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Research paper

Real-time heat flux measurement using directional flame thermometer

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HIGHLIGHTS

- Heat conduction in two layers analyzed for inverse heat conduction problem (IHCP).
- Coupled solutions from two layers estimates heat flux using two sensors in layer 2.
- Solution interpreted as digital filter suitable for online estimation of heat flux.
- Variable properties accommodated via interpolation of filter coefficients.

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ABSTRACT

Real-time measurement of heat flux is an important challenge for several industrial applications, including furnace control. For efficient operation of high-temperature process furnaces, accurate and stable temperature measurements are needed. Directional Flame Thermometer (DFT) offers the ability to use both temperature and heat flux measurements for furnace control. Currently, analysis of dynamic temperature data from DFT to compute heat flux information must be performed off-line using the gathered temperature data and a full-non-linear inverse heat conduction problem (IHCP) analysis. Developing a near real-time algorithm for accurate reduction of the data will allow for continual monitoring of the furnace during operation. This will result in better furnace control and significant savings in energy and cost. This paper provides a solution strategy based on the filter concept for the IHCP associated with DFT. The filter-based solution has the capability of heat flux estimation in near real-time. Two IHCPs are discussed and a coupled solution is proposed to estimate the unknown surface heat flux. The variation of thermal properties with temperature is taken into the account through interpolation of the filter coefficients computed at different temperatures. The solution procedure is validated by comparing the results with a numerical test case developed in ANSYS. Results are also computed using data from a physical experiment with DFT (see Ref. [13]). The heat fluxes obtained are found in good agreement with those obtained from a full non-linear IHCP analysis.

1. Introduction

Effective temperature control in furnaces needs accurate measurement of heat flux. Currently, two major types of measuring sensors are used in standard fire tests for measuring the heat flux, known as active (non-equilibrium) and passive (equilibrium) sensors [1].

Active sensors, such as Gardon and Schmidt-Boelter gauges, measure the heat flux across a measured temperature difference [2,3]. These sensors work based on the concept of measuring the temperature gradient within the sensor. For this purpose, water needs to continuously pass through the sensor to maintain a temperature gradient from the fire. As the result, the use of active sensors is limited to applications where adequate water is available and water tubes can be installed safely. Possible condensation of the unburned fuel or water on the surface of the sensor could be also problematic when using active sensors [1].

The second type of heat flux measurement sensors, equilibrium sensors, generally consist of two metal plates with an insulation

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Nomenclature

f	filter coefficients (coupled solution)
$\mathbf{F}$	filter matrix for the coupled solution associated with $\mathbf{Y}$
$\mathbf{F_1}$	filter matrix (X22 case, layer 1)
$\mathbf{F_2}$	filter matrix (X21 case, layer 2)
g	filter coefficients (coupled solution)
G	Green's function
G	filter matrix for the coupled solution associated with $\mathbf{y}$
$\mathbf{H}$	first order regularization matrix
k	thermal conductivity, W/m-K
L	thickness of the layer, m
m_f	number of future time steps
m_p	number of past time steps
q	heat flux, W/m^2
S	sum of squares of the temperature error, K^2
t	time, s
T	temperature, K
x	spatial coordinate, m
x′	dummy integration variable, Eqs. (1) and (13)
$\mathbf{X}$	sensitivity matrix for unknown surface heat flux
y	measured temperature at boundary $x = L$
Y	measured temperature at location $x = x_1$
$\mathbf{Z}$	sensitivity matrix for measured temperature boundary condition at $x = L_2$

Greek/roman

α	thermal diffusivity, k/C, m^2/s
α_T	Tikhonov regularization parameter
β	eigenvalue
ϕ	step response function for unit heat flux at $x = 0$
η	step response function for unit temperature at $x = L$
τ	integration variable, Eqs. (1) and (13)
ε	threshold for choosing non-negligible filter coefficients

