Identification of Coating Thickness in Cement Rotary Kiln

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ABSTRACT: *The cement industry is one of the major industries in every country. This industry is the driving force behind the development of a nation. The heart of this industry is the rotary kiln. One of the significant concerns about a rotary kiln is forming a cover of molten materials on the kiln's inner wall called coating. The low thickness of this coating cause burns to the wall refractory bricks and heavy damage to the kiln, while its high thickness reduces the production volume and quality of products. Currently, the kilns are checked by experienced technicians for empirical coating estimation. This paper aims to identify the thickness of the coating for the automatic control purpose of the kiln. The identification problem of coating thickness is based on thermal resistances in different layers of the kiln and heat transfer equations between these layers. For this purpose, linear and nonlinear identification methods such as Ordinary Least Squares (OLS), Recursive Least Squares (RLS), global search methods, and genetic algorithms are used. The coating can be identified in the proposed identification approach by having the kiln's ambient and internal solid temperature profiles. The raw data for the identification process has been extracted by Finite Element Analysis (FEA) for a given solid temperature profile along with the kiln and different kiln coating thicknesses. The modeling and simulations carried out in this paper show that the identification methods were able to determine the amount of coating with acceptable errors depending on the method.*

KEYWORDS: *Cement rotary kiln; Coating identification; FEA; OLS.*

INTRODUCTION

Since lack of accurate monitoring of the coating in the kiln, reducing its thickening at any point, especially in the burning area, may cause severe erosions on the refractory liner. These erosions ultimately can lead to the stoppage of the kiln for refractory liner repairs. Therefore, identifying and predicting cement rotary kilns' coating thickness is very important in the cement industry (*Bokaiian* [1,2]). The raw data for identifying the coating thickness in rotary cement kilns can be obtained by temperature measurements of the outer shell and calculation of the inner shell temperature profile by mixed thermal, chemical reactions, and material flow model.

One of the successful models for formulating the cement rotary kiln is *Spang* [3] model. Spang has modeled the rotary kiln by combining partial differential equations, including twelve mass balance equations for chemical component concentrations, three thermal equations for gas, solid material, and internal wall temperatures, and two equations for flame and reaction heat generation. This model calculates the gas, kiln wall, solid material

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temperature profiles, and components concentrations along with the kiln. The Spang model is dynamic. However, it does not provide good quality in terms of flame modeling in the burning area. This model is one-dimensional. The differential equations are averaged for the radius and angle in cylindrical coordinates (*Gorog et al.*, [4]). Notably, dynamic simulations have more complexity and a high computational burden compared to steady-state models. While, they are not necessary for this study because this paper aims to identify a very slow dynamic phenomenon,n, i.e., kiln coating thickness variation,s which is very slow. Steady-state models for kilns have been proposed in some literature, such as *Darabi* [5] and *Goshayeshi et al.* [6]. Also, by *Shahriari et al.* [7], the kiln's dynamic has been described in the form of a state-space representation using system partial differential equations (PDE) with parameters varying by the operating conditions of the kiln. This model can easily be embedded in classical state-space control algorithms and is suitable for control methods.

As declared in the literature, [8-9] by the kiln's thermal model, the gas and solid temperature profiles along the kiln must be calculated to determine the coating's inner surface temperature. In this paper, one of the static solid temperature profiles reported by *Spang* [3] has been used as one of the input data for identification. By using this temperature profile, the other input data for the identification process has been obtained by finite element analysis for any longitudinal point along with the kiln. After gathering the raw data for the identification process, the thermal resistive model of kiln layers can be analyzed with two obtained boundary conditions to identify coating thickness.

Some studies that have been conducted in this area are as follows. *Noshiravani et al.* [10] used a temperature profile of the outer shell. They performed the necessary calculations using the thermal conduction mathematical model to calculate the coating thickness in cement rotary kilns. Similar works have been reported by *Sadighi et al.* [11] and *Al-Yasiri et al.* [12] to estimate kiln coating with integrated modeling of the kiln with shell temperature measurement. Also, by *Ravindran et al.* [13], modeling of different coating thicknesses with varying bed temperatures for both burning and transition zones using ANSYS 2-D model has been proposed to determine the optimum coating thickness for good insulation and durability of the kiln. In the next section, the modeling approach and theoretical concepts, as well as the necessary border conditions, have been provided.

