature gage that does not require water cooling and can be placed directly onto a surface to quantify the exposure boundary conditions. In this research, the hybrid gage was mounted onto three different samples and used to determine exposure conditions for predicting the transient temperature rise of the samples. Tests were performed in an ASTM E1354 cone calorimeter at cold surface heat flux levels of 10, 20 and 35 kW/m$^2$. Boundary condition details such as the incident radiant heat flux and the convective heat transfer coefficient were determined with the hybrid gage. The measured boundary conditions were input into the finite element package Abaqus to predict the transient through thickness temperature rise of aluminum alloy 5083, Marinite P, and UNIFRAX Duraboard LD ceramic board. Transient temperature predictions were generally within 1-6% of the experimental data, further demonstrating the use of the hybrid gage to determine the mixed mode boundary condition details for fire applications.

NOMENCLATURE LISTING

- $A_s$: area of exposed surface (m$^2$)
- $C$: specific heat capacity (kJ/kg-K)
- $g$: gravitational constant (m/s$^2$)
- $h$: average heat transfer coefficient (W/m$^2$-K)
- $k$: thermal conductivity (kW/m-K)
- $L$: length scale of expose surface (m)
- $Nu_L$: average Nusselt number (- -)
- $P$: perimeter of sample (m)
- $q''$: heat flux (kW/m$^2$)

- $\beta$: thermal expansion coefficient (K$^{-1}$)
- $\delta$: gage thickness (m)
- $\varepsilon$: emissivity (- -)

Subscripts

- $P$: perimeter of sample (m)
- $G$: Gage
- $q$: cold
3.2 INTRODUCTION

Accurate transient temperature predictions of materials are essential for determining the response of materials in fire applications. To predict the temperature rise, the thermal boundary conditions of the fire environment must be quantified. The radiation/convection mixed-mode heat transfer environment produced by fires results in a complex boundary condition to quantify. Currently, experimental measurement of the boundary condition either relies on assumptions about the environment or uses a representative condition to model the fire environment. Methods for measuring the actual boundary conditions are needed to help support fire model development, develop a better understanding of fire behavior, and produce more accurate transient temperature predictions of materials.

A common method to model the thermal boundary condition is to use a water cooled Schmidt-Boelter or Gardon total heat flux gage to acquire a cold surface heat flux using,

\[
q_{\text{net}}^* = q_{\text{cold}}^* - \varepsilon_s \sigma (T_s^4 - T_{\text{cold}}^4) - h(T_s - T_{\text{cold}})
\]  

where \( T_{\text{cold}} \) is the temperature of the reradiating cold surface. Assumptions about the heat transfer coefficient are typically required to apply the boundary condition, and the fraction of radiation and convection from the heat source are not measured. This heat flux boundary condition is then typically coupled with a version of Fourier’s Law to generate temperature profile predictions though the thickness of the sample,

\[
\rho c \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right)
\]
There are several examples of using this approach to predict temperature rise in samples for a variety of problems related to fires. Enniful and Torvi [1] used this methodology to predict the temperature rise of soil samples exposed to 25-75 kW/m² cold surface heat flux levels in the cone calorimeter. Using a mathematical model based on variable thermal properties, Enniful and Torvi [1] were able to predict lethal heat penetration depths within 2-10% of the experimentally measured values. Similarly, Manzello et al [2] performed temperature and cold surface heat flux measurements on fire exposed glass assembles and used their Schmidt-Boelter cold surface heat flux data as an input into a computer program called BREAK, which uses a variation of Equation (2) to predict time to failure for glass based on temperature rise [3]. Spearpoint [4] attempted to predict the temperature rise of protected and unprotected steel members exposed to a full-scale fire by specifying temperature measurements into the FEA program THELMA [5], which utilizes a form of Equation (2) to perform its analysis. Lattimer [6] used a Schmidt-Boelter gage and Equation (1) to determine the time varying surface temperature, which was coupled with Equation (2) to predict the temperature profile though a coupon sized glass reinforced vinyl ester composite and obtained results that were within 10% of the experimentally measured data.

Another technique to predict the temperature rise of a material exposed to fire is to use the adiabatic surface temperature. The adiabatic surface temperature is the temperature that a perfectly insulated surface would achieve. This approach uses the adiabatic surface temperature to represent the thermal environment. As a result, the actual fraction of radiation and convection from the environment are not known and assumptions on the heat transfer coefficient are needed. The adiabatic surface temperature has been proposed as a means of connecting fire models to structural models with plate thermometers in radiation dominated environments [7-11]. The adiabatic surface temperature can be obtained from a fire model such as FDS, or it can be measured directly with a plate thermometer [7-8]. Experiments have been performed on structural steel where measurements were obtained using plate thermometers and the results were compared to FDS and ANSYS models by Wickstrom et al [7] with good results. Sandstrom [8] performed a theoretical analysis of using the adiabatic surface temperature to predict the temperature rise of fire exposed materials by using a finite element package called TASEF. TASEF can make heat transfer calculations based on a prescribed time temperature curve, such as an adiabatic surface temperature curve. TASEF then uses a two dimensional version of Equation (2) to make temperature profile predictions. Wickstrom et al [9] experimentally used plate thermometers to measure the adiabatic surface temperature to fire exposed square tubes and I-beams then used TASEF to compare measured temperatures with predicted temperatures with good results. Duthinh et al [10] have similarly used the adiabatic surface temperature to predict the temperature rise of a steel truss that is exposed to a compartment fire and found that model results compared well with data.

The focus of this research is to present an alternative method to quantify exposure conditions and to use these boundary conditions to predict the temperature rise of a material. This method is based on using a hybrid heat flux gage to measure the thermal boundary condition for different samples exposed to fire conditions in a cone calorimeter. Using methods developed previously [18,19], the hybrid heat flux gage was used to determine the boundary condition details on exposed samples including the net heat flux through the gage, incident radiant heat flux, incident convective heat flux,
and convective heat transfer coefficient. With these boundary conditions, the commercial finite element package Abaqus was used to predict the transient temperature rise of samples having a range of thermal properties. Temperature predictions were compared with transient temperature profile data to further validate the boundary condition details.

### 3.3 EXPERIMENTAL METHODS

A series of experiments was performed in an ASTM E1354 cone calorimeter at cold surface heat fluxes of 10, 20, and 35 kW/m$^2$. Samples of aluminum alloy 5083 H116, Marinite P, and UNIFRAX Duraboard LD ceramic board were exposed in the test with the hybrid heat flux gage mounted to the surface of each sample. All samples were 101.6 mm by 101.6 mm. The aluminum 5083 was 6.35 mm thick, the Marinite P was 12.7 mm thick and the UNIFRAX Duraboard LD ceramic board was 25.4 mm thick. All of the samples were painted black with high temperature flat paint with an emissivity of 0.95. Measurements were recorded using a Data Acquisition System from National Instruments with the data collected using a LabView program with a sampling frequency of 1 Hz.

The cone calorimeter was retrofitted with a swing arm assembly in order to expose the gage and sample to the heat source instantaneously, which is shown in Figure 3.1. The swing arm assembly was fabricated from 25 mm aluminum angle that was 305 mm long and wrapped with Superwool 607 ceramic insulation. Attached to the end of the angle was a steel mesh with overall dimensions of 101.6 mm by 101.6 mm. Four finishing nails were spot welded to the mesh with their pointed ends facing upwards. Samples were placed on top of the finishing nails to minimize heat loss between the sample and the swing arm assembly.

All of the samples had four 1.85 mm through holes drilled into their top surfaces in order to mount the hybrid gage. In addition, all of the samples had one side hole of 0.254 mm diameter that was drilled to a depth of 38.1 mm to insert an 0.250 mm diameter Type K, sheathed thermocouple. This sheathed thermocouple was used to measure the midpoint temperature of the samples. For the aluminum, the midpoint temperature was the only temperature that was measured because of the negligible temperature gradient through its thickness. The marinite and ceramic board both had temperatures measured at their top and bottom surfaces with 0.254 mm diameter, butt-welded, Omega CHAL-010-BW thermocouples. These thermocouples were attached by drilling small holes through the thickness of the ceramic board and marinite samples and pulling the thermocouple wire taught such that the thermocouple junction was in contact with the surface of the sample. Each sample was tested three times at each cold surface heat flux level for a total of nine experiments.

Three separate experiments were performed to inspect the uniformity of the temperature on the exposed surface during the transient stage of heating using a FLIR SC 655 IR camera. For these experiments, the cone calorimeter was set to a temperature that corresponded to a cold surface heat flux of 10 kW/m$^2$. The aluminum and marinite samples were exposed for 30 seconds after which they were rotated to their original positions to measure the surface temperature distribution using the IR camera. The ceramic board sample was exposed for 10 seconds prior to the IR camera temperature measurement.
3.3.1 Hybrid Heat Flux Gage

The hybrid heat flux gage is a novel heat flux gage that was recently designed and tested for fire applications [14,18,19]. The gage is capable of withstanding temperatures that are in excess of 1000°C without the need for water cooling [12]. The gage uses a thermopile design, made with Type K thermocouple materials in order to generate a voltage signal, which can then be converted into a heat flux [13]. The gage directly outputs a voltage signal, a top surface temperature and a bottom surface temperature. The hybrid heat flux gage has four screw holes so that it can be mounted onto a given sample.

The hybrid heat flux gage derives its name from the methodology it employs to calculate heat flux. The gage functions as both a differential heat flux gage and as a slug calorimeter [14]. A differential heat flux gage is a type of gage that utilizes the one dimensional version of Fourier’s Law in order to calculate the net heat flux through the thickness of the gage,

$$\dot{q}_{\text{diff}} = \frac{k(T_s - T_b)}{\delta}$$

The main drawback to a differential heat flux gage is that it requires a good heat sink and thus must be mounted onto a good conductor.