Subscripts

0	surface location or reference value
Avg	average
c	reference value for non-dimensionalization
i	time index
m	eigenvalue index
ss	steady state
$i_{\max}$	last time index
X12	Cartesian heat conduction problem with type 1 and type 2 boundary conditions
X21	Cartesian heat conduction problem with type 2 and type 1 boundary conditions
X22	Cartesian heat conduction problem with type 2 and type 2 boundary conditions

Superscript

~	dimensionless parameter

layer in between. Thermocouples are installed on the backside of each plate and covered with insulation material. The plate's temperature increases quickly and reaches quasi-equilibrium with the fire environment. An Inverse Heat Conduction Problem (IHCP) is defined in order to determine the heat flux on the surface by using the measured temperature values. Equilibrium sensors are relatively inexpensive and do not need water for operation. The easy installation is an asset which allows use of Directional Flame Thermometer's (DFT's) for different environments and variety of applications. Moreover, since the surface temperature is close to the gas temperature, there is no concern for condensation of water/unburned fuel and the resulting uncertainties. Different types of equilibrium sensors such as Plate Thermometers, Sandia Hemispherical Heat Flux Gage and Directional Flame Thermometers (DFT) are tested and discussed in Refs. [4–6].

A schematic of a DFT is shown in Fig. 1. The original DFT design involved a thin metal disk mounted in a steel tube [7,8]. To minimize heat loss from the unexposed surface of the disk, multiple radiation shields and some ceramic fiber insulation were mounted behind the front disk. Sandia National Laboratories improved DFTs for use in large pool fire and other tests. Their goal was to provide both transient and quasi-steady heat transfer measurements in various fire environments [9]. Samuel et al. [10] used DFTs to measure the heat flux in wildland–urban interface (WUI) fires. They emphasized that the limited access to water in such areas urges the use of DFTs. They used water cooled total heat flux sensors for a direct comparison of the heat flux obtained from the DFTs. Lam and Weckman [11] examined the steady state response of four heat flux gauges including DFTs under various radiative and convective conditions and compared the results. In another study, Sultan [12] investigated the performance of six different temperature sensors in fire resistance test. The result showed that all the sensors yield similar results after approximately 10 min.

Analyzing DFT data over the entire test duration needs an inverse heat conduction code which uses two temperature measurement histories for estimating the net heat flux to the exposed surface (q_{front}, in Fig. 1). Considering the wide range of temperature variation, the material properties of the DFT changes significantly which introduces non-linearity to the problem. Therefore, an accurate solution technique for IHCP associated with the DFT application, must be able to account for the variation temperature dependent material properties. Presently, analysis of dynamic temperature data from the DFTs to compute heat flux information must be performed off-line at the conclusion of data-gathering. Availability of a near real-time algorithm for accurate reduction of data will allow for continual monitoring of the furnace during operation. This will result in better furnace control and significant savings in energy and cost. Recently, Kokel et al. [13] developed a heat transfer model to provide the user with a simple forward

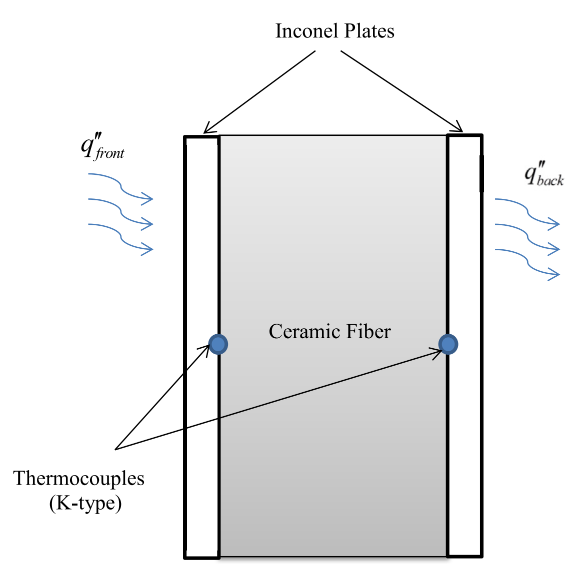

Fig. 1. Schematic of a directional flame thermometer.