THEORETICAL SECTION

The approach of this paper for identification of coating thickness inside the kiln is as: a) Modeling the heat transfer through the kiln layers according to the formulation discussed provided in [11], for use in subsequent sections. b) Preparing the raw data of different layers' thermal conductivities and different layer thicknesses from identification techniques using Finite Elements Method (FEM) methods. Finally, the results of coating thickness identification by using four different identification methods are presented and discussed. Also, the theories, concepts, and boundary conditions applied to the identification methods are presented, as well.

Modeling of heat transfer from the kiln layers

Fig. 1 shows the parameters used for the radiuses and the heat transfer coefficients in different layers of the kiln wall. Knowing the parameter r_c, then the parameter r_w is the important parameter that we are seeking for identification.

The temperature distribution equation in the cylindrical coordinate can be written as Eq. (1).

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}+\frac{\partial^2 T}{\partial Z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

The above equation is simplified to Eq. (2) by the following assumptions.

- Because of coating variations' very low dynamics, the steady-state study is exactly sufficient.
- Heat transfer in the axial direction is ignored.
- In each cross-section of the wall, a lumped temperature is assumed for angular direction.
- There is no heat generation in the resistive layers.

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=0 \qquad (2)$$

For different layers, the boundary conditions are as Eqs. (3)-(6).

- Coating layer

$$@\, r=r_w, T=T_w \;\&\; @\, r=r_c, T=T_c \qquad (3)$$

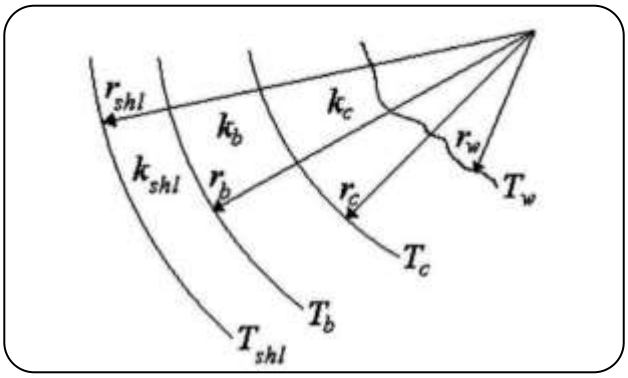

Fig. 1 Parameters used in the kiln wall heat transfer model, [11]

- Refractory layer

$$@r = r_c, T = T_c \ \& @r = r_b, T = T_b \quad (4)$$

- Metal shell layer

$$@r = r_b, T = T_b \ \& @r = r_{shl}, T = T_{shl} \quad (5)$$

- Outside air layer

$$@r = r_{shl}, T = T_{shl} \ \& @r = r_a, T = T_a \quad (6)$$

By rearranging Eq. (2), Eq. (7) can be derived.

$$\frac{\partial\left(\frac{\partial T}{\partial r}\right)}{\left(\frac{\partial T}{\partial r}\right)} = \frac{-\partial r}{r} \quad (7)$$

After integrating Eq. (7), Eq. (8) can be derived.

$$\frac{\partial T}{\partial r} = \frac{k'}{r} \quad (8)$$

The integrating constant, *k'* can be obtained by assuming Eq. (9), which is the definition of heat transfer coefficient (k), Eq. (2) can be solved according to the above boundary conditions in the cylindrical coordinates as follows.

$$Q_T = -kA\frac{\partial T}{\partial r} \quad (9)$$

$$T_2 - T_1 = \frac{Q}{k 2\pi \Delta z}\ln\left(\frac{r_1}{r_2}\right) \quad (10)$$

By applying the boundaries defined in Eqs. (3)-(6), we obtain the equations of heat transfer from the various kiln layers as Eqs. (11)-(15) similar to *Sadighi et al.*, [11]:

$$Q_T = \frac{2\pi\Delta z k_c\left(T_w - T_c\right)}{\ln\left(r_c/r_w\right)} \quad (11)$$

$$Q_T = \frac{2\pi\Delta z k_b\left(T_c - T_b\right)}{\ln\left(r_b/r_c\right)} \quad (12)$$

$$Q_T = \frac{2\pi\Delta z k_{shl}\left(T_b - T_{shl}\right)}{\ln\left(r_{shl}/r_b\right)} \quad (13)$$

$$Q_T = \frac{2\pi\Delta z k_a\left(T_{shl} - T_a\right)}{\ln\left(r_a/r_{shl}\right)} \quad (14)$$

$$\delta = r_c - r_w \quad (15)$$

Eq. (15) determines the coating thickness δ. Obviously, by a given internal radius of the refractory surface (r_c), the coating thickness can be calculated by identifying the inner wall radius (r_w).

