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MODELING OF HEAT TRANSFER IN BURNING ZONE OF ROTARY CEMENT KILN

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ABSTRACT

Rotary Kilns are one of the most widely used pieces of processing equipment. They are used for drying or calcinng a variety of products including sand, aggregates, limestone and food products. Heat transfer in rotary kilns encompasses all the modes of transport mechanisms, that is conduction, convection and radiation. In rotary kiln operations the chemical reactions in the bed required high temperatures. The energy to raise the temperature and drive endothermic reactions is from the combustion of a range fuels such as heavy oil, natural gas, coal and more alternative fuels. Heat transfer from the gas to the bed is complex and occurs from the gas to the bed surface and kiln wall to bed surface via conduction, convection and radiation. The study concerned to perform a mathematical modeling to simulate of the heat transport in the cement rotary kiln to predict the temperatures at internal and external wall surfaces of the rotary kiln to preventing many industrial problems through the operation process such as (loss of coating, red spots formation, ….) also to predict the optimum range conditions for safe operation. The results obtained show that, the predicted data using a mathematical model satisfied with industrial data for burning zone. The study showed a derived mathematical model can be used with a good reliability to description of heat transfer in burning zone of rotary cement kilns.

Keywords

Rotary kiln, heat transfer, Burning zone, Cement.

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1. INTRODUCTION

The manufacture of cement has been the focus of considerable attention worldwide because of the high energy usage and high environmental impact. So the heart of this industry is the rotary kiln. Rotary kilns are one of the most widely used pieces of processing equipment. They are used for drying or calcining a variety of products including sand, aggregates, limestone and food products. With an ever increasing focus on reducing greenhouse gas emissions, the continued or increased use of rotating kilns can only be achieved by reducing the thermal and electrical energy consumption used in these processes. Heat transfer in kilns is very complex, with radiation, convection and conduction all contributing to energy transfer between the gas, the feed and the vessel wall. A fluid bed calciner or dryer achieves rapid drying by the large heat transfer coefficient obtained through the high air volume being circulated. The penalty is the increase in electrical energy required to circulate this high air volume. Rotary kilns on the other hand have poor heat transfer coefficients, hence higher thermal energy demand, due to the need for larger devices and thus more opportunity for heat to be lost [1].

Heat transfer in rotary kilns encompasses all the modes of transport mechanisms, that is, conduction, convection, and radiation. In the freeboard, radiation is believed to be the dominant mode of heat transfer constituting over 90%, primarily due to the large flame and curvature of the combustion chamber. Convection in the freeboard occurs as a function of the turbulent flow of gases and participates in the transfer of heat to the bed's free surface and the refractory wall in a manner similar to flow over heated plates. Convection also occurs in the interparticle interstices within the particulate bed. Heat is conducted from the freeboard to the outside environment through the refractory wall and must overcome the resistances to heat flow through the composite walls of refractory materials to reach the outer kiln shell. Within the bed, heat transfer is by interparticle conduction, which, together with interparticle convection and radiation, forms an effective conductance of heat through the particulate medium. In this chapter we will review classic heat transfer mechanisms and point out where the phenomenon comes into play in the freeboard of the rotary kiln. Figure 1 shows the schematic indication of the heat transfer in cement rotary kiln.

In most rotary kiln operations the chemical reactions in the bed require high temperature. The energy to raise the temperature and drive endothermic reactions is from the combustion of a range of fuels such as heavy oil, natural gas, coal and more and more alternative fuels. Heat transfer from the gas to the bed is complex and occurs from the gas to the bed surface and kiln wall to bed surface via conduction, convection and radiation.

There are many investigations developments related to the internal design of rotary kilns done to improve to description of the heat transfer. These models developed in mathematically mode of solid phase in one dimensional such that given by Gorog et al.[2], Mujumdar et al. [3], or in two dimensions such as Boateng and Barr [4], or in multiphase as given by Chaudhuri et al. [5], or developed by numerical solutions as given by Liu et al. [6]. All these studies concern on the simulation of the heat transport in the rotary kiln to predict the temperatures at internal and external wall surface of the rotary kiln, to predict the regions which have minimum and maximum temperatures and axial heat flux to the solids of bed and refractory wall to preventing many industrial problems through the operation process such as (loss of coating, red spots formation, …etc.) also to predict the optimum range conditions for safe operation. The main objective of the study is modeling of a simple mathematical model to prediction of the internal and external temperatures of cement rotary kiln wall in burning zone to achieve the optimum range conditions for safe operation with low losses of heat.

2. Modeling and Simulation of Heat Transport

In the region where combustion takes place, radiant heat transfer from the burning flame is controlling, whereas convectional heat transfer is one order of magnitude less. For convenient application to practical design calculation, there are simplified model to represent the heat transfer mechanism in this region as shown in Figure 2. Mathematical modeling of inside heat transport of a rotary kiln with and without coating done as following;

2.1 Mathematical modeling of heat transport on a rotary kiln with coating

2.1.1 Radiant heat transport from flame and combustion gas

In the region where combustion takes place, radiant heat transfer from the burning flame is controlling, whereas convectional heat transfer is one order of magnitude less. For convenient application to practical design calculation, there are simplified model to represent the heat transfer mechanism in this region [7].

