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Full-field surface heat flux measurement using non-intrusive infrared thermography

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ABSTRACT

A method was developed to measure full-field, transient heat flux from a fire onto a surface using infrared (IR) thermography. This research investigated metal plates that were directly exposed to fire while the unexposed side temperature of the plate was measured using IR thermography. These temperatures were then used in a two-dimensional finite difference inverse heat transfer analysis to quantify the heat flux. The method was demonstrated through a series of experiments with direct fire exposures onto vertical and horizontal plates. Fires were produced using a propane sand burner and ranged from 20 to 100 kW. Point heat flux measurements were also measured using a Schmidt–Boelter heat flux gauge. It was found that heat fluxes obtained via IR thermography were within one standard deviation of those from the Schmidt–Boelter gauge. The effect of plate material was studied both numerically and experimentally for stainless steel and aluminum plates. It was found that although precision is affected by material, appropriate resolutions can be selected to obtain similar precision for both materials. Spatial and temporal resolution effects were also investigated and it was found that the precision of the heat flux measurement is inversely proportional to both spatial and temporal resolutions.

1. Introduction

The measurement of exposed surface heat flux due to fires is important in several facets of fire safety engineering and is frequently difficult to obtain. Traditional techniques for measuring the exposure heat flux on a surface involve mounting an air-purged or water-cooled gauge on or within the surface. Difficulties with these techniques arise when no suitable mounting surface exists, or cooling systems cannot be protected. Significant research has been conducted over the past 20 years in overcoming these difficulties including the introduction of several new types of heat flux sensors [1–4], and the use of imbedded temperature measurements with inverse calculation methods to quantify heat flux [5–9].

Large fire exposures are inherently highly transient and spatially non-uniform. For many purposes single point heat flux measurements are not adequate for a full characterization of the surface heat flux field because of these variations. This is especially true for quantifying heat fluxes for thermo-structural modeling. Traditionally, these full-field heat flux measurements would be made with an array of single point measurement sensors [10–13]. However, this methodology can be quite expensive from purchasing and maintaining a large number of sensors and it can be very time consuming to setup such an extensive array. Because of these limitations, the obtainable spatial resolution is quite low (>10 cm). As a result, the use of temperature based heat flux measurements with an inverse heat transfer calculation method to capture full-field heat flux maps is preferable. Initially, Dillon measured limited spatial heat flux distributions using an array of thermocouples welded to metal plates [14]. Although not expensive, this method is still quite time consuming and the minimum spatial resolution that can be achieved is still quite large (>2.5 cm).

In recent years, infrared (IR) thermography has been introduced as a method for obtaining full-field surface temperature measurements. On a small scale, IR thermography of thin stainless steel foils ($l<75$ μm) has been implemented to obtain full-field measurements of local convective heat transfer coefficients [15–18], jet impingement fluxes [19], and fluidized bed fluxes [20]. The advantage to using IR thermography measurements is the high level of spatial resolution (<1 cm at intermediate scales) and the ease of experimental implementation. IR thermography is also a non-intrusive measurement technique so temperature measurements can be obtained without affecting fire performance.

In this study, a method was developed for the use of IR thermography to measure full-field, transient fluxes from fires to nearby surfaces via an inverse heat transfer analysis using the unexposed surface temperature as shown in Fig. 1. Using a thermally isolated stainless steel surface, this method was then validated against existing data and traditional heat flux measurement

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Nomenclature

A_s	Surface Area (m^2)
c_p	Specific Heat $(\frac{J}{kgK})$
D	Equivalent Fire Diameter (m)
F	Fire Size (kW)
g	Gravitational Constant
h	Convection Coefficient $(\frac{W}{m^2K})$
k	Thermal Conductivity $(\frac{W}{mK})$
L	Characteristic Length
l	Plate Thickness (m)
Nu	Nusselt Number
P	Perimeter (m)
Pr	Prandtl Number
Q	Total Energy Differential (W)
q	Heat Flux $(\frac{W}{m^2})$
Ra	Rayleigh Number
S	Uncertainty Coefficient
T	Temperature (K)
t	Differential Time Step (s)
z	Height Above Burner (m)
β	Volumetric Thermal Expansion Coefficient (K^{-1})
Δ	Discretized Element Length (m)
ε	Surface Emissivity
ρ	Density $(\frac{kg}{m^3})$