The algorithm for calculating the kiln coating thickness, based on the shell temperature measurements, consists of two stages. The first stage is figuring out the solid temperature profile at each kiln longitudinal cross-section, which can be applied using the whole model of kiln thermal and material balance equations. The next stage is to calculate the coating thickness using the measured outer shell temperature and calculated solid temperature at different kiln sections.

Determination of kiln layers temperatures using the Finite Elements Method (FEM)

The studied kiln's geometrical dimensions in this paper are selected the same as the one which was studied in [11]. The length, the inside, and outside diameters of the kiln were 66.7, 3.95, and 4.35 m, respectively. The thickness of the magnetite refractory lining was 19 cm, which could be considered uniform through the burning zone. The slope of the kiln was selected as 4% to facilitate the axial displacement of the solid bed. Finite Element Analysis (FEA) at any longitudinal cross-section has been performed using FEMM software for generating the raw data for the identification process at a given solid temperature profile along with the kiln and different kiln coating thicknesses. The FEA problem's internal and external boundary conditions are coating surface temperature and ambient temperatures, respectively. In all simulations, the air temperature is considered to be 300 Kelvin. The FEA has been applied to 62 cross-section points and the kiln

Table 1.The finite element analysis parameter values

Parameter	Value
k_c	0.0035 W/m/K
k_b	0.008 W/m/K
k_{shl}	0.45 W/m/K
k_a	0.0181 W/m/K
r_c	197.5 cm
r_b	217.5 cm
r_{shl}	220.5 cm
r_a	260 cm

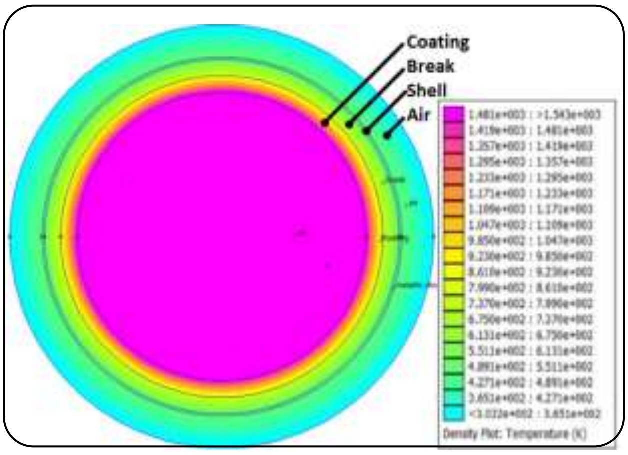

Fig. 2: A sample FE analysis output.

for four different coating thickness values in the burning zone as 5, 10, 15, and 20 cm. The FEA runs were 248 times. The FEA results in the outer shell temperature for all cross-sections and coating thicknesses.

The outer shell temperature profile is used to identify the coating thickness in any rotary kiln cross-section. Fig. 2 shows a sample FE analysis result, calculated for inner coating surface temperature equal to 1480 K and coating thickness selected as 20 cm. The simulations had been run 248 times to generate all the raw data intended for the 62 cross-sections from the identification process. The calculated thermal conductivities for different layers *k* and the different layers *r* are given in Table 1.

The results from all 248 FEA calculations are presented in the diagrams shown in Fig. 3. By obtaining the shell temperature profiles from FEMM and the inner coating surface temperature extracted from [11] (referred to as wall temperature), the rotary kiln can be considered as a black box with the known coating surface temperature profile and outer shell temperature profile to be solved for finding the coating thickness profile along with the kiln.

In the subsequent sections of the paper, the various applied identification methods are discussed.

Identification methods

The concept of identification is to determine the unknown parameters of the system with some measured variables. Some works recently conducted in this area such as *Singh, et al.* [14] and *Nejati, et al.* [15]. In this section, four different identification methods are discussed for application to FEA's extracted data and compared with each other. The Ordinary Least Squares (OLS), the Recursive Least Squares (RLS), the Genetic Algorithm (GA) as well as global search (GS) methods have been used for the identification of coating thickness.

