Applied Thermal Engineering 110 (2017) 265–274

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Inverse heat transfer prediction of the state of the brick wall of a melting furnace

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HIGHLIGHTS

- A non-isothermal solid/liquid phase change process is developed.
- The Levenberg-Marquardt-Method combined with the Broyden-Method is adopted.
- A Finite-Volume Model (FVM) of melting furnace is elaborated.
- The characteristics of the brick wall and of the temperature sensor are examined.
- The erosion of melting furnace is investigated.

ARTICLE INFO

Article history:
Received 22 July 2016
Revised 25 August 2016
Accepted 25 August 2016
Available online 26 August 2016

Keywords:
Inverse method
Solid-liquid phase change
Levenberg–Marquardt method
Broyden method
Melting furnace

ABSTRACT

An inverse heat transfer method for predicting the state of the lateral refractory brick wall of a melting furnace is presented. By collecting temperature data with a thermocouple embedded into the brick wall, the inverse method is able to predict (1) the time-varying thickness of the protective bank that covers the inner lining of the furnace wall; (2) the thermal contact resistance between the inner lining and the protective bank; and (3) the possible erosion of the refractory brick wall. The inverse procedure rests on the Levenberg Marquardt algorithm combined with the Broyden method. The effect (1) of the noise on the collected temperature data; (2) of the thermal diffusivity of the brick wall; (3) of the location of the embedded temperature sensor; and (4) of the Biot number on the inverse predictions is investigated. Recommendations are made for the optimum position of the embedded sensor and its operation.

1. Introduction

Melting furnaces such as electric arc furnaces (EAFs) are used for material processing that requires high power density and elevated temperatures. Some of their applications concern the smelting of copper, of nickel calcine, of steel and of pre-reduced iron ore and the melting/recycling of scrap metals. A schematic of a typical EAF is provided in Fig. 1. High voltage electrodes (only one electrode is shown here) discharge their electric current into a bath of conducting slag. The current dissipates the heat (Joule effect) needed for the smelting process. The smelting reaction takes place in the slag layer and the denser metal sinks and accumulates at the bottom of the bath. Continuous loading of ore material is achieved though openings in the vault. Tapping of slag and metal is carried out at regular time intervals through perforated holes in the lateral walls. The furnace suffers heat losses though the vault via the freeboard gas above the slag layer. Heat is also lost by conduction through the refractory brick walls. Thermocouples are usually embedded into the vault and into the brick walls to monitor their temperature and, as it will be seen shortly, to provide information on the thermal conditions that prevail inside the furnace [1–4].

An interesting solid/liquid phase change process that arises in these furnaces is the formation of a solid layer, called ledge or bank, on the inner surface of the refractory brick walls (Fig. 1). The presence of this phase change material bank (PCM) is of the utmost importance [5,6]. It protects the inner lining of the walls from the chemical attack of the molten material, thereby maintaining the integrity of the facility and prolonging its active life. On the other hand, too thick a bank is detrimental to the furnace output. It diminishes the bath volume available for smelting. Therefore, from an industrial point of view, the challenge is to operate the furnace by keeping a bank of optimum thickness that is a bank that protects the inner wall without hampering the furnace production.

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.162
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)
$L_{Erosion}$	width of the erosion (m)
L_{PCM}	width of the PCM layer (m)
N	number of unknown parameters
$q''(t)$	heat flux (W/m^2)
P	vector of unknown parameter
PCM	phase change material
R_c	thermal contact resistance (K·m^2/W)
$RRMSE$	relative root-mean-square errors (%)
$Error$	estimation errors (%)
$E(t)$	bank thickness (m)
t	time (s)
$\widehat{T}$	estimated temperature (K)
x	Cartesian spatial coordinate (m)
Y	measured temperature (K)
α	thermal diffusivity
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
∞	ambient
Brick	brick wall
exact	exact solution
E	eutectic
$E(t)$	bank thickness
F	freezing point
liq	liquidus
liquid	liquid (PCM)
max	maximum
PCM	phase change material
P	parameter
$q''(t)$	heat flux
R_c	thermal contact resistance
sol	solidus
solid	solid (PCM)

Superscripts

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

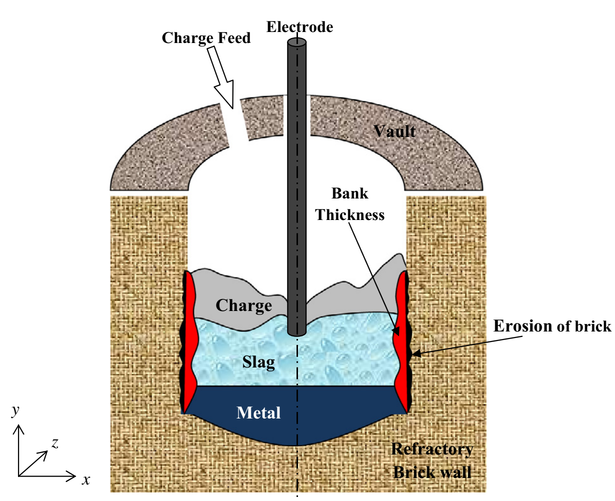

Fig. 1. Cross view of a typical electric arc melting furnace.

Predicting the thermal behavior of banks inside EAFs is however a challenging problem. Their time-evolution depends on the complex heat transfer processes that prevail inside the molten bath as well as on the way the furnace is designed and operated. Measuring banks with probes plunged into the molten bath is impractical no to say dangerous. Simulating the heat transfer and the flow circulation inside the slag and the metal is feasible with modern CFD tools [7–13]. But this computational approach is time and resources consuming and it may not be the most suitable method to be implemented on line for the control system of an industrial facility. The most promising alternative appears to be the inverse heat transfer approach.

The prediction of phase change banks inside high temperature melting furnaces with inverse heat transfer methods has received increasing attention over the last decade [1–4,14–20]. Sensors imbedded inside the refractory brick walls provide temperatures and/or heat fluxes to an inverse heat transfer algorithm that calculates the time-varying thickness of the bank.

In all the aforementioned studies however, the prediction of the thermal contact resistance between the brick wall and the bank was ignored. The erosion of the brick wall was also neglected.

The thermal contact resistance reflects the imperfect contact between two materials [21–24], in the present case these materials are the brick wall and the bank. The contact resistance attenuates the temperature and/or the heat flux signal captured by the sensor and fed to the inverse algorithm. As a result, the accuracy of the predictions of the bank made with the inverse algorithm is affected. In some cases, the predictions may even be worthless.

Another problem that arises in high temperature EAFs is the erosion of the inner lining of the refractory brick wall [25–29]. This phenomenon occurs when the bank is lost and the inside lining of the wall suddenly becomes exposed to the hostile molten material. Erosion of the brick wall is a slow and insidious process that may eventually lead to the destruction of the facility [30–33].

These problems are addressed in the present study. An inverse heat transfer procedure is proposed for predicting simultaneously: (1) the time-varying lateral heat flux (and therefore the protective bank thickness) and the thermal contact resistance; and (2) the time-varying lateral heat flux and the erosion of the refractory brick wall. The numerical simulation of the solid/liquid phase change of the bank rests on the enthalpy method [34,35]. The