A slug calorimeter measures the amount of thermal energy that is absorbed by the slug as a function of time. This type of device utilizes an energy balance to determine the heat flux,

$$\dot{q}_{\text{slug}} = \rho C \delta \frac{dT}{dt}$$

where the derivative in Equation (4) is performed on the average of the front and back surface temperatures of the gage. Slug calorimeters have the drawback of not being able to record measurements at steady state, since the slug requires a temperature gradient with time. Slug calorimeters make very accurate measurements during a transient state, while differential sensors make their best measurements at steady state. Hubble and Diller [14] developed a methodology that combined these two types of sensors, thereby maximizing the best features of both types of gages.

$$\dot{q}_{\text{net}} = \dot{q}_{\text{diff}} + \frac{1}{2}(\dot{q}_{\text{slug}})$$

3.3.2 Gas Temperature Measurements

In order to separate the different components of heat flux with a hybrid gage, a gas temperature measurement must be performed. However, as Ref. [15] mentions, there is an error associated with taking a gas temperature measurement with a bare bead thermocouple in a radiation dominated environment such as the cone calorimeter. In order to reduce this measurement error, an
aspirated thermocouple assembly was used. This aspirated thermocouple assembly consisted of a bare bead thermocouple within a 6.35 mm diameter stainless steel tube that was attached to a pump. The pump drew air over the thermocouple bead, creating a convection dominated response over the thermocouple bead that reduced the radiation error. The bead within the aspirated thermocouple assembly was located 20 mm from the tube inlet and was located on the center axis of the tube. The dimensions for this aspirated thermocouple assembly were kept as close as possible to those described in Ref. [15]. A bare bead thermocouple measurement was also performed with a 0.254 mm diameter Omega CHAL-010-BW butt welded thermocouple. This gas temperature measurement was necessary in order to quantify convection to the unexposed surface. This lower thermocouple was placed such that its bead would be centered and approximately 25.4 mm from the unexposed surface, which is seen in Figure 3.2. An aspirated thermocouple probe was not required for the unexposed side, since the sample acts as a radiation shield. Gas temperatures near the unexposed surface of the sample were much less than gas temperatures near the exposed surface. Using the results of Ref. [15] it was determined that the radiation error to the bare bead thermocouple beneath the sample was negligible.

3.4 MODELING

Simulations were performed to obtain transient temperature predictions through the thickness of a given sample using Abaqus. The boundary condition details input into Abaqus were determined from the hybrid heat flux gage. A simulation was performed for every experimental trial in order to directly compare the experimentally measured temperature profiles with the Abaqus predicted temperature profiles.

3.4.1 Model Geometry, Mesh, and Material Properties

The sample geometries created in Abaqus were of the sample only. The holes for mounting the gage and thermocouples were neglected, and the hybrid gage was not included in the model. The aluminum and marinite had mesh sizes of 200 nodes and the ceramic board model had a mesh size of 400 nodes. Quadratic solid heat transfer elements were used in the analysis. A convergence analysis was performed on the mesh for all three samples, which proved that the mesh sizes were appropriate.

Temperature varying material properties were used for all three samples. Specific heat as a function of temperature, thermal conductivity as a function of temperature, and constant densities were used to create aluminum 5083, marinite and ceramic board in the model. Material densities used in the modeling included aluminum 2660 kg/m$^3$, marinite 961 kg/m$^3$ and ceramic board 272 kg/m$^3$. The aluminum data was obtained from Ref. [20] while the marinite and ceramic board properties were provided by the manufacturers.

3.4.2 Model Boundary Conditions

The samples were modeled as simple flat plates surrounded by air on all sides. Contact between the sample holder and the sample was minimized by using finishing nails to elevate the sample. Conduction between these nails and the sample was neglected. Exposed surface boundary conditions for the sample were determined by the hybrid gage and are composed of the radiation from the heater,
convection, and reradiation. The boundary conditions on the sides and unexposed surface of the sample are convection and reradiation.

3.4.3 Exposed Surface Boundary Condition

The exposed surface boundary condition was implemented in a couple of different ways to determine the most accurate method for predicting transient temperature rise. Initially, the net heat flux measured by the hybrid gage was considered for describing the exposed surface boundary condition. As seen in Figure 3.5., the gage temperature and sample surface temperature were not the same during the transient stages of the exposure. An energy balance at the gage surface provides relations for the net heat flux to the gage and sample surfaces,

\[ q_{\text{net},G}^* = \varepsilon_s q_{\text{rad}}^* + h_G (T_\infty - T_{S,G}) - \varepsilon_s \sigma T_{S,G}^4 \]  
\[ q_{\text{net},\text{Sam}}^* = \varepsilon_s q_{\text{rad}}^* + h_{\text{Sam}} (T_\infty - T_{S,\text{Sam}}) - \varepsilon_s \sigma T_{S,\text{Sam}}^4 \]  

Due to the sample and gage surfaces not having equal temperatures, the net heat flux into the gage is not the same as the net heat flux into the sample. As a result, the gage net heat flux could not be used as the boundary condition in this application.

The method selected to model the boundary condition was to quantify the radiation and convection components. Equation (6) and (7) indicate that both the gage and the sample are both subjected to the same incident radiation, \( q_{\text{rad}}^* \). The incident radiation is also independent of the surface temperature and the convective heat transfer coefficient. Using the methods described in [18] to obtain \( h_G \), and an aspirated thermocouple measurement to obtain \( T_\infty, q_{\text{rad}}^* \) with time was determined through,

\[ q_{\text{rad}}^* = \frac{q_{\text{net}}^* - h_G (T_\infty - T_{S,G}) + \varepsilon_s \sigma T_{S,G}^4}{\varepsilon_s} \]  

The convection portion of the boundary condition was included in the model by providing the measured \( h_G \) and the measured gas temperature.

3.4.4 Unexposed Surface Boundary Condition

The unexposed surface boundary condition was composed of convection and reradiation to the laboratory. Reradiation from the surface was determined by the model based on the predicted temperature. Convection to the unexposed surface was modeled using a correlation for the cool side of
a flat plate in natural convection obtained from Ref. [16]. For a flat plate in natural convection, the cool side is typically modeled using,

\[ Nu_L = \frac{hL}{k} = 0.27Ra_L^{1/4} \tag{9} \]

where \( Nu \) is the dimensionless Nusselt number, \( Ra \) is the dimensionless Rayleigh number and \( L \) is a length scale that is used to improve accuracy,

\[ L = \frac{As}{p} \tag{10} \]

Modeling convection to the back surface also required a gas temperature measurement, which was measured using a bare bead thermocouple.

3.4.5 Side Surfaces Boundary Condition

The boundary condition for the sample sides was composed of convection and reradiation to the laboratory. Reradiation from the surface was determined by the model based on the predicted temperature. Convection to the vertical sides of the flat plate was modeled using a correlation found in Ref. [16]. Because of the smaller surface area, convection to the vertical sides was less significant than convection to the front or back sides. The convective heat transfer coefficient was determined using,

\[ Nu_L = 0.68 + \frac{0.670Ra_L^{1/4}}{[1 + (0.492/Pr)_{10}]^{4/9}} = \frac{hL}{k} \tag{11} \]

where, the Rayleigh number was determined from

\[ Ra_L = \frac{g\beta(T_S - T_\infty)L^3}{\nu\alpha} \tag{12} \]

where, \( g \) is the gravitational constant, \( Pr \) is the dimensionless Prandtl number, and \( \beta \) is the thermal expansion coefficient (1/\( T_S \)). All of the properties used temperature dependent data for air found in Ref. [16] and were evaluated at the film temperature. The gas temperature used was the exposed surface gas temperature measured using the aspirated thermocouple probe.

3.5 RESULTS AND DISCUSSION

Both the experimental results and model predictions are provided in this section. This section includes measured boundary condition details such as the net heat flux to the gage, convective heat transfer coefficients, and separated components of heat flux. IR camera results are presented for transient heating to check the uniformity of the surface temperature. Gas temperature measurements
for the exposed and unexposed surfaces are also presented. In addition, the temperature profile predictions from the Abaqus model are compared to the measured temperature profiles for aluminum, marinite, and ceramic board measured at cold surface heat fluxes of 10, 20, and 35 kW/m². Repeatability data is also presented for all three samples at the 10 kW/m² cold surface heat flux level.

3.5.1 Exposed Surface Boundary Conditions

The hybrid heat flux gage directly measures the net heat flux through itself. Normalized net heat flux measurements for the hybrid gage are shown in Figure 3.3 for aluminum, marinite, and ceramic board exposed to a cold surface heat flux of 10 kW/m². The net heat flux through the gage changes depending on the material, despite that the samples and gage were exposed to the same incident heat flux levels in the cone calorimeter. This is particularly evident at longer times when the sample has reached a steady state. Differences in the net heat flux are attributed to the thermal properties of the sample affecting the temperature rise of the hybrid gage. Hybrid heat flux gage surface temperatures for aluminum, marinite, and ceramic board are shown in Figure 3.4 for the 10 kW/m² cold surface heat flux level. Inspection of Equation (6) shows that a higher gage surface temperature results in more convective losses and reradiation from the gage, resulting in a lower steady state net heat flux, which is observed in Figure 3.5.

A FLIR SC 655 infrared camera was used to analyze the uniformity of the exposed surface of the sample during the transient heating periods. Images for the three materials are shown in Figure 3.5. The IR images for the aluminum and marinite were taken after 30 seconds of exposure while the IR image for the ceramic board was taken after 10 seconds of exposure. The exposed surface of the samples appear to be uniform during the transient state. What appears to be the outermost edges of the plate, which is at a different temperature than the rest of the plate, is actually the metal grate of the swing arm. Also apparent from these images is that the hybrid gage does not have the same surface temperature as the sample. Because the hybrid gage is not the same temperature as the sample, the net heat flux measured by the hybrid gage is not the same as the net heat flux into the sample.