Identification by Ordinary Least Squares (OLS) method

Theoretically, the physically derived equations of a system can calculate the unknown parameter, the coating thickness value. But in practice, since there is measurement noise in measuring the kiln's outer shell temperature, it is better to use the least-squares method to offer the best value according to the so-called BLUE (best linear unbiased estimator) theorem *Norton* [15]. The ordinary least squares method consists of the following three steps:

- Applying the input to the system and collecting output information
- Defining the identification structure and obtaining the linear regression equation
- Calculating and estimating the vector of unknown parameters

According to the heat transfer equations proved in the "Modeling of heat transfer" section, the linear regression equation can be derived by using Eqs. (16)-(20) as follows.

$$Q_T \ln\left(\frac{r_c}{r_w}\right) = 2\pi k_c T_w - 2\pi k_c T_c \tag{16}$$

$$Q_T \ln\left(\frac{r_b}{r_c}\right) = 2\pi k_b T_c - 2\pi k_b T_b \tag{17}$$

$$Q_T \ln\left(\frac{r_{shl}}{r_b}\right) = 2\pi k_{shl} T_b - 2\pi k_{shl} T_{shl} \tag{18}$$

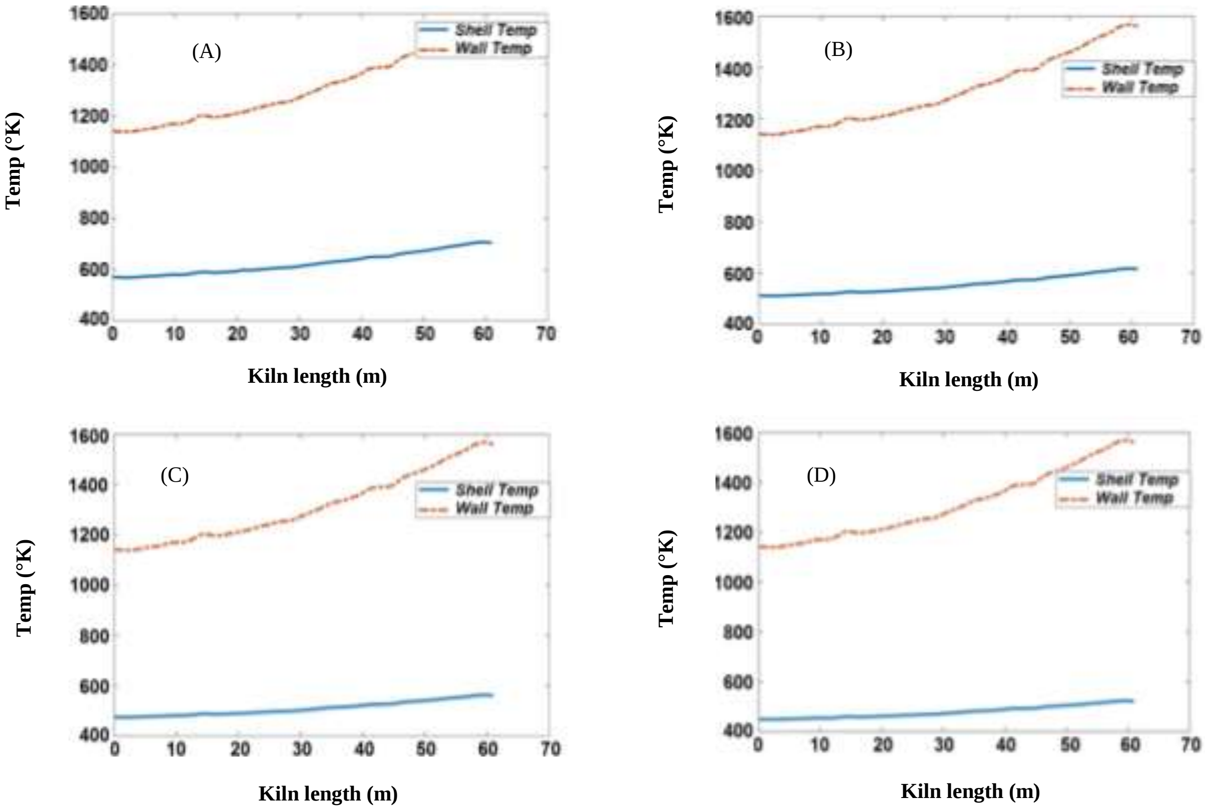

***Fig. 3:** Temperature variations of the shell of the kiln for A) 5 cm B) 10 cm C) 15 cm D) 20 cm coating thickness.*

$$Q_T = \frac{2\pi\Delta z k_a\left(T_{shl} - T_a\right)}{\ln\left(r_a / r_{shl}\right)} \tag{19}$$

$$T_c = \frac{Q_T \ln\left(\frac{r_b}{r_c}\right) + 2\pi k_b T_b}{2\pi k_b} \tag{20}$$

