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Partitioning measurements of convective and radiative heat flux

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ABSTRACT

New measurement techniques are presented to simultaneously determine the radiative and convective components in a mixed-mode heat transfer environment. These techniques rely on making hot surface heat flux measurements using a hybrid heat flux gage capable of measuring heat flux at surface temperatures up to 1000 °C without water cooling. Experiments were performed with an apparatus where the convection and radiation heat fluxes could be independently controlled to produce convection only, radiation only, and mixed convection and radiation environments. Using these experiments two methods were compared for quantifying the heat transfer coefficient: a reference method and a slope method. These methods yielded heat transfer coefficients of 1.11 kW/m^2 °C with a relative uncertainty of ±14.0% and 1.00 kW/m^2 °C with a relative uncertainty of ±11.3% for the mixed-mode heat transfer environment, respectively. The calculated heat transfer coefficients were then used to separate the radiative and convective heat fluxes. The separated irradiation heat flux was 18.1% less than in the radiation only case. This was thought to be caused by error in the gas temperature measurement as well as by the uncertainty in the convective heat transfer coefficient. Sensitivity of the separated irradiation heat flux values to the gas temperature was evaluated.

1. Introduction

The ability to accurately quantify the thermal boundary condition is necessary to predict the temperature rise of materials that are exposed to a mix of convective and radiative heat transfer modes, such as in fires. 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 exposed surface. Direct measurements of heat flux at different surface temperatures can be used to provide this separation.

The hybrid gage is a heat flux gage that is capable of measuring heat flux at temperatures above 1000 °C without water cooling [1,2]. The hybrid heat flux gage has been used to quantify the heat flux components in a mixed-mode environment where the radiation and convection were not known [1,3]. The focus of the present research is to validate these methods using carefully designed experiments where the convection 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 [4]. 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 surface that is maintained at the same temperature as that of the water used to cool it [5]. Conversely, the hybrid gage can measure the net surface heat flux at elevated temperatures representative of the actual surface conditions. A comparison between the two conditions can be made assuming that the cold and hot surfaces are exposed to the same thermal environment, are gray and diffuse bodies, and have identical emissivities. The energy balances for these two conditions can be written as,

$$q''_{cold} = \varepsilon_s q''_{irr} - \varepsilon_s \sigma T^4_{cold} + h(T_\infty - T_{cold}) \quad (1)$$

$$q''_{net} = \varepsilon_s q''_{irr} - \varepsilon_s \sigma T^4_s + h(T_\infty - T_s) \quad (2)$$

where T_{cold} is the temperature of the water cooled surface, T_s is the temperature of the hot surface, and T_∞ is the gas temperature. The first term on the right hand side of each equation is the absorbed irradiation to the exposed surface, the second term is the amount of reradiation from the exposed surface, and the third term is the amount of convection into the surface. In this work it is assumed that T_∞ is the same for both temperature conditions and h and ε_s are independent of surface temperature. Solving Equation (1) for

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Nomenclature

c	sensitivity coefficient
C_p	specific heat capacity (kJ/kg K)
CL	confidence level (%)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (kW/m K)
m	slope
q''	heat flux (kW/m^2)
s	seconds
S	elevated temperature sensitivity (mV/(kW/m^2))
S_o	room temperature sensitivity of differential gage (mV/(kW/m^2))
T	temperature (°C or K)
t	time (s)
u	uncertainty

Greek

δ	gage thickness (m)
ε	emissivity (–)
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant (5.67×10^{-11} kW/m^2 K^4)

Subscripts

avg	average over the gage thickness
b	back (unexposed) surface
bias	bias uncertainty
cold	cold surface
diff	differential heat flux
exp	exposure heat flux
irr	irradiation
net	net surface heat flux
random	random uncertainty
s	exposed surface
slug	slug heat flux
∞	gas temperature

q''_{irr}, substituting into Eq. (2) and rearranging leads to the following expression relating the net heat flux of the hot surface to the cold surface heat flux [6,7],

$$q''_{net} = q''_{cold} - \varepsilon_s \sigma \left(T_s^4 - T_{cold}^4\right) - h(T_s - T_{cold}) \tag{3}$$

Water cooling these heat flux gages keeps their surface temperature at a nearly constant value; however, water-cooled heat flux gages have several drawbacks. For instance, these gages typically 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. [8] to partition radiative and convective heat fluxes using a Schmidt Boelter gage during an ISO 9705 test. In addition, these gages require water lines, making them more difficult to incorporate into an experiment.

In the absence of a single device that is 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. [9] used this approach with two thermopile gages and Lennon and Silcock [10] 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 using this approach in fire tests [10]. A similar approach was used by Khaled et al. [11] 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 the method being less sensitive to a higher convective environment.

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. Consequently, the convection can be determined from the difference in outputs of the two gages. Such an analysis was performed by Frankman et al. [12] to quantify the heat transfer from discontinuous fuel beds. Blanchat et al. [13] 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 to prevent soot deposition, the need to place both sensors near each other to preserve the assumption of both sensors experiencing the same incident source radiation and the need to know the window transmittance. Nakos and Keltner [14] 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. The convection heat flux was determined using the known net, radiation, and reradiation heat fluxes.

Lam and Weckman [15] attempted to quantify the magnitudes of convection and radiation at steady state using several different heat flux gages, including Schmidt–Boelter and Gardon gages. Their study was performed by exposing a single gage to (1) a radiation dominated environment inside a cone calorimeter, (2) a convection dominated environment with a heat gun, and (3) a mixed-mode environment with both the heat gun and the cone heater. 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