Applied Thermal Engineering 141 (2018) 981–989

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Inverse method for simultaneously estimating multi-parameters of heat flux and of temperature-dependent thermal conductivities inside melting furnaces

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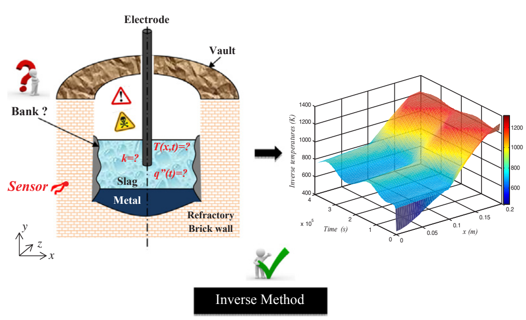
HIGHLIGHTS

- The proposed inverse approach will improve the control of the bank in melting furnaces.
- The proposed *LMM/BM* algorithm is computationally more efficient than the conventional *LM* algorithm.
- Multi-parameter estimation of a melting furnace by inverse approach has been carried out.
- Analysis of the results yielded recommendations concerning the location and the operation of sensors.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Inverse heat transfer
Melting furnace
Phase change
Levenberg–Marquardt method
Broyden method
Bank

ABSTRACT

The purpose of this study is to predict the time-varying protective bank that coats the internal surface of the refractory brick walls of a melting furnace. An inverse heat transfer procedure is presented for predicting simultaneously operating and thermal parameters of a melting furnace. These parameters are the external heat transfer coefficient, the thermal conductivity of the phase change material (PCM) and the time-varying heat load of the furnace. Once these parameters are estimated, the time-varying protective PCM bank can be predicted. The melting and solidification of the PCM is modeled with the enthalpy method. The inverse problem is handled with the Levenberg-Marquardt Method (LMM) combined to the Broyden method (BM). The models are validated and the effect of the position of the temperature sensor embedded in the furnace wall, of the data capture frequency and of the measurement noise, is investigated. A statistical analysis for the parameter estimation is also carried out. Analysis of the results yielded recommendations concerning the location of the embedded sensor and the data capture frequency.

1. Introduction

Melting furnaces, such as electric arc furnaces, are used for material processing that requires high powers and elevated temperatures (Fig. 1). Their main applications are the smelting of materials such as steel, copper and nickel calcine. High voltage electrodes discharge their electric load into the bath of electrically conducting slag (or phase change material PCM). The current is carried between the electrode tip and the slag to generate the heat required for the smelting process.

An interesting solid/liquid phase change phenomenon that arises in these furnaces is the formation of solid layer, called a bank, that covers the internal surface of the refractory brick walls. This bank plays a

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https://doi.org/10.1016/j.applthermaleng.2018.06.041
Received 29 December 2017; Received in revised form 7 March 2018; Accepted 13 June 2018
Available online 14 June 2018
1359-4311/

Nomenclature

C_p	specific heat [J/kg K]
dt	time step [s]
f	liquid fraction
h_∞	heat transfer coefficient [W/m^2 K]
I	total number of measurements
J	Jacobian matrix
k	thermal conductivity [W/m K]
L_{Brick}	width of the brick wall [m]
L_{PCM}	width of the PCM layer [m]
N	number of unknown parameters
PleaseCheck	heat flux [W/m^2]
$\vec{P}$	vector of unknown parameter
PCM	phase change material
RRMSE	relative root-mean-square errors [%]
Error	estimation errors [%]
$E(t)$	bank thickness [m]
t	time [s]
$\hat{T}$	estimated temperature [K]
x	Cartesian spatial coordinate [m]
Y	measured temperature [K]

Greek symbols

ε	small number
μ	damping parameter
ρ	density [kg/m^3]
σ	standard deviation of the measurement error
ψ	sum of squares norm
ξ	small number
δH	enthalpy [J/m^3]
Δ	difference
Ω^k	diagonal matrix
λ	heat of fusion [J/kg]
ω	random number

Subscripts

0	initial value
∞	ambiant
Brick	brick wall
exact	exact solution
$E(t)$	bank thickness
liq	liquidus
liquid	liquid (PCM)
max	maximum
P	parameter
PCM	phase change material
sol	*solidus*
solid	solid (PCM)

Superscripts

k	time iteration number
T	transposed matrix
^	estimated parameter
$\rightarrow$	vector
$\leftrightarrow$	matrix

crucial role. It protects the brick walls from the highly corrosive molten material, thereby prolonging the life of the facility. Too thick a bank is however detrimental to the furnace throughput as the volume available for smelting is reduced. Keeping a bank of optimal size is therefore crucial for the safe and profitable operation of the smelting furnace.