In these equations, Δz is assumed to be 1 meter. By replacing T_b from Eq. (18), T_c can be calculated as Eq. (21).

$$T_c = \frac{Q_T k_{shl} \ln\left(\frac{r_b}{r_c}\right) + Q_T k_b \ln\left(\frac{r_{shl}}{r_b}\right)}{2\pi k_b k_{shl}} + T_{shl} \tag{21}$$

Also, replacing the derived equation for T_c in Eq. (16) T_w can be calculated as Eq. (22).

$$T_w = \frac{Q_T \ln\left(\frac{r_c}{r_w}\right)}{2\pi k_c} + \frac{Q_T k_{shl} \ln\left(\frac{r_b}{r_c}\right) + Q_T k_b \ln\left(\frac{r_{shl}}{r_b}\right)}{2\pi k_b k_{shl}} + T_{shl} \tag{22}$$

By replacing Q_T from Eq. (19) in Eq. (22) and rewriting that in the form of the linear regression equation, Eq. (23) can be derived.

$$y = u_t^T \theta \tag{23}$$

$$T_w = \begin{bmatrix} 1 + \dfrac{2\pi k_a G}{\ln\left(\dfrac{r_a}{r_{shl}}\right)} \\ -\dfrac{2\pi k_a G}{\ln\left(\dfrac{r_a}{r_{shl}}\right)} \end{bmatrix}$$

$$G = \frac{\ln\left(\frac{r_c}{r_w}\right)}{2\pi k_c} + \frac{k_{shl} \ln\left(\frac{r_b}{r_c}\right) + k_b \ln\left(\frac{r_{shl}}{r_b}\right)}{2\pi k_b k_{shl}}$$

As can be seen, the linear regression equation's known vector consists of T_{shl}, T_a and its output is T_w. For simplicity, we consider the parameter's coefficient T_a to be a_0 the unknown parameter of the vector θ. The coating thickness, which is equal to the difference between r_c and r_w, can be calculated by obtaining r_w as Eqs. (24)-(26).

$$a_0 = \frac{2\pi k_a}{\ln\left(\frac{r_a}{r_{shl}}\right)}\left[\frac{\ln\left(\frac{r_c}{r_w}\right)}{2\pi k_c} + \frac{k_{shl}\ln\left(\frac{r_b}{r_c}\right) + k_b \ln\left(\frac{r_{shl}}{r_b}\right)}{2\pi k_b k_{shl}}\right] \quad (24)$$

$$a_0 = \frac{k_a \ln\left(\frac{r_c}{r_w}\right)}{k_c \ln\left(\frac{r_a}{r_{shl}}\right)} + \frac{k_a k_{shl}\ln\left(\frac{r_b}{r_c}\right) + k_a k_b \ln\left(\frac{r_{shl}}{r_b}\right)}{k_b k_{shl}\ln\left(\frac{r_a}{r_{shl}}\right)} \quad (25)$$

$$r_w = \frac{r_c}{e^{\left(\frac{\left(a_0 - \frac{k_a k_{shl}\ln\left(\frac{r_b}{r_c}\right) + k_a k_b \ln\left(\frac{r_{shl}}{r_b}\right)}{k_b k_{shl}\ln\left(\frac{r_a}{r_{shl}}\right)}\right) * k_c \ln\left(\frac{r_a}{r_{shl}}\right)}{k_a}\right)}} \quad (25)$$

Identification by recursive least squares (RLS) method

The principles of the RLS method are the same as the OLS method described earlier. This method identifies unknown parameters vector θ from existing N input-output samples, then updates θ by reading sample N+1. In this method, the main idea is to obtain θ_{N+1} as a function of θ_N. The RLS identification method consists of the following steps:

- Initializing unknown parameters vector θ_0 and covariance matrix P_0
- Reading the current input-output samples x_t , y_t
- Creating the known vector u_t^T as Eq. (23)
- Calculating the vector k_t as Eq. (27)

$$k_t = \frac{P_{t-1}u_t}{1 - u_t^T P_{t-1} u_t} \quad (27)$$

- Updating the parameters vector θ_t from Eq. (28)

$$\theta_t = \theta_{t-1} + k_t\left(y_t - u_t^T \theta_{t-1}\right) \quad (28)$$