Exposed surface convective heat transfer coefficients were obtained using a reference method that was developed in [18]. A time varying heat transfer coefficient was obtained from,

$$ h = \frac{(q''_{cold} - q''_{net,G}) - \varepsilon_s \sigma (T_s^4 - T_{cold}^4)}{(T_s - T_{cold})} $$  \hspace{1cm} (13)

where \( q''_{cold} \) and \( T_{cold} \) were calculated by averaging the first 5 seconds of \( q''_{net} \) and \( T_{s,G} \) values, starting from the value that corresponds to the highest \( q''_{net} \) value. Equation (13) produces \( h \) values that are dependent on the surface temperature of the hybrid gage. The hybrid gage surface temperature is dependent on the material that it is mounted on, thus the convective heat transfer coefficient is a function of the material that the gage is mounted on. A drawback to this method is that during the initial 100 seconds of exposure time the convective heat transfer coefficient is physically unrealistic because \( T_s \) is near \( T_{cold} \). For the Abaqus model, constant steady state convective heat transfer coefficients were used for the duration of the simulation. This approximation was believed to be appropriate because of
the low magnitude of convection during the initial 100 seconds of exposure. Table 3.1 lists the average value steady state convective heat transfer coefficients for each material for each cold surface heat flux level. Table 3.1 also contains the heat transfer coefficient calculated using natural convection correlations as well as standard deviation of each method.

Using the methods developed in Ref. [18] the separate components of heat flux were calculated and are shown in Figure 3.6 for aluminum for the different cold surface heat flux levels. As expected, the incident source radiation provided by the cone calorimeter is nearly constant. The convection briefly heats the hybrid gage until the hybrid surface temperature becomes larger than the gas temperature, at which point convection becomes a source of cooling. Also as expected, radiation was the dominant mode of heat transfer.

3.5.2 Gas Temperatures

Gas temperatures were measured above the top surface of the gage and sample with an aspirated thermocouple assembly and gas temperatures were measured at the bottom surface with a stationary bare bead thermocouple. Figure 3.7 shows the gas temperature measurements that were taken at the 10, 20, and 35kW/m² cold surface heat flux level for marinite samples. Aspirated gas temperature measurements were independent of the sample. Figure 3.8 shows the unexposed side gas temperature measurements that were taken at the same 10, 20, and 35 kW/m² cold surface heat flux level for all three samples. The unexposed surface gas temperature was measured with a bare bead thermocouple that was stationary and placed under the cone heater for all time, including during the baseline. Thus, the gas temperature initially was above ambient, then decreased once the sample was rotated under the heater with the swing arm assembly. With time the gas temperature slowly increases due reradiation from the sample. For aluminum, this reradiation was significant for the 35 kW/m² exposure where the gas temperature reaches 95°C.

3.5.3 Temperature Profile Predictions

Measured boundary conditions details were input into Abaqus to predict the through thickness temperature profiles of aluminum, marinite and ceramic board exposed to cold surface heat fluxes of 10, 20 and 35 kW/m². Gas temperatures at the top and back surfaces of the flat plate samples were also measured and input into Abaqus for each test. Correlation determined values for the unexposed side heat transfer coefficient, and vertical side heat transfer coefficients were also input into the model. Constant value steady state heat transfer coefficients were used for each simulation.

The resulting model predictions and the experimentally measured temperature values are shown in Figure 3.9 for the aluminum, Figure 3.10 for the marinite, and Figure 3.11 for the ceramic board. Only one temperature was measured for aluminum, the midpoint temperature, because of the negligible temperature gradient through its thickness. Average measured and predicted temperature values for each sample at each cold surface heat flux value are shown in Table 3.2, with their corresponding percent differences. Three measurements were performed for each heat flux setting and for each sample to show repeatability. The temperature measurements for the 10kW/m² cold surface
heat flux level are shown in Figure 3.12 for all three trials of all three samples showing the thermal response of the materials was repeatable.

The predicted aluminum temperatures had most agreement with the measured temperatures. All of the aluminum models were within 2.5% of the measured temperatures. This was attributed to the proximity of the aluminum temperature to the hybrid gage surface temperature. The hybrid gage surface temperature was generally within 10°C of the aluminum temperature for the entire test duration. An assumption to modeling these samples was that the convective heat transfer coefficient to the gage was the same as the heat transfer coefficient to the sample. The heat transfer coefficient is a function of surface temperature, thus convection to the aluminum model was very similar to convection to the gage. Convection data from the gage was input to the model, which explains the close proximity of the measured and modeled results.

The marinite model provided the closest agreement with the data. Results were within 4% of the measured values at steady state, which are shown in Table 3.2. The good agreement can be attributed to the relative insensitivity of marinite to convection on its unexposed and vertical surfaces. The most deviation for the marinite occurred at the unexposed surface, which was expected because of the use of a correlation for the convective heat transfer coefficient. Top surface temperature predictions were within 2% of measured values at steady state, and center point predictions were within 2.2% of the measured values at steady state.

The ceramic board model was also able to accurately predict the measured temperatures. Deviation in the model and data was attributed to a nonuniform through thickness initial temperature, which was not included in the modeling. The largest deviation occurred at the unexposed surface. The model predicts an unexposed surface temperature that is almost identical in shape, but shifted downward by a difference that is approximately equal to the difference in initial starting temperature.

3.6 CONCLUSIONS

It has been proven that the methods previously developed to quantify the thermal boundary condition with the hybrid heat flux gage are accurate. With the measured gas temperature, the hybrid heat flux gage was used to determine the incident radiant heat flux and the exposed surface convective heat transfer coefficient. Measured boundary condition details were input into Abaqus to predict the temperature rise of aluminum 5083, Marinite P, and UNIFRAX Duraboard LD ceramic board exposed to different heat fluxes. Temperature results from the model were generally within 6% of the data.
Figure 3.1. CAD figures of a) the swing arm assembly, b) the swing arm assembly with the sample and gage being rotated under the cone calorimeter heater, and c) a zoomed in view of the swing arm assembly, sample and gage.
Figure 3.2. A CAD figure of the swing arm assembly, sample, gage, and gas temperature measurement probes. The top surface gas temperature was measured with an aspirated thermocouple assembly, and the unexposed surface gas temperature with a butt-welded bare bead thermocouple.
Figure 3.3. Gage net heat flux measurements at a cold surface heat flux level of 10kW/m² for the a) aluminum 5083, b) marinite, and c) ceramic board.
Figure 3.4. Hybrid heat flux gage surface temperatures at the 10kW/m² cold surface heat flux level for aluminum 5083, marinite, and ceramic board.
Figure 3.5. IR images of transient heating at the 10kW/m² cold surface heat flux level for a) aluminum 5083, b) marinite, and c) ceramic board.
Table 3.1. Comparisons of average steady state exposed surface convective heat transfer coefficient values for the heat transfer coefficients determined by the reference method approach and for values determined from a natural convection correlation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cold Surface Heat Flux (kW/m²)</th>
<th>Steady State h from Hybrid Gage (W/m⁻²°C)</th>
<th>Steady State h from Correlation (W/m⁻²°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum 5083</td>
<td>10</td>
<td>14.02 ± 0.987</td>
<td>11.74 ± 0.083</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>14.93 ± 0.973</td>
<td>12.87 ± 0.109</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>18.28 ± 1.18</td>
<td>12.90 ± 0.076</td>
</tr>
<tr>
<td>Marinite P</td>
<td>10</td>
<td>17.12 ± 1.10</td>
<td>12.06 ± 0.051</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>18.00 ± 0.834</td>
<td>12.73 ± 0.044</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>22.08 ± 0.863</td>
<td>13.14 ± 0.064</td>
</tr>
<tr>
<td>Ceramic Board</td>
<td>10</td>
<td>14.34 ± 0.685</td>
<td>12.48 ± 0.059</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>14.61 ± 0.639</td>
<td>13.12 ± 0.077</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>12.63 ± 0.704</td>
<td>13.38 ± 0.063</td>
</tr>
</tbody>
</table>
Figure 3.6. The separated components of heat flux for aluminum at cold surface heat fluxes of a) 10 kW/m$^2$, b) 20 kW/m$^2$, and c) 35 kW/m$^2$. 

(a) 

(b) 