Subscripts

∞	Back Side Gas
AA	Aluminum Alloy
b	Plate Back Surface
CL	Along Centerline
0	at Standard Temperature (298 K)
exp	Exposure
f	Plate Front Surface
gas	Exposed Side Gas
i	Current Time
$i-1$	Previous Time
L	Characteristic Length
$NETD$	IR Camera Noise Equivalent Temperature Differential
p	Paint
$peak$	Peak Measured Flux
rad	Radiative
rr	Reradiated
SS	Stainless Steel
s	Surface
T	Temperature Measurement
t	Temporal
x,y	Analysis Pixel
Δ	Spatial

techniques. The effects of spatial and temporal resolution on the accuracy of the measurement were also investigated. In addition the use of other surface materials was studied.

2. Experimental setup

In this research, two sets of experiments were conducted to validate the inverse heat transfer method for measuring full-field heat flux maps. This included tests with a radiant heater exposure onto a vertical plate as well as fires in direct contact with vertical and horizontal plates.

2.1. Radiant panel tests

The first set of experiments consisted of a 0.97 mm thick vertically oriented stainless steel plate exposed on one side to a radiant heater as shown in Fig. 2. The measurement surface of the plate was 0.61 m by 0.61 m. For all the tests, both sides of the plate were painted with a high temperature, high emissivity flat black paint ($\varepsilon = 0.95 \pm 0.01$). This allowed for higher accuracy in quantifying the emissivity of the

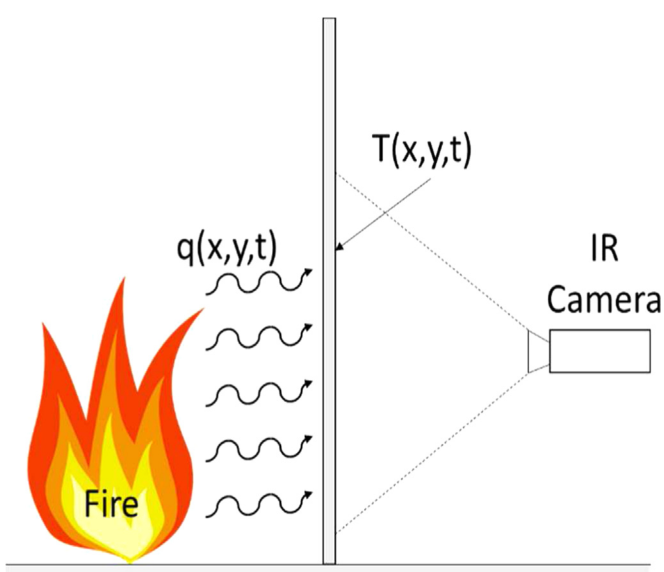

Fig. 1. Single sided fire exposure with IR thermography measurements of unexposed surface.

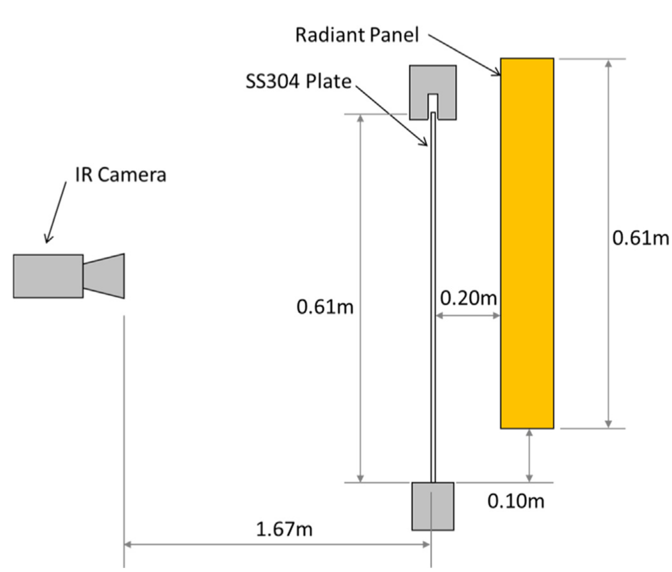

Fig. 2. Experimental test setup for measuring surface heat flux from a radiant heater panel.