- Updating the covariance matrix P_t using Eq. (29)

$$P_t = \left(I - k_t u_t^T\right) P_{t-1} \quad (29)$$

It is worth noting that the RLS method is an online identification method but the OLS method is its off-line counterpart

Identification by global search (GS) method

In previous methods, due to the dependency between known vector (u_t) elements, only one unknown value could be identified by the linear identification methods. For this reason, in order to identify the coating thickness and other important unknown parameters such as the coating thermal conductivity value k_c, nonlinear identification methods must be used. Two nonlinear identification methods have been used in this paper. The first method is named the Global Search (GS) method and the other is the intelligent genetic algorithm method. The idea behind the GS is very simple. In this method, all possible values of all desired unknown parameters for identification are assigned in reasonable intervals and value steps. For any identical unknown parameters vector, a fitness function that can simply be the absolute value of identification error is calculated. Finally, the unknown parameters vector with the smallest fitness function value can be selected as the identification process's output. In this work, the described GS method has been applied to the derived four data sets from FEA to identify the coating thickness and coating thermal conductivity value. In this method, the possible values for r_w are constrained in the interval 1.6 to 2 and for k_c in the interval 0.1 to 0.5, both with steps of 0.0001. All values between these two intervals are applied to the heat transfer equations of the rotary kiln according to Eq. (30) and (31), and the identification error value is calculated. In this method, the error of actual and calculated temperature differences between the wall and shell (Eq. (30)) has been selected as a fitness function. Finally, this error's minimum value, which represents the best unknown value, has been selected.

$$Q_T = \frac{2\pi k_a\left(T_{shl} - T_a\right)}{\ln\left(\frac{r_a}{r_{shl}}\right)} \quad (30)$$

$$f = Q_T\left(\frac{\ln(r_c)}{2\pi k_c} - \frac{\ln(r_w)}{2\pi k_c} + \frac{\ln\left(\frac{r_b}{r_c}\right)}{2\pi k_b} + \frac{\ln\left(\frac{r_{shl}}{r_b}\right)}{2\pi k_{shl}}\right) - \left(T_w - T_{shl}\right) \quad (31)$$

Identification by Genetic Algorithm (GA) method

The genetic algorithm is the second nonlinear method used to identify unknown parameters of the kiln. Because of the nonlinear inherent of this method, it can determine

Table 2: Results of coating thickness identification by OLS method.

Real coating	Identified coating (cm)	Relative error (%)
5	5.12	2.4
10	10.71	7.1
15	15.67	4.4
20	20.83	4.1

Table 3: Results of the coating thickness identified by RLS method

Real coating (cm)	Identified coating (cm)	Relative error (%)
5	5.09	1.8
10	10.67	6.7
15	15.58	3.8
20	20.74	3.7

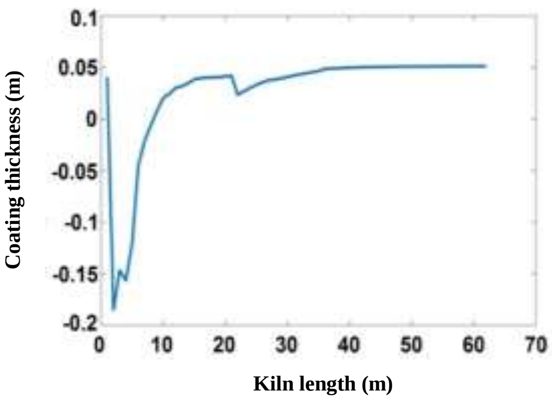

Fig. 4: Estimation of coating thickness (m) for 5 cm coating data by RLS Method.

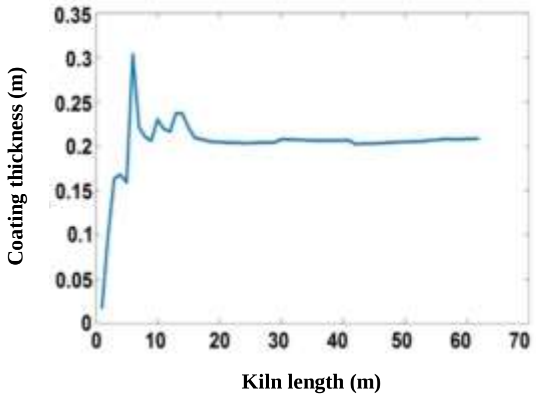

Fig. 5: Estimation of coating thickness (m) for 20 cm coating data by RLS Method.

numerous unknown parameters. In this paper, the GA is used to identify three unknown parameters, coating thickness thermal conductivity coefficients of coating, and refractory layers.