(c)
Figure 3.7. Gas temperature measurements taken with an aspirated thermocouple probe assembly, taken above the top surface of the gage and sample for cold surface heat flux levels of (a) 10kW/m$^2$, (b) 20kW/m$^2$, (c) 35kW/m$^2$. 
Figure 3.8. Gas temperature measurements for the bottom unexposed side of the aluminum 5083 sample for cold surface heat flux levels of a) 10kW/m$^2$, b) 20kW/m$^2$, c) 35kW/m$^2$.
Figure 3.9. Temperature profile predictions versus experimentally measured temperature for aluminum 5083 at the a) 10kW/m², b) 20kW/m², and c) 35kW/m² cold surface heat flux levels.
Figure 3.10. Temperature profile predictions versus experimentally measured temperatures for the top surface, center, and bottom surfaces of marinite exposed to cold surface heat flux levels of a) $10\text{ kW/m}^2$, b) $20\text{ kW/m}^2$, and c) $35\text{ kW/m}^2$. 
Figure 3.11. Temperature profile predictions versus experimentally measured temperatures for the top surface, center, and bottom surfaces of ceramic board exposed to cold surface heat flux levels of a) 10kW/m$^2$, b) 20kW/m$^2$, and c) 35kW/m$^2$. 
**Table 3.2.** A summary of steady state (average of the final 200 seconds of exposure) temperature values for both the model and experimentally measured values for individual trials across all samples, cold surface heat flux exposure levels and measurement locations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cold Surface Heat Flux Level (kW/m²)</th>
<th>Measurement Location</th>
<th>Steady State Experimental (°C)</th>
<th>Steady State Model (°C)</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum 5083</td>
<td>10</td>
<td>Center</td>
<td>201.20</td>
<td>204.00</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Top Surface</td>
<td>275.08</td>
<td>286.16</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Center</td>
<td>192.63</td>
<td>196.00</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bottom Surface</td>
<td>122.73</td>
<td>127.81</td>
<td>3.97</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>Top Surface</td>
<td>388.54</td>
<td>396.64</td>
<td>2.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Center</td>
<td>267.80</td>
<td>269.62</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bottom Surface</td>
<td>160.26</td>
<td>166.17</td>
<td>3.56</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>Top Surface</td>
<td>535.74</td>
<td>542.78</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Center</td>
<td>372.84</td>
<td>364.58</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bottom Surface</td>
<td>220.12</td>
<td>212.15</td>
<td>3.62</td>
</tr>
<tr>
<td>Marinite</td>
<td>10</td>
<td>Top Surface</td>
<td>309.77</td>
<td>318.60</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Center</td>
<td>191.52</td>
<td>189.48</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Top Surface</td>
<td>429.94</td>
<td>436.94</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Center</td>
<td>279.83</td>
<td>265.78</td>
<td>5.02</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>Top Surface</td>
<td>567.98</td>
<td>589.13</td>
<td>3.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Center</td>
<td>397.41</td>
<td>373.56</td>
<td>6.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bottom Surface</td>
<td>152.07</td>
<td>124.56</td>
<td>18.09</td>
</tr>
<tr>
<td>Ceramic Board</td>
<td>10</td>
<td>Top Surface</td>
<td>309.77</td>
<td>318.60</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Center</td>
<td>191.52</td>
<td>189.48</td>
<td>1.07</td>
</tr>
<tr>
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<td>20</td>
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<td></td>
<td>35</td>
<td>Top Surface</td>
<td>567.98</td>
<td>589.13</td>
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<td></td>
<td>Bottom Surface</td>
<td>152.07</td>
<td>124.56</td>
<td>18.09</td>
</tr>
</tbody>
</table>
Figure 3.12. Temperature measurements for three trials of a) aluminum 5083, b) marinite, and c) ceramic board at a cold surface heat flux of 10kW/m².
3.7 REFERENCES


CHAPTER 4

Partitioning Convective and Radiative Components of Heat Flux using the Hybrid Heat Flux Gage

Vega, T., Lattimer, B.Y., and Diller, T.E.

Virginia Tech

4.1 ABSTRACT

A new experimental apparatus was fabricated to expose the hybrid heat flux gage to isolated intensities of convection and radiation using an impinging jet, tungsten lamp, and gage holster assembly. The gage holster assembly was capable of water cooling, which allowed the hybrid gage to function as a water cooled total heat flux gage when desired. The hybrid gage was exposed to isolated radiation, isolated convection and mixed-mode heat transfer conditions. Two different methods were developed to obtain a convective heat transfer coefficient using heat flux measurements from the hybrid gage at elevated temperature. Convective heat transfer coefficients from these methods were 9-12% of values determined while the hybrid gage was water cooled in convection dominated conditions. Both of these methods were used to separate the components of net heat flux taken during the mixed-mode measurement. The incident radiation to the gage was isolated by water cooling the gage and exposing it to radiation dominated conditions produced by only running the lamp. The incident radiation predicted in mixed-mode conditions was 11-16% using the measured convective heat transfer coefficients. For the mixed-mode heat transfer conditions, the incident radiation was found to be sensitive to the measured gas temperature. Bounds were determined for the range of possible gas temperatures and a sensitivity analysis on the incident radiation was performed by varying the gas temperatures within this range.

NOMENCLATURE LISTING

\[ C \] specific heat capacity (kJ/kg-K)  
\[ \rho \] density (kg/m\(^3\))  
\[ h \] average heat transfer coefficient (W/m\(^2\)-K)  
\[ \sigma \] Stefan-Boltzman constant (5.67x10\(^{-11}\) kW/m\(^2\)-K\(^4\))  
\[ k \] thermal conductivity (kW/m-K)  
\[ q' \] heat flux (kW/m\(^2\))  
\[ T \] temperature (°C or K)  
\[ t \] time (s)  
\[ q'_{\text{diff}} \] differential heat flux  
\[ q'_{\text{rad}} \] Incident radiation  
\[ \delta \] gage thickness (m)  
\[ q'_{\text{exposed}} \] exposed surface  
\[ q'_{\text{slug}} \] slug heat flux  

Subscripts:
- \( q'_{\text{cold}} \) cold surface
- \( q'_{\text{diff}} \) differential heat flux
- \( q'_{\text{rad}} \) Incident radiation
- \( q'_{\text{exposed}} \) exposed surface
- \( q'_{\text{slug}} \) slug heat flux
4.2 INTRODUCTION

The ability to accurately quantify the thermal boundary condition is necessary in order to predict the temperature rise of materials that are exposed to fire. Ideally, this boundary condition could be defined if the separate components of convection and radiation to a fire exposed surface were known. The ability to simultaneously determine these separate heat flux components requires knowledge of the convective heat transfer coefficient and net heat flux to the fire exposed surface. A hybrid heat flux gage that can measure heat flux with the gage at elevated temperatures has been used to quantify these heat flux components. The focus of this research is to validate these methods using carefully designed experiments where the convective and radiation components are known.

The most common method to measure heat flux in fire testing is to use water cooled total heat flux gages such as the Schmidt-Boelter gage or Gardon gage. These gages do not actually measure the net heat flux to the fire exposed surface, rather they measure the cold surface heat flux, which is the heat flux to a water cooled surface [1]. The following expression relates the net heat flux to the cold surface heat flux,

\[
q_{\text{net}} = q_{\text{cold}} - \varepsilon_s \sigma (T_S^4 - T_{\text{cold}}^4) - h(T_S - T_{\text{cold}})
\]

where \(T_{\text{cold}}\) is the temperature of the water cooled reradiating surface. Water cooling these heat flux gages keeps their surface temperature at a nearly constant value when exposed to a constant heat flux. Water cooled heat fluxes have several drawbacks. For instance, these gages will only measure the total heat flux, and the convection and radiation terms cannot be separated unless a correlation is invoked based on assumed geometry and flow conditions to estimate convection. Such an analysis was performed by Bryant et al [3] to partition radiative and convective heat fluxes using a Schmidt Boelter gage during an ISO 9705 test. In addition, these gages also require water lines, which can limit their usefulness.

In the absence of devices that are capable of separating the components of total heat flux alternative methods have been developed. Typically, these measurements rely on using multiple sensors. One such method is to use two different heat flux sensors with different but known emissivities thereby creating a two equation system of simultaneous energy balance equations with two unknowns, the convective and radiative fluxes. Lattimer et al [5] used this approach with two thermopile gages and Lennon and Silcock [6] used this method with two thin plate devices. This approach resulted in acceptable results for medium to high level heat fluxes; however, it was inaccurate at low heat fluxes and soot collection on the low emissivity surface created issues for this using this approach in fire tests. A similar approach was used by Khaled et al [7] for car underhood applications, and it was determined that this method could be used to obtain results with errors less than 10%. However, a sensitivity
analysis revealed that this method was particularly sensitive to the ratio of convective to radiative heat flux, with a higher convective environment being less sensitive.

Another common method for separating the components of heat flux is to use two total heat flux gages with one fit with a sapphire window. The windowed heat flux gage will only measure the incident radiation scaled by the gage emissivity and the transmittance of the sapphire window. The non-windowed gage measures the contribution of both heat flux components and the convection can be determined from the difference in outputs of the two gages. Such an analysis was performed by Frankman et al. [8] to quantify the heat transfer from discontinuous fuel beds. Blanchat et al. [9] performed a similar analysis, with a windowed and non-windowed total heat flux gage, to quantify the radiative and convective components of heat flux to the surface of a cylindrical calorimeter in a large methanol pool fire. This method suffers from several drawbacks such as the need to continuously purge the surface of the window with compressed air, the need to place both sensors near each other to preserve the assumption of both sensors experiencing the same incident source radiation and the window transmittance must be known. Nakos and Keltn [10] performed a separation analysis to quantify the contributions of radiation and convection from large pool fires. In their analysis a pool fire was ignited between two vertical steel plates. Each steel plate had thermocouples on its exposed and unexposed surfaces. In addition, radiometers were placed on the exposed surface of each plate. An inverse heat conduction code was used on the data obtained from the unexposed surface thermocouples to determine the net heat flux to the steel plates. With the net heat flux known, the incident radiation known, and the surface reradiation known the convection was determined.

Lam and Weckman [11] attempted to quantify the magnitudes of convection and radiation at steady state using several different heat flux gages, including Schmidt-Boelter and Gardon gages, by taking measurements in radiative, convective and mixed-mode environments. Their analysis was performed by exposing a single gage to a radiation dominated environment inside a cone calorimeter, then using a heat gun with the cone heater off to induce convection, and then using both the heat gun and the cone heater to create mixed-mode conditions. In their experiments Gardon gage measurements were up to 18% lower than the Schmidt-Boelter gage measurements for mixed-mode environments. The Schmidt-Boelter gage provided good results; however, the measurements were sensitive to the selection of the natural convection coefficient correlation. All of the aforementioned methods suffer from the drawback of necessitating multiple sensors. Using two heat flux sensors doubles the intrusiveness of the measurement.

This research focuses on using a single heat flux gage to separate the convective and radiative components of heat flux under mixed-mode heat transfer conditions. To perform these measurements, a new experimental apparatus was developed to expose the gage to known levels of radiation and convection using a tungsten lamp, impinging jet, and gage holster assembly. The hybrid gage is capable of heat flux partitioning because the gage is not water cooled, thus it has a variable surface temperature. Methods were developed and validated to determine the heat transfer coefficient of the environment. With this information, the radiation and convection heat transfer components were
4.3 EXPERIMENTAL METHODS

In order to verify that the hybrid heat flux gage was capable of separating the components of heat flux, an apparatus was designed to expose the gage to a convective heat flux, radiative heat flux, and mixed-mode conditions. Figure 4.1 contains an illustration of this separation apparatus. The separation apparatus consists of an impinging jet assembly to apply the convective heat flux, a tungsten lamp assembly to apply the radiative heat flux, and a gage holder assembly that was used to water cool the gage when necessary. Data was acquired by LabView with a National Instruments DAQ at a sampling frequency of 10Hz.

