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Fire thermal boundary condition measurement using a hybrid heat flux gage

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ABSTRACT

New experimental methods have been developed using a hybrid heat flux gage to quantify the thermal boundary condition to a surface exposed to fire. The hybrid heat flux gage is capable of measuring the net heat flux and exposure heat flux at gage temperatures up to 1000 °C without the need for water cooling. Using these heat fluxes at elevated surface temperatures, new methods were developed to quantify the convective heat transfer coefficient and adiabatic surface temperature. In addition, a procedure is presented for determining the convective and radiative heat flux components when the gas temperature is measured close to the gage surface. Techniques were validated in a series of experiments performed in a cone calorimeter at different heat fluxes. Cold surface heat fluxes from the hybrid heat flux gage were within 5% of heat fluxes measured using a water-cooled Schmidt-Boelter gage. Temporal adiabatic surface temperature measurements from the hybrid gage compared well with steady-state plate thermometer measurements.

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1. Introduction

Knowledge of the thermal boundary condition for a material that is exposed to a fire is necessary to make accurate predictions of material temperature rise. 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 methods to measure the net heat flux and heat transfer coefficient as well as the individual 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. As Diller [2] points out, the physical presence of a heat flux gage alters the convection to the material by changing the local surface temperature distribution.

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 analyses 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 (plate thermometers) 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. [3–5]. Ingason and Wickstrom [6] 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 [7] uses inverse analysis on plate temperature measurements separated by an insulation layer to determine heat flux using a directional flame thermometer. A drawback to this approach is that these devices tend to have a slow response because of their large thermal mass and their results are only valid at steady state.

The convective heat transfer coefficient used in analysis of fires is typically calculated based on a correlation for either forced or natural convection in 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 [9] and Lattimer et al. [10] used inverse heat transfer analysis and steady state surface temperatures to quantify heat transfer coefficients in mixed-mode environments. Staggs [4,11] 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

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Nomenclature

A	area of exposed surface (m^2)
C	specific heat capacity (kJ/kg-K)
g	gravitational constant (9.81 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 (dimensionless)
P	perimeter of sample (m)
q''	heat flux (kW/m2)
Ra_L	Rayleigh number (dimensionless)
S	elevated temperature gage sensitivity (mV/(kW/m^2))
S_o	room temperature gage sensitivity (mV/(kW/m^2))
T	temperature (K)
t	time (s)

Greek

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K-1)
δ	gage thickness (m)
ε	emissivity (dimensionless)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant (5.67×10–11 kW/m^2-K^4)

Subscripts

avg	average
b	back (unexposed) surface
cold	cold surface
diff	differential
exp	exposure
f	film
net	net into surface
rad	incident radiation
rr	reradiation from surface
s	exposed surface
s,ad	adiabatic surface
slug	slug
∞	surrounding gas

temperature was derived. Staggs [4,11] 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. A plate thermometer has been proposed to measure the adiabatic surface temperature to quantify the severity of the fire exposure and connect fire models to structural models [12–15]. The plate thermometer directly measures the adiabatic surface temperature after the device reaches steady state, which is approximately 3–5 min. This is attributed to thermal lag as well as conduction losses to the insulating pad [6]. 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 [16,17]. Lattimer et al. [17] 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 [16]. 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 [18] 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 fire conditions. 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 [19]. With knowledge of the net heat flux through the gage at elevated surface temperatures, exposure conditions to the surface of the sample can be determined. Methods were developed to experimentally measure the convective heat transfer coefficient, exposure 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 at different heat fluxes.

2. Experimental

Boundary condition details were measured through a series of experiments in an ASTM E1354 cone calorimeter at cold surface total heat fluxes of 10, 20, and 40 kW/m^2. As shown in Fig. 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 3.0 mm thick, 24 mm wide, and 305 mm long aluminum arm with a 102 mm × 102 mm, 1.0 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 mm thick Superwool 607 ceramic board, Schmidt-Boelter gage mounted surface flush in a 25 mm thick Superwool 607 ceramic board, hybrid gage on the surface of the plate thermometer insulation board, and plate thermometer. These setups are shown in Fig. 2. All setups were 102 mm × 102 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. This was done to compare the adiabatic surface temperature determined using the hybrid gage onto the insulation surface with the adiabatic surface

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