RESULTS AND DISCUSSION

The results of using different identification methods are presented in this section and compared with each other. By applying the OLS identification method and derived linear regression equation to data extracted from FEA, the identified value of coating has been calculated for each data set discussed and depicted in Table 2.

In the second part, the results of the kiln coating thickness identified by RLS method for 4 data set has been proposed in Table 3 and Figs. 4 and 5. As can be seen, the results have some smaller errors compared to OLS results.

In the third part, the final results of GS method for identification of coating thickness and thermal conductivity are depicted in Table 4. As can be seen, due to two parameters identification, the identified coating thickness shows some more error compared to the linear identification method, especially for the 10 cm data set. The real value of kc is 0.0035 W/m/K.

The results of the genetic algorithm method are shown in Table 5. The real values of kc and kb are 0.0035 and 0.008 W/m/K, respectively.

The percentage errors of coating identification for all proposed methods are depicted in Table 6. As can be seen, OLS and RLS methods have an approximately equal percentage of errors because the mathematical origin of these two methods is similar. Still, the RLS method has an online operating capability that can be used for online identification purposes. The GS has a higher error, especially for low coating values, but it can identify coating thermal conductivity compared with the two previous methods. GA has some higher errors than GS, but it can locate additional bricks' thermal conductivity parameters. Therefore linear identification methods such as OLS and RLS have more minor errors with a limited number of identification parameters. Still, nonlinear identification methods such as GS and GA can identify more parameters but with lower accuracy. It must be noted that nonlinear identification methods have higher computational volumes compared with linear counterparts.

Table 4: Identification of coating thickness and coating thermal conductivity coefficient by GS method.

Real coating (cm)	Identified coating (cm)	Relative error (%)	Identified kc (W/m/K)	Relative error (%)
5	4.59	-8.2	0.0033	-5.7
10	12.33	23.3	0.0042	20
15	14.58	-0.1	0.0033	-5.7
20	19.03	-4.8	0.0033	-5.7

Table 5: Coating values obtained from the genetic algorithm method.

Real Coating (cm)	Identified Kb (W/m/K)	Relative error (%)	Identified Kc (W/m/K)	Relative error (%)	Identified Coating (cm)	Relative error (%)
5	0.008	0	0.004	14.2	5.6	12
10	0.008	0	0.003	-14.2	9.5	-5
15	0.009	12.5	0.003	-14.2	15.8	5.3
20	0.007	-12.5	0.004	14.2	19.4	-3

Table 6: Compared coating thickness identification errors (%) for all methods.

Real Coating (cm)	OLS	RLS	GS	GA
5	2.4	1.8	8.2	12
10	7.1	6.7	23.3	5
15	4.3	3.8	2.8	5.3
20	4.1	3.7	4.8	3

CONCLUSIONS

In this paper, the heat transfer equations inside the kiln was examined, and the identification models for identifying the coating thickness and thermal conductivity coefficients are formulated. Various linear and nonlinear methods were performed to identify coating thickness and other unknown parameters in the rotary cement kiln. To extract the data for identification, simulations were performed in FEMM software, and the outer shell temperature profile was obtained by known air temperature and inner wall temperature profiles. As a first identification method, the OLS method was used, and despite the errors in measurement and modeling, it was able to identify the coating thickness. Then, the RLS method has used as the second linear identification method. It was found that the results of these two methods have acceptable small errors. In general, numerous unknown parameters cannot be identified by linear methods because the elements of linear regression known vector are not linearly independent and have linear dependences. Because of this constraint, the coating value and some thermal conductivity coefficients were identified by two nonlinear methods named Global Search (GS) and Genetic Algorithm (GA). GS searches all possible values for unknown parameters and selects the smallest fitness function values as identification output. This method provides a unique solution throughout the search space, while the genetic algorithm will find a different value at each run. The advantage of these two methods over classical linear identification methods is that they can identify several unknown parameters together. In contrast, the accuracy of their identification is less than linear identification methods. It is worth noting that averaging exists in inherent of the used methods. In the OLS method, for any coating thickness, all 62 points are used in one step but in RLS, the moving average value of 2 points) is used to calculate the best thickness value with a minimum sum of squared errors. Also, in GS and GA, all 62 points are used in one step to calculate the selected fitness function to finally select the best parameter values, all with a minimum sum of squared errors.