All of the different subassemblies were mounted to the table and aligned. The gage holder assembly was designed such that it could translate forward and backward so that it could be closer or further from the impinging jet outlet. The tungsten lamp was similarly designed such that it could translate forward and backward. The lamp was also designed to be able to pivot and rotate approximately 90 degrees. The impinging jet assembly was stationary for all tests. A compressed airline was directed through an electrical resistance heater on the wall, which then connected into the bottom of the impinging jet. This hot airline was adjustable for air velocity and for air temperature. The tungsten lamp was connected to a variac, which made the incident source radiation adjustable. The lamp was inside an acrylic mold. A pump was used to water cool the gage holder. This pump was submerged in water and the water temperature was maintained between 25°C and 26°C.

For convection testing, a two minute baseline was performed prior to testing. After this baseline measurement was performed, the airline and resistance heater were turned on. Once the impinging jet reached a steady state temperature, the pump for the gage holder was turned on to water cool the gage. Once the water temperature reached the desired range, data was collected. The hybrid gage was subjected to the convection dominated heat flux for 300 seconds while being water cooled. After 300 seconds the pump was turned off and the hybrid gage surface temperature was allowed to vary. Testing continued for another 1100 seconds to allow the hybrid gage to reach a steady state. Similar experiments were performed for the radiative and mixed-mode tests. For each test, the hybrid gage was water cooled for 300 seconds while being subjected to the dominant mode of heat transfer. Water cooling was then turned off and the gage surface temperature was allowed to vary with time until a steady state was reached. For mixed-mode tests, this portion of the data gathering lasted for 1100 seconds while for radiation dominated tests it lasted for 3000 seconds.

4.3.1 Hybrid Heat Flux Gage

The hybrid heat flux gage was recently designed and tested for fire applications [13-15]. The gage is capable of withstanding temperatures that are in excess of 1000°C without the need for water cooling [16]. The gage uses a thermopile design, made with Type K thermocouple materials in order to generate a voltage signal that can then be converted into a heat flux [15]. The gage directly outputs a
voltage signal, a top surface temperature and a bottom surface temperature. The hybrid heat flux gage has four screw holes so that it can be mounted onto a given substrate. The hybrid gage was painted with high emissivity (0.95) flat black paint.

The hybrid heat flux gage derives its name from the methodology it employs to calculate heat flux. The gage functions as both a differential heat flux gage and as a slug calorimeter [15]. A differential heat flux gage is a type of gage that utilizes the one dimensional version of Fourier’s Law in order to calculate the net heat flux through the thickness of the gage,

$$q_{\text{diff}} = \frac{k(T_s - T_b)}{\delta}$$  \hspace{1cm} (2)

The main drawback to a differential heat flux gage is that it requires a good heat sink and thus must be mounted onto a good conductor.

A slug calorimeter measures the amount of thermal energy that is absorbed by the slug as a function of time. This type of device utilizes an energy balance,

$$q_{\text{slug}} = \rho C \delta (\frac{dT}{dt})$$  \hspace{1cm} (3)

where the derivative in Equation (3) is performed on the average of the front and back surface temperatures of the gage. Slug calorimeters have the drawback of not being able to record measurements at steady state, since the slug requires a temperature gradient with time. Slug calorimeters make very accurate measurements during a transient state, while differential sensors make their best measurements at steady state. Hubble and Diller [15] developed a methodology that combined these two types of sensors, thereby maximizing the best features of both types of gages,

$$q_{\text{net}} = q_{\text{diff}} + \frac{1}{2}(q_{\text{slug}})$$  \hspace{1cm} (4)

### 4.3.2 Temperature Measurements

A variety of temperature measurements were performed with a series of Type K thermocouples to further quantify the test conditions. A bare bead thermocouple probe was inserted into the junction of the impinging jet assembly to monitor the outlet gas temperature. Another gas temperature measurement was taken with a sheathed thermocouple assembly 25.4 mm in front of the surface of the hybrid gage for the convection and mixed-mode tests. Heat flux measurements were performed with and without the gas thermocouple present. Heat flux data with and without the probe were very similar, which proved that any error from the intrusiveness of the physical presence of the thermocouple was negligible. For the radiation tests the gas temperature was assumed to be that of the ambient surroundings.
4.4 ANALYSIS AND DISCUSSION

Presented in this section are the cold surface heat flux results, net heat flux results, and hybrid gage temperature results for all three experimental conditions as well as the gas temperature measurements. Methodologies for determining the heat transfer coefficient are presented and used to quantify the convective heat transfer coefficient for the convective and mixed-mode cases. The convective heat transfer coefficient was isolated for the special case of convection to a water cooled sensor. The convective heat transfer coefficients determined by the two different methods were compared to this isolated heat transfer coefficient. Separated components of transient incident convection and radiation results are shown in this section for the mixed-mode heat flux exposure. The separated incident radiation from the mixed-mode case is then compared to the incident radiation determined from water cooling the hybrid gage in the radiation dominated case. A sensitivity analysis is shown to illustrate the sensitivity of the incident radiant heat flux to the measured gas temperature.

4.4.1 Cold Surface Heat Flux

For the first 300 seconds of every experiment performed, the hybrid gage was water cooled with a pump. After 300 seconds the pump was turned off and the gage temperature was allowed to vary with time. A heat flux gage that is water cooled is measuring a cold surface heat flux. A cold surface heat flux is the total heat flux to a water cooled surface. Rearranging Equation (1) results in an expression for $q_{\text{cold}}^*$ in terms of $q_{\text{net}}^*$,

$$q_{\text{cold}}^* = q_{\text{net}}^* + \varepsilon S(T_s^4 - T_{\text{cold}}^4) + h(T_S - T_{\text{cold}})$$

where $T_{\text{cold}}$ is the temperature of the reradiating surface of the gage. While the hybrid gage was initially water cooled it was directly measuring $q_{\text{cold}}^*$. Shown in Figure 4.2 are cold surface heat flux measurements taken with the hybrid gage for heat transfer conditions characterized with only the impinging jet on, only the lamp on, and both devices on. All of the cold surface heat fluxes shown in Figure 4.2 are approximately constant, which occurs because the surface temperature of the hybrid gage is kept constant by the cooling water. Interestingly the cold surface heat fluxes are not additive. The average value cold surface heat flux from Figure 4.2 during convection was 19.8 kW/m$^2$, for radiation 18.4 kW/m$^2$, and for mixed-mode 32.0 kW/m$^2$. Cold surface heat flux can also be expressed as,

$$q_{\text{cold}}^* = \varepsilon S q_{\text{rad}}^* + h(T_\infty - T_{\text{cold}}) - \varepsilon S \sigma T_{\text{cold}}^4$$

where, $q_{\text{rad}}^*$ is the incident radiation entering the gage. Equation (6) can be written once for each of the modes of heat transfer shown in Figure 4.2. When the gage is only heated by convection, $q_{\text{rad}}^*$ is attributed to heat entering the gage by radiation from the ambient surroundings. The convective heat transfer coefficient is large because the convection is forced. The gas temperature generated by the heating jet is greater than ambient causing a heat flux into the gage. For radiation dominated heat transfer, $q_{\text{rad}}^*$ is predominantly from heat entering the gage due to the lamp. The gas temperature is assumed ambient because of the vertical orientation of the gage assembly. Convection in this scenario is
natural and not forced. When Equation (6) is written for mixed-mode heat transfer, forced convection dominates and there is no natural convection. The cold surface heat fluxes are not additive because the gas temperature in the mixed-mode case is not the same as the gas temperature in the convection case. The increase in gas temperature reduces the convective heat flux in the mixed-mode case. In addition, because convection was forced \( h \) was large and minor changes in gas temperature produced large changes in convective heat flux.

4.4.2 Net Heat Flux

After 300 seconds the pump was turned off and the surface temperature of the hybrid gage was allowed to vary. Since the hybrid gage was no longer water cooled its heat flux output could now be interpreted as the net heat flux through the gage. Figure 4.3 shows net heat flux and gage temperature versus time plots for the convective, radiative, and mixed-mode heating conditions. The net heat flux into the gage can be expressed as,

\[
\dot{q}_{net} = \varepsilon_S \dot{q}_{rad} + h(T_m - T_S) - \varepsilon_S \sigma T_S^4
\]

(7)

To further understand the net heat flux plots, the gage temperatures were analyzed. Figure 4.3 also shows the exposed and unexposed surface temperatures for the hybrid gage in the convective, radiative, and mixed-mode experiments during the transient region when water cooling was shut off. For the convective case shown in Figure 4.3, reradiation from the exposed surface of the hybrid gage was minimal since the surface did not surpass 55°C. Radiation into the gage was also minimal because it was primarily from the ambient surroundings. Thus, \( q_{net}^c \) in the convective case is almost entirely due to forced convection from the impinging jet. For the radiative case, reradiation and natural convection were significant because the surface temperature of the gage reached above 220°C. The mixed-mode case had a negative steady state net heat flux. Inspection of the hybrid gage surface temperatures in Figure 4.3 reveals that for convection dominated conditions the hybrid gage converged to approximately 55°C. For mixed-mode conditions the hybrid gage exposed surface temperature converged to approximately 84°C. Thus, for the convection to have become a source of cooling, the gas temperature must lie somewhere between these two values.