In Figure 2, radiant heat (mainly infrared ray) is emitted from the burning flame at high temperature, some fraction of which arrives at the surface of the rotating solids layer, and the other arrives at the inner refractory surface. The rest is absorbed in the combustion gas around the flame. For predicting radiant heat transfer, however, radiant heat transfer is simplified to apply to the complex mechanism of heat transfer in a rotary kiln, without losing significant fundamentals. Radiant heat absorbed in combustion gas around the flame is converted to thermal energy, which should be emitted as infrared ray from the gas to the rotating solids and inner wall surface. Thus may be assume that all the radiant heat emitted from the flame arrives at the surface of the rotating solids and the inner wall surface.

The radiant heat transfer coefficient, h_{rg} of two solid surfaces is calculated by Kunii and Chisaki [7];

$$h_{rg} = \frac{(d_{ti}/d_F)(\varepsilon_F \varepsilon_m)(4.88)\left[\left(\frac{T_F+273}{100}\right)^4 - \left(\frac{T^*+273}{100}\right)^4\right]}{T_F - T^*} \quad \ldots\ldots\ldots\ldots\ldots.(1)$$

The average temperature T^* is calculated using Eqn.(2).

$$T^* = \varkappa T_C + (1-\varkappa)T_H \quad \ldots\ldots\ldots\ldots\ldots.(2)$$

where d_f is the outer diameter of the flame, d_{ti} is the internal diameter of the kiln, ε_f is the emissivity of the flame, ε_m is the average emissivity of the solids layer surface and the inner wall surface, and T^* is the average temperature of the above two surfaces. The average diameter of flame d_f depends strongly on the hydrodynamic feature of turbulent diffusion.

So, the radiant heat transferred from flame and combustion gas is;

$$Q''_{Flame} = (1-\varkappa)h_{rg}(T_F - T_H) \quad \ldots\ldots\ldots\ldots\ldots.(3)$$

2.1.2 Radiant heat transport from inner wall surface to surface of rotating solids

In Figure 2, the fraction of inner surface area χ, to which rotating solids contact, is needed for further calculation. By simple calculation, χ versus the volumetric fraction of solids γ is given in Figure 3.

Radiant heat emitted from the wall surface per unit surface area of the inner wall of the reactor is given by Kunii and Chisaki [7];

$$(1-\chi)\varepsilon_H(4.88)\left(\frac{T_H+273}{100}\right)^4 \qquad \text{................(4)}$$

The geometrical view (angle) factor from the inner surface $\pi d_{ti}(1\text{-}\chi)$ to the rotating layer of solids is represented by F_{HC}.

$$(1-\varkappa)F_{HC} = \varkappa \, \mathrm{F}_{CH} \qquad \text{................(5)}$$

Since $F_{CH} = 1$, and $F_{HC} = \chi / 1\text{-}\chi$.

Radiant heat, emitted from the inner surface, is mainly infrared ray. When it passes through the flame and combustion gas, some part of the infrared ray is absorbed by them. So, take ε_g^* to be the average value of emissivity for the flame and combustion gas. Thus, the rate of radiant heat transfer from the inner wall surface to the rotating solids layer is calculated approximately with Eqn. (6);

$$(1-\chi)(\varepsilon_H\varepsilon_C)(4.88)\left[\left(\frac{T_H+273}{100}\right)^4-\left(\frac{T_C+273}{100}\right)^4\right]\mathrm{F}_{HC}(1-\varepsilon_g^*) \qquad \text{............(6)}$$

The radiant heat transfer coefficient from the hot inner wall to the layer of solids by $(h_{rs})_{HC}$, on the basis of the surface area of the inner wall, to which the rotating solids contact;

$$\chi(h_{rs})_{HC}(T_H-T_C) \qquad \text{................(7)}$$

Combination of Eqns. (6) and (7) leads to the following equation,

$$(h_{rs})_{HC} = \frac{\varepsilon_H(1-\varepsilon_g^*)\varepsilon_C(4.88)\left[\left(\frac{T_H+273}{100}\right)^4-\left(\frac{T_C+273}{100}\right)^4\right]}{T_H-T_C} \qquad \text{................(8)}$$

So, the radiant heat transferred from inner wall surface to surface of rotating solids layer is;

$$Q''_{solid\ 1} = \varkappa\,(h_{rs})_{HC}(T_H-T_C) \qquad \text{................(9)}$$