Nomenclature

T	Temperature, K
r	Radius, m
k	Thermal conductivity, W/m/K
w	Index for wall
b	Index for brick
shl	Index for shell
a	Index for ambient
C	Index for coating
Q_T	Thermal flow, W
z	The distance along with the kiln, m
δ	Coating thickness, m
y	LS output vector
u_t	LS known vector
θ	LS unknown parameters vector
P	RLS covariance matrix
t	Time, s
f	Fitness function

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REFERENCES

[1] Bokaiian M., "Refractory Materials in Rotary Kilns, Eng. Handbook", [Persian ed]., Training Department of Abyek Cement Industrial Complex, Iran, (1993).

[2] Bentaieb N., Benarima Z.A., Belaadi S., Calorimetric and Thermal Analysis Studies on the Influence of Coal on Cement Paste Hydration, *Iran. J. Chem. Chem. Eng. (IJCCE)*, **39**: 237-244 (2020).

[3] Spang H., A Dynamic Model of Cement Kiln, *Automatica*, **8**: 309-323 (1972**)**.

[4] Gorog J.P., Adams T.N., Brimacombe J.K., Regenerative Heat Transfer in Rotary Kilns, *Metall. Trans. B*, **13**: 153-163 (1982).

[5] Darabi P., A Mathematical Model for Cement Kilns, MSc. Thesis, The University of British Columbia, Vancouver, (2007).

[6] Goshayeshi H.R., Kerdarpoor F., Modeling of Rotary Kiln in Cement Industry, *Iranian J. of Energy*, **19**: 23 (2016).

[7] Shahriari K., Tarasiewicz S., Modelling of a Clinker Rotary Kiln Using Operating Functions Concept, *The Canadian J. of Chem. Eng.*, **89**: 345 (2011).

[8] Gu C., Yuan Z., Sun S., Guan L., Wu K., Simulation Investigation of Drying Characteristics of Wet Filamentous Biomass Particles in a Rotary Kiln, *Fuel Processing Technology*, **178**: 344 (2018).

[9] Ramanenka D., Gustafsson G., Jonsén P., Influence of Heating and Cooling Rate on the Stress State of the Brick Lining in a Rotary Kiln Using Finite Element Simulations, *Engineering Failure Analysis*, **105**: 98-109 (2019).

[10] Noshiravani G., Shirvani M., Mamani J.A., Nourzadeh H., Coating Thickness Estimation in Rotary Cement Kiln by Using Shell Temperature Measurements and Kiln Modeling, *Zement Kalk Gibs (ZKG) mag.*, (2013).

[11] Sadighi S., Shirvani M., Ahmad A., Rotary Cement Kiln Coating Estimator: Integrated Modelling of Kiln with Shell Temperature Measurement, *Can. J. Chem. Eng.*, **89**: 116-125 (2011).

[12] Al-Yasiri A.J.K., Muhammed M.A., Estimating the Thickness of Coating in the Burning Zone of Cement Kiln Including the Aging Factor, *Iraqi J. for Mech. and Mat. Eng.*, **12**: 545-563 (2012).

[13] Ravindran J., Krishnan S., "Studies on Thermal Analysis of Cement Rotary Kiln Based on Clinker Coating Materials on Refractories", *Energy and Monetary Savings*, *Presented at Int. Cong. on Recent Development in Engineering and Technology (RDET-16)*, Kuala Lumpur, August (2016).

[14] Singh R.S., Prasad D., Srivasrav A., Pandey D., Kumar M., System Identification and Design of Inverted Decoupling IMC PID Controller for Non-minimum phase Quadruple Tank Process, *Research Note, Iran. J. Chem. Chem. Eng. (IJCCE)*, **40(3)**: 990-1000 (2020).

[15] Nejati A., Shahrokhi M., Mehrabani A., Adaptive Input-Output Linearization Control of pH Processes, *Iran. J. Chem. Chem. Eng.*, **27(3)**: 25-35 (2008).

[16] Norton J.P., "An Introduction to Identification", Academic Press, 310 (1986).