4.4.3 Gas Temperatures

Gas temperature measurements relative to the exposure surface for the convective and mixed-mode cases were performed with a Type K sheathed thermocouple. This sheathed thermocouple was located 25.4mm from the exposed surface of the hybrid gage and was coaxial with the impinging jet outlet. Gas temperature measurements for the convective and mixed-mode cases are shown in Figure 4.4. The gas temperature for the radiative case is omitted from Figure 4.4 because it was presumed to be ambient. The gage holster was vertically oriented. For the radiative case, convective cooling is due to natural convection. Natural convection is driven by buoyancy forces, which for this vertical orientation meant that cooler ambient air was constantly being driven upwards over the exposed surface of the gage. Thus, a constant gas temperature of 29°C was used for the radiative case. The convective and
mixed-mode gas temperatures shown in Figure 4.4 were nearly constant, which was expected because
the velocity and temperature of the impinging jet were kept constant. The convective case had an
average gas temperature of 61.9° C and the mixed-mode case had an average gas temperature of 66.9
° C. The mixed-mode gas temperature was expected to be higher than the convective case because the
reradiation was larger due to the gage surface temperature being higher as seen in see Figure 4.3.

Figure 4.4 also contains nozzle gas temperature measurements. Nozzle gas temperature
measurements were taken with a bare bead Type K thermocouple, which was located in the junction of
the impinging jet assembly where the flow splits into two. These temperatures can be interpreted as the
outlet temperature of the air stream. These temperatures were not used in any of the calculations in
this paper, but are included to demonstrate repeatability. Nozzle gas temperature for the convective
and mixed-mode cases were constant and averaged 110.1 ° C and 113.7 ° C, respectively. The proximity of
these measurements indicates that similar jet conditions were applied in both the convective and
mixed-mode experiments.

**Convective Heat Transfer Coefficient**

4.4.4 Method One

The first method used to determine the heat transfer coefficient was developed and
implemented in Ref.[13,14] and utilizes a reference method approach. This method rearranges Equation
(1) and solves for \( h \),

\[
q''_{\text{cold}} = \frac{q''_{\text{net}}}{T_S - T_{\text{cold}}} - \frac{\varepsilon_S \sigma (T_S^4 - T_{\text{cold}}^4)}{T_S - T_{\text{cold}}} = \frac{q''_{\text{net}}}{T_S - T_{\text{cold}}} - \frac{\varepsilon_S \sigma T_S^4}{T_S - T_{\text{cold}}}
\]

where \( q''_{\text{cold}} \) and \( T_{\text{cold}} \) are determined by averaging the initial \( q''_{\text{net}} \) and \( T_S \) measurements for the first five
seconds of exposure without water cooling. The downside to this approach is that initial \( h \) values are
unrealistic because \( T_{\text{cold}} \) is by definition near \( T_S \). Convective heat transfer coefficients determined using
this method are shown in Figure 4.5 for the convective and mixed-mode cases. The convective and
mixed-mode cases were both approximately constant once \( T_S \) was sufficiently far from \( T_{\text{cold}} \), which was
75 seconds into the test. Both results seem reasonable for the forced convection flow conditions.

4.4.5 Method Two

A second method to determine the convective heat transfer coefficient was developed based on
the incident heat flux into the hybrid gage. Defining the total incident heat flux into the hybrid gage as
the sum of the incident source radiation and incident convection and rearranging Equation (7) leads to,

\[
q''_{\text{inc}} = \varepsilon_S q''_{\text{rad}} + h (T_\infty - T_S) = q''_{\text{net}} + \varepsilon_S \sigma T_S^4
\]

taking the derivative of \( q''_{\text{inc}} \) with respect to \( T_S \) and assuming that \( q''_{\text{rad}} \) and \( T_\infty \) are constant results in,
\[
\frac{dq_{\text{inc}}^*}{dT_S} = -h
\]  

where \( h \) is the slope of the line generated by plotting \( q_{\text{inc}}^* \) versus \( T_S \). Figure 4.6 shows the results of plotting incident heat flux versus gage surface temperature for the convective and mixed-mode experimental conditions. Linear regression lines were fit through the plots found in Figure 4.6 and the corresponding \( h \) and \( R^2 \) values are shown in Table 4.1. The drawback to this approach is that you get an average \( h \) value whereas the first method generates a time varying \( h \). Method 2 also requires that the incident heat flux be transient. Once the gage reaches a steady state and incident heat flux no longer changes with respect to temperature their relationship will no longer be linear. In addition, Method 2 is only valid if the incident radiation and gas temperature are constant.

### 4.4.6 Validation Case

The validation case for the heat transfer coefficient is a special case that can only be applied to the convection dominated experiment. When the gage was water cooled the net heat flux was approximately equal to the cold surface heat flux, which is a direct output of the gage. In addition, the gas temperature was measured and the surface temperature of the gage was known. Thus, the convective heat transfer coefficient can be determined by,

\[
h = \frac{q_{\text{cold}}^*}{(T_\infty - T_S)}
\]  

where, \( T_\infty \) is the exposed surface gas temperature measurement shown in Figure 4.4 and \( q_{\text{cold}}^* \) is the cold surface heat flux shown in Figure 4.2 for convection. The results of this calculation are shown in Figure 4.7. This approach results in an average \( h \) value of 1064.5 W/(m\(^2\)\(^\circ\)C). This method was used to validate the results of the previous two methods. Table 4.1 summarizes the \( h \) results for all three methods and provides percent difference calculations for Methods 1 and 2 to the validation case. For the convective case Methods 1 and 2 produced values within 9.4% and 12.1% of the validation case respectively. For the mixed-mode case Methods 1 and 2 produces heat transfer coefficient values within 4.7% and 5.9% of the validation case respectively.

### 4.4.7 Separated Heat Flux Components

The components of heat flux were separated using a methodology described in Ref.[13]. The incident radiation is separated from the net heat flux by rearranging Equation (7) and solving for \( q_{\text{rad}}^* \),

\[
q_{\text{rad}}^* = \frac{q_{\text{net}}^* - h(T_\infty - T_S) + \varepsilon_S \sigma T_S^4}{\varepsilon_S}
\]  

where \( h \) can be determined by using either Method 1 or Method 2. Figure 4.8 shows the results of performing this analysis using both methods of determining \( h \). As expected, the convection has transitioned to a source of cooling because the gage surface temperature exceeds the measured gas
temperature. The incident radiation was nearly constant, which was also expected because the lamp was maintained at a constant voltage. Both Method 1 and Method 2 produced similar results, which was anticipated because both methods produced similar $h$ values.

The results shown in Figure 4.8 can be validated by comparing the incident radiant heat flux obtained using Methods 1 and 2 to the cold surface heat flux that was obtained during the radiation measurement. When only the lamp was on and hybrid gage was water cooled, the cold surface heat flux was approximately equal to the incident radiation. Figure 4.9 shows a comparison of the incident radiation obtained from using Methods 1 and 2 to the isolated incident radiation obtained from the cold surface heat flux measurement in the radiation dominated case. The incident radiation fluxes obtained using Methods 1 and 2 appear to underestimate the actual incident radiation. Method 1 produced an incident radiation that was 10.9% less than the actual while Method 2 predicted 16.4% below the isolated radiation. However, the incident radiation value was sensitive to the gas temperature measurement. This was anticipated because of the large $h$ produced during forced convection and the relatively small temperature difference between the gas temperature and the surface temperature of the hybrid gage. Because of these effects even a slight difference between the measured gas temperature and the actual gas temperature was significant. Figure 4.10 illustrates this sensitivity to gas temperature by plotting incident radiation values obtained using different constant gas temperatures. The incident radiation values shown in Figure 4.10 were determined using Method 2 to obtain the convective heat transfer coefficient. The only parameter that was varied was the gas temperature. The $h$ obtained using Method 2 was a constant 1001.1 W/m$^2$K, thus every 1°C temperature change in gas temperature resulted in an approximate 1kW/m$^2$ change in incident radiant heat flux.

A simple analysis can be performed to determine the range of values that the true gas temperature lies in. When only the impinging jet was on and convective heating dominates, Equation (7) is well posed. The incident radiation into the gage is known to be from the ambient surroundings, the convective heat transfer coefficient can be determined by either Methods 1 or 2, and the rest of the parameters are known constants or are outputs of the hybrid gage. For this special case all of the variables are known except for the gas temperature. Rearranging Equation (7) and solving for gas temperature,

$$q_{net} - \varepsilon_S q_{rad} + \varepsilon_S \sigma T_S^4 + h T_S = T_\infty$$ \hspace{1cm} (13)

Using Method 1 to determine $h$ produces an effective gas temperature of 61.2°C at steady state. The measured gas temperature was 61.9°C at steady state. The proximity of the measured gas temperature to the theoretical gas temperature validates the placement of the thermocouple probe. The effective theoretical gas temperature of 61.2°C should serve as a lower bound for the actual gas temperature in mixed-mode conditions. Intuitively, the gas temperature in mixed-mode conditions should be higher because the same impinging jet temperature exists, but now the air is additionally heated by reradiation from the gage holster assembly. In addition, the gas temperature measured by the thermocouple should serve as a maximum for the range of possible gas temperature values. Thermocouple measurements in environments were radiation is prominent are well documented to be higher than the actual gas...
temperatures because of radiation effects on the thermocouple bead [12]. The average steady state measured gas temperature in mixed-mode conditions was 66.9 °C. This analysis should strengthen the incident radiation values shown in Figure 4.9 because of all the results shown in Figure 4.10 the incident radiation corresponding to the measured gas temperature was the furthest from the actual incident radiation, and this gas temperature was at the logical extreme of possible values that the effective gas temperature could have been.