It is extremely difficult to measure the bank thickness using probes submerged into the molten bath. The hostile conditions that prevail in the melt damage and destroy the probes. This method is time consuming, risky and often inaccurate. Moreover, the transient formation of the bank is a most complex process that depends on the power input, the boundary conditions and the thermophysical properties of the slag.

In recent years, the problem of bank formation inside high temperature melting furnaces has been tackled with various inverse heat transfer methods [1–15]. The inverse heat transfer methods rest on the conjugate gradient method with the adjoint equation [3,12–15], the Kalman-filter method [4–9] and the Levenberg-Marquardt method [1–2,10–11]. In these studies, the thermophysical properties of the materials and the operating conditions of the furnace are fixed. The focus is on the inverse prediction of the time-varying heat load of the furnace (the heat flux $q''(t)$ at $(x = L_{Brick} + L_{PCM})$ (Fig. 2)). Once the heat load is determined, the time-varying bank thickness $E(t)$ is predicted.

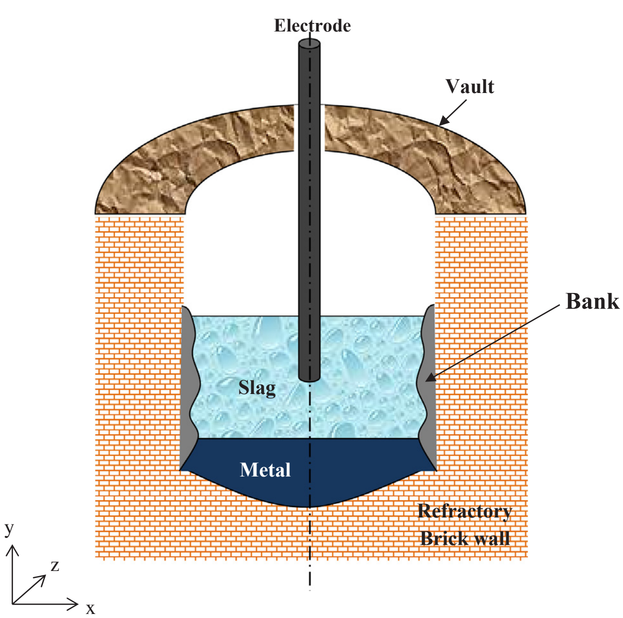

Fig. 1. Cross view of a melting furnace.

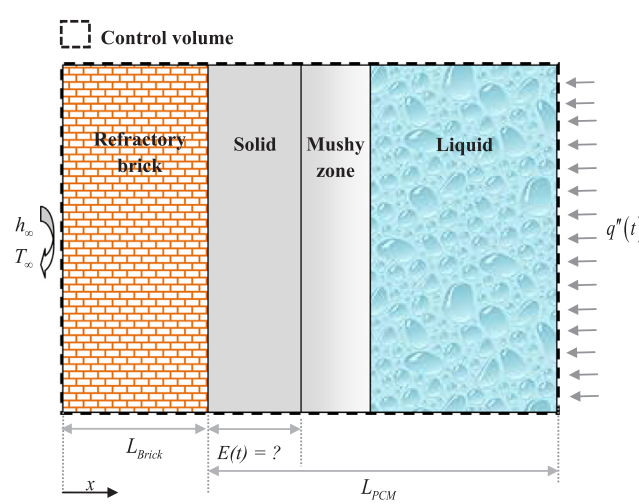

Fig. 2. Schematic of the 1-D direct problem.