4.5 CONCLUSIONS

It has been shown that the hybrid heat flux gage is capable of separating the radiative and convective components of heat flux in mixed-mode heat transfer environments. Using a separation apparatus that consisted of a lamp, an impinging jet, and a gage holster assembly that allowed the hybrid gage to function as a water cooled gage when desired, the various components of heat flux were isolated and mixed. Two different methods for determining the convective heat transfer coefficient were presented. Water cooled heat flux measurements, taken when only the impinging jet was on, were used to determine an isolated convective heat transfer coefficient value that was then used as a basis for comparison for the other two methods. The convective heat transfer coefficient determined using Method 1 was within 9.4% of the validation case. For Method 2, the measured convective heat transfer coefficient was within 12.1% of the validation case value. Using the convective heat transfer coefficient values determined by these two methods the radiative and convective components of heat flux were separated from the net heat flux. Water cooled heat flux measurements taken when only the lamp was on were used to validate that the hybrid gage was predicting an accurate incident radiation. The separated incident radiative heat fluxes using Methods 1 and 2 to determine the convective heat transfer coefficient were within 10.9% and 16.4% of the validation incident radiant flux. The convective heat flux component and thus the radiative heat flux component were determined to be sensitive to gas temperature values because of the high $h$ and small temperature difference observed in the mixed-mode case. It was determined that a degree difference in gas temperature altered the predicted incident radiation by approximately 1kW/m². However, an upper and lower bound for the actual gas temperature range was established and values of incident radiant heat flux were plotted using several different constant gas temperature conditions. The maximum possible deviation from the validation incident radiant heat flux using Method 2 was determined to be 16.6%.

ACKNOWLEDGEMENTS

The author would like to thank Joseph Starr for all of his efforts and assistance in building the separation apparatus. The author would also like to thank Dr. David Hubble for his guidance in the design of this experiment.
Figure 4.1. A CAD schematic of the separation apparatus assembly. The schematic consists of a water cooled gage holster assembly, an impinging jet to apply a convective load, and a tungsten lamp to apply a radiative load.
Figure 4.2. Cold surface heat flux values for the predominantly convective, radiative and mixed-mode conditions.
Figure 4.3. Net heat flux and corresponding exposed surface and unexposed surface hybrid gage temperatures for predominantly a) convection, b) radiation, and c) mixed-mode conditions.
Figure 4.4. Gas temperature measurements for the predominantly convective and mixed-mode conditions.
Figure 4.5. Convective heat transfer coefficient values obtained using a reference method approach for predominantly a) convective, and b) mixed-mode conditions.
Figure 4.6. Plots of incident heat flux versus gage surface temperature for predominantly a) convective, and b) mixed-mode conditions.
Figure 4.7. The convective heat transfer coefficient determined by using the validation method for the convection dominated case.
Table 4.1. A summary of the steady state convective heat transfer coefficients obtained by using the reference method, slope method, and validation case.

<table>
<thead>
<tr>
<th>Method</th>
<th>Experimental Type</th>
<th>Steady State h (W/m(^{o}\text{C}))</th>
<th>Percent Different to Validation Method (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>Convection</td>
<td>964.2 ± 20.89</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>Mixed-Mode</td>
<td>1014.7 ± 8.06</td>
<td>4.7</td>
</tr>
<tr>
<td>Method 2</td>
<td>Convection</td>
<td>935.6 (R(^2) = 0.9961)</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>Mixed-Mode</td>
<td>1001.6 (R(^2) = 0.9979)</td>
<td>5.9</td>
</tr>
<tr>
<td>Validation Case</td>
<td>Convective</td>
<td>1064.5 ± 13.25</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Figure 4.8. The separated components of heat flux for the mixed-mode case using (a) Method 1 and (b) Method 2 to obtain the convective heat transfer coefficient.
Figure 4.9. A comparison of the incident radiation values obtained using Methods 1 and 2 to obtain the convective heat transfer coefficient to the cold surface heat flux value obtained during the radiation dominated case.
Figure 4.10. A sensitivity analysis of the incident radiation to gas temperature. Incident radiation calculations were performed using Method 2 to determine the convective heat transfer coefficient. The cold surface heat flux represents a validation case for the incident radiation.
4.6 REFERENCES


CHAPTER 5

Conclusions and Recommendations

5.1 CONCLUSIONS

It has been proven that the hybrid gage can be used to model the thermal boundary condition produced by fire. Hybrid gage measurements were used to determine net heat flux through the gage, incident heat flux, cold surface heat flux, heat transfer coefficient, adiabatic surface temperature and partitioned radiative and convective components. Using these boundary condition details the exposure conditions to samples of aluminum 5083, Marinite P, and ceramic board were modeled and through thickness temperature profile predictions were made that were typically within 6% of measured temperatures. Hybrid gage measurements were verified in multiple ways. Hybrid gage predicted cold surface heat fluxes were directly compared to Schmidt-Boelter gage outputs and results were within 5%. Hybrid gage adiabatic surface temperatures were compared to plate thermometer measured adiabatic surface temperatures and were within 2.5% at steady state. Separated radiative and convective heat transfer components were verified by fabricating an experimental apparatus that exposed the gage to isolated, mixed, and known components of radiation and convection. Two different methods were developed to determine the convective heat transfer coefficient during a hybrid gage measurement. The heat transfer coefficients obtained using both methods were within 12.1% of the isolated heat transfer coefficient. Both of these heat transfer coefficients were used to separate the radiative and convective components of net heat flux in mixed-mode conditions. The incident radiant heat fluxes obtained using these two different methods were within 16.4% of the isolated incident radiation.
5.2 RECOMMENDATIONS

For the hybrid gage to become a viable tool in fire dynamics the methods developed in this research have to be extended to include transient non constant heat transfer conditions. All of the testing done in this research was performed in steady and controlled environments. The cone calorimeter provided a constant radiative heat flux to the gage surface. The separation apparatus provided constant radiative and convective heat fluxes. Real fires will not provide constant radiative heat fluxes. The most promising path forward is to further develop the slope method for determining the convective heat transfer coefficient to the gage. A MATLAB code will have to be written that solves for the slope instantaneously, which would create a transient $h$ value. If this method proves effective then the hybrid gage could turn into a powerful and transformative tool for quantifying the thermal boundary condition due to real fires.

Methods should be developed to see if the net heat flux into the gage is proportional to the net heat flux into the sample for a given measurement. Existing data does not seem to confirm that this is true, however poor thermal contact may be responsible for this. New experiments will have to be conducted with the hybrid gage surface mounted onto several different sample surfaces. Extreme care will have to be taken that contact resistance is kept minimal. If net heat flux measurements are proportional, then gas temperature measurements, convective heat transfer coefficients, and partitioned heat flux components wouldn’t be necessary to make temperature rise predictions. This would make the hybrid heat flux gage an even more powerful tool to fire researchers.

Comparisons should be made to structures that are modeled using the adiabatic surface temperature to structures that are modeled using the thermal boundary condition measured by the hybrid gage. Ideally, this would be done using plate thermometers and the hybrid gage in real fire scenarios. However, for this to take place methods must first be developed to quantify a transient $h$ for variable incident radiation heat flux conditions.

The hybrid gage can be used to quantify convection in the cone calorimeter for standardized tests with and without the exhaust fan on. This would be a simple set of experiments to perform that can be done immediately. In general, the hybrid gage can be used to quantify the convection/radiation in any standardized test with constant heat flux conditions immediately.

Lateral conduction effects from the hybrid gage should be analyzed. I believe that lateral conduction is relevant when the hybrid gage is flush mounted into conductive samples. Comparative experiments should be performed with the hybrid gage surface and flush mounted onto a conductive material and surface and flush mounted onto an insulator to quantify these effects. Furthermore, best practices should be developed on how to attach the hybrid gage.

The hybrid gage can be used to determine effective gas temperature measurements in the cone calorimeter for a given temperature setting under standardized testing conditions. Gas temperature measurements in radiation dominated environments are difficult to quantify due to radiation error on
thermocouple beads. Aspirated thermocouple probes reduce this error, but do not eliminate it. Hypothetically, if the Schmidt-Boelter and hybrid gage were placed in a standardized cone calorimeter test together with the temperature setting at 400°C the entire energy balance to a given surface would be posed except for the effective gas temperature. These gas temperatures can then be recorded over a series of temperature setting in the cone, providing researchers with a basis of comparison for their research.

Debate seems to exist in the literature for what \( T_{\text{cold}} \) actually is. Most researchers assume that water cooled heat flux gages are maintained at the constant temperature of the water that is used to cool them. I believe that \( T_{\text{cold}} \) is the temperature of the reradiating surface. This surface is much hotter than the water temperature. The water is typically used to maintain the bottom surface of a heat flux gage at a nearly constant level. A temperature gradient is created between the top and bottom surfaces of the gage, which generates a voltage that is converted into a heat flux. To my knowledge, water cooled gages do not provide a top or bottom surface temperature output. Experiments should be developed where the hybrid gage is water cooled and exposed to known radiative and convective heat fluxes. This would allow for the reference \( T_{\text{cold}} \) to be isolated, which would help close this gap in knowledge.
APPENDIX A.

Included in this section is select data from experiments corresponding to the second chapter of this thesis.

Figure A.1. The convective heat transfer coefficient at the 10kW/m² cold surface heat flux level for the second trial of experimentation.
Figure A.2. The net heat flux, hybrid predicted cold surface heat flux, and Schmidt-Boelter cold surface heat flux for the second trial of the 10kW/m\(^2\) cold surface heat flux trial.
Figure A.3. The convective heat transfer coefficient at the 20kW/m² cold surface heat flux level for the second trial of experimentation.
Figure A.4. The net heat flux, hybrid predicted cold surface heat flux, and Schmidt-Boelter cold surface heat flux for the second trial of the 20kW/m² cold surface heat flux trial.
Figure A.5. Separated heat flux components for the second trial of the hybrid gage mounted onto the plate thermometer insulation experiments. This data was taken at a cold surface heat flux of 20kW/m².
Figure A.6. The convective heat transfer coefficient at the 40kW/m² cold surface heat flux level for the second trial of hybrid gage mounted onto plate thermometer experiment.
APPENDIX B

Included in this section is select data from experiments corresponding to the third chapter of this thesis.

Figure B.1. Measured and predicted temperature profile data for the second trial of the 20kW/m² marinite data.
Figure B.2. Separated heat flux components for the second trial of marinite at the 20kW/m^2 cold surface heat flux level.
Figure B.3. Measured and predicted temperature profile data for the second trial of the 20kW/m² ceramic board data.
Figure B.4. Heat transfer coefficient values for aluminum exposed to a 10kW/m² cold surface heat flux.
Figure B.5. The vertical convective heat transfer coefficient for the 10kW/m² cold surface heat flux aluminum first trial.
Figure B.6. The correlation determined convective heat transfer coefficient for the unexposed surface of aluminum for the 10kW/m² cold surface heat flux level.
APPENDIX C

Included in this section is select data from experiments corresponding to the third chapter of this thesis.

![Graph showing convective heat transfer coefficient values](image)

**Figure C.1.** Convective heat transfer coefficient values obtained using Method 1 for the second trial of the convection dominated experiments.
Figure C.2. The convective heat transfer coefficient determined using the slope method for the second trial of the convection dominated experiment.

\[ y = -982.09x + 330233 \]

\[ R^2 = 0.9923 \]
Figure C.3. The verification case convective heat transfer coefficient for the second trial of the convection dominated experiment.
Figure C.4. The cold surface incident radiation heat flux measured by the hybrid gage during the second trial of the radiation dominated experiment.
Figure C.5. The separated components of heat flux using Method 1 to determine the heat transfer coefficient for the second mixed-mode trial.
Appendix D.

Included in this section are instructions on how to perform a general hybrid gage experiment, how to process hybrid gage data in Excel, how to recreate the cone calorimeter experiments from Chapter 3, and how to recreate the separation experiments from Chapter 4.

Hybrid Gage Measurements:

Before setting up the gage the following must be known:

- Every hybrid heat flux gage has three sensitivities, a differential, slug, and a high temperature. The differential sensitivity changes from gage to gage and is determined by performing a calibration. The hybrid gage is exposed to radiation from a halogen lamp and its voltage output is compared to a reference Schmidt-Boelter gage that is exposed to the same level of radiation. A sample differential calibration is shown in Figure D.1,

![Figure D.1. A differential calibration for a hybrid heat flux gage.](image)

- Every hybrid gage has its own unique slug sensitivity, which is a measure of the thermal mass of the gage. The thermal mass of the gage, $\rho C\delta$, was measured by transient tests on the gage. For this calibration, the sensor was mounted on top of a thermal insulator and exposed to heat fluxes that ranged from 5-35 kW/m$^2$ for a 30 second time period. A sample slug calibration is shown in Figure D.2,
The hybrid gage also has a high temperature sensitivity. This is necessary because the thermal mass of the gage changes with increasing temperature. The high temperature sensitivity is expressed by,

$$S = S_0 (1 + 3.4923 \times 10^{-4} T_{Avg} + 1.0238 \times 10^{-6} T_{Avg}^2 - 3.5056 \times 10^{-9} T_{Avg}^3 + 1.9126 \times 10^{-12} T_{Avg}^4)$$

where, $S_0$, is the differential sensitivity of the gage and $T_{Avg}$ is the average temperature of the gage. This is a generalized equation that can be used for all temperatures.

For a heat flux gage measurement, a measurement can be taken across the positive leads of the gage or the negative leads of the gage. Measuring across the positive leads of the gage has a different differential sensitivity than measuring across the negative leads. The gage used in this research measured across the positive leads of the gage, thus the differential sensitivity corresponds to this. In addition, each gage has its own unique differential sensitivity and its own unique slug sensitivity.

A baseline measurement should be taken with the gage where the gage is exposed to ambient conditions. This average baseline voltage should then be subtracted from the hybrid gage voltage output to make the heat flux initially zero.

**To setup the hybrid gage:**

- Figure D.3. should be used as a reference.
- The hybrid gage comes preassembled with output leads attached to Omega Type K connectors.
- Three DAQ channels are necessary to output two temperatures and a voltage output.
- To set up the top surface temperature output, connect the positive and negative leads from connector $T_1$ to DAQ channel $T_1$.
- To set up the bottom surface temperature output, connect the positive and negative leads from connector $T_2$ to DAQ channel $T_2$. 
To output the voltage difference corresponding to a given net heat flux, connect the positive lead from the T<sub>2</sub> connector to the positive input of the heat flux channel. Then connect the negative lead from the T<sub>1</sub> connector to the negative input of the heat flux channel. This setup corresponds to a positive leads sensitivity. In addition, this setup defines heat flux entering the gage as positive. This setup is illustrated in Figure D.3.

Figure D.3. A connection diagram of the hybrid heat flux gage and a thermocouple DAQ corresponding to a positive leads sensitivity.

- Write a LabView program that measures two temperatures and a voltage as a function of time.

Post processing data:

- Figures D.4-D.6 should be used a reference.
- The gage directly outputs two surface temperatures and a voltage.
- Take the average value of your baseline voltage (where the gage is only exposed to ambient conditions).
- Subtract your heat flux voltage from your baseline voltage e.g. V(t) − V<sub>Baseline</sub>.
• Take the average of your two surface temperatures. Define the surface that is facing the heat source as the top surface and the surface that is attached to a sample as a bottom surface. \( T_{\text{Avg}} = \frac{(T_s - T_b)}{2} \)

• Use Equation 2.5 to determine your high temperature sensitivity:

\[
S = S_0(1 + 3.4923 \times 10^{-4} T_{Avg}^2 + 1.0238 \times 10^{-6} T_{Avg}^6 - 3.5056 \times 10^{-9} T_{Avg}^8 + 1.9126 \times 10^{-12} T_{Avg}^{12})
\]

In this equation \( S_0 \) is the differential sensitivity of the gage in use and this parameter changes from gage to gage.

• Use the slug calorimeter equation to determine the slug portion of heat flux

\[
q_{\text{slug}} = \rho C \delta \left( \frac{dT}{dt} \right)
\]

In this equation \( \rho C \delta \) is determined from the slug calibration. The derivative of temperature with respect to time was calculated by using a four second moving average. The top surface of the gage was used (not the average temperature).

• Next, calculate the differential heat flux component using,

\[
q_{\text{diff}} = \frac{V(t) - V_{\text{Baseline}}}{S(T_{Avg})}
\]

A unit conversion will most likely be necessary.

• Net heat flux is then calculated using,

\[
q_{\text{net}} = q_{\text{diff}} + \frac{1}{2} (q_{\text{slug}})
\]

This will provide the net heat flux through the gage versus time. Figures D.4 -6 provide sample Excel sheets of these calculations.
Figure D.4. A sample Excel sheet of the hybrid gage temperature and voltage outputs, the average gage temperature calculation, and the differential signal (voltage minus the baseline).

<table>
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<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<td>4</td>
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</tbody>
</table>

Figure D.5. A sample Excel sheet of the elevated temperature sensitivity calculation.

<table>
<thead>
<tr>
<th>A</th>
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</table>
How to recreate the cone calorimeter from Chapter 3 experiments:

- Remove the cone calorimeter sample holder and attach the swing arm.
- Paint both sample and gage black with high temperature flat black paint.
- Use 0.5 inch long #1 screws to attach the hybrid gage to the sample.
- Insert a 0.250 mm diameter Type K Omega sheathed thermocouple assembly into the 0.254 mm hole drilled into the side of each sample.
- For the ceramic board and marinite experiments, use an x-acto knife to etch out a thin channel from both the top and bottom surface that is the length of the strip. Reference Figure D.7. for dimensions.
• Place a 0.01 inch diameter Omega butt welded thermocouple in the etched out channel. Use the tip of a screw driver to compress the thermocouple wire into the insulator. Caution must be exercised to not embed the wire too far into the insulator.
• Repeat this procedure for the bottom sample surface using the same dimensions shown in Figure D.7.
• For the aluminum sample etching out channels was not necessary. The temperature gradient through the aluminum was negligible, so a single aluminum temperature was taken at the center point.
• With the hybrid gage and sample attached to the swing arm and the cone calorimeter off, place a sheet of aluminum foil between the heater and the assembly.
• Turn the cone calorimeter on to a temperature that corresponds to a desired incident radiation. Use a Schmidt-Boelter gage to establish the temperatures correspond to the desired incident radiation.
• While the gage is exposed to ambient air and the cone calorimeter is heating take a two minute baseline measurement with LabView.
• Once the cone calorimeter has reached a steady state rotate the swing arm such that the gage and sample are centered under the cone heater.
• Run the test for 900 seconds. After 900 seconds rotate the gage back to its initial position and stop LabView.

How to recreate the separation apparatus:

• Figure 4.1 should be used as a guide.
• The separation apparatus consisted of a radiative lamp, an impinging jet, and a gage holster assembly.
• The radiative lamp was connected to a Variac. The Variac that was used could reach 120V. All experiments performed in Chapter 4 were performed with the Variac set to 70V.
• The diameter of the outlet of the impinging jet was 0.25 inches. An airline was connected to the bottom of the impinging jet. This airline was connected to a resistance heater. Experiments were performed with an air pressure of 15 psi and the air heater set to 80.
• The gage holster assembly was connected by a series of plastic tubing to a pump that was submerged in a bucket of water.
• All of the components were connected with 80/20, which is a brand of aluminum T-slots. The impinging jet was completely stationary. The gage holster assembly was made to translate closer to and further from the impinging jet outlet. The radiative lamp was connected to a bracket, which was supplied by 80/20 in order to rotate the gage and in order to translate it further and closer from the gage holster.
• All of the parts were kept at the same elevation.
• All of the parts were connected into a steel table. This steel table had counter bore holes drilled into it such that the 80/20 pieces could stand vertically.
• The hybrid gage was screwed into the gage holster assembly and thermal grease was used to reduce contact resistance between the gage and gage holster.
• A bare bead thermocouple was glued into the junction of the impinging jet to measure the outlet nozzle temperature.
• A sheathed thermocouple assembly was placed approximately an inch from the surface of the gage and was used to measure the gas temperature relative to the gage surface.
• The impinging jet and the radiative lamp were both approximately 2.5 inches away from the exposed surface of the gage.
• Each experiment had 300 seconds of measurement where the gage was water cooled. After 300 seconds water cooling was turned off and tests were run until a steady state was reached.