2.1.3 Heat transfer by direct contacting of solids from the hot wall surface

In a rotary kiln, solids are heated by direct contact with the hot wall surface. The inner wall surface functions as a kind of regenerator, changing the surface temperature periodically during the rotation. Theoretical calculation reveals that the amplitude in the periodical change of surface temperature is not too much, as long as the rotation is larger than 2 rpm. By taking of the time averaged temperature of the wall. For a packed of solids, which suddenly contact the hot surface and then leave it after residing there for a time *t*, Kunii and Levenspiel [8] gave the following equation to calculate the time averaged value of the heat transfer coefficient due to the above contact, on the basis of contacting surface area;

$$(h_p)_{HC} = h_{packed} = 1.13\left[\frac{K_e\,\bar{\rho}\,C_s}{t}\right]^{0.5} \qquad \text{................(10)}$$

where K_e is the effective thermal conductivity of a packet of solids, $\bar{\rho}$ is the bulk density, and C_s is the specific heat of solids.

$$t = \chi/N \qquad \text{................(11)}$$

By Substitution of Eqn. (11) to (10) to gives;

$$\left(h_p\right)_{HC} = h_{packed} = 1.13\left[\frac{K_s\,\bar{\rho}\,C_s\,N}{\chi}\right]^{0.5} \qquad \text{................(12)}$$

So, the heat transferred by direct contacting of solids from the hot wall surface is;

$$Q''_{solid\ 2} = \varkappa\left(h_p\right)_{HC}(T_H - T_C) \qquad \text{................(13)}$$

2.1.4 Heat loss to outside of coating

Heat flux loss to the surface of rotary kiln through coating may be calculating based on the basic principles of heat transfer as following;

$$Q''_{loss} = \frac{T_H - T_W}{\frac{\ln(r_2/r_1)}{k_{coating}} + \frac{\ln(r_3/r_2)}{k_{bricks}} + \frac{\ln(r_4/r_3)}{k_{shell}}} \qquad \text{................(14)}$$

where r_1, r_2, r_3 and r_4 are the inner radius of coating, inner radius of bricks, inner radius of shell and outer radius of shell respectively. $k_{coating}$, k_{bricks} and k_{shell} are thermal conductivities of coating, bricks and shell respectively.

2.1.5 Heat balance on the inner surface of the cement rotary kiln

The overall energy balance on the inner surface of the kiln according to Figure 2 are given by the following Eqn.;

$$Q''_{Flame} = Q''_{Solid} + Q''_{loss} \qquad \text{................(15)}$$

$$(1-\varkappa)h_{rg}(T_F - T_H) = \varkappa\left[\left(h_{rs}\right)_{HC} + \left(h_p\right)_{HC}\right](T_H - T_C) + \frac{T_H - T_W}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{coating}} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{bricks}} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{k_{shell}}}$$

............(16)

Due to a hard known or prediction of T_W values because it is a function of T_H. thus by using Eqn. (16) may be estimation of T_H at a given value of flame temperature T_F, then reusing to estimate T_W values.

2.2 Mathematical modeling of heat transport on a rotary kiln without coating

The same procedure done in section 2.1 from Eqn.(1) to Eqn.(13), by eliminating the first term in the denominator of Eqn.(14). So Eqn.(16) for without coating becomes;

$$(1-\varkappa)h_{rg}(T_F - T_H) = \varkappa\left[\left(h_{rs}\right)_{HC} + \left(h_p\right)_{HC}\right](T_H - T_C) + \frac{T_H - T_W}{\frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{bricks}} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{k_{shell}}}$$

..........(17)

To solve Eqns.(16 and 17), some of data must be known. So, a known data used are a field data taken from Alburge Cement Plant (ACP), is one of plants followed to Arab Union of Cement Company (AUCC), have been collected cover a long period of time. The plant use a dry process with series of cyclones type pre-heaters and an incline kiln. The kiln is 4.35 *m* in. diameter and 75 *m* long. The average daily production capacity is 4200 ton of clinker and the used fuel is natural gas. A large number of measurements have been taken during 1 year and averaged values are used as a field data to investigate of a results obtained from Eqn.(16). The field data are shown in Table 1.

3. Results and Ddiscussion

A program of Fortran 90 is built to solve Eqns.(16 and 17), for a given data to prediction T_H values then compared them with field data also to calculation the values of amount of heat loss and compare them with field data measured.

The results showing in Table 2, reveals to the internal wall surface temperatures T_H predicted by model are satisfied field data obtained from industrial process (ACP) with acceptable deviation. In which the deviation is not exceed 10% for each point.
Table 3 present both internal and external temperatures of rotary kiln for the burning zone, they are function of flame temperature, and increasing with increase the flame temperature as illustrate in Figure 6.

Table 4 shows that, both internal and external temperatures of rotary kiln for the burning zone; are function of flame temperature, and increasing with increase the flame temperature. Also, the heat loses increase, due to decrease a resistance of heat transport between inside and outside of shell surfaces due to the coating is not exist. Figure 7 show that, the outer shell surface in without coating is higher than with coating, due to decrease of the thermal resistance in which by coating, (*i.e.* decreasing thickness because there is no coating layer).

The optimum external wall surface temperature in industrial processes ranged (250-340 ^oC), (ACP, 2009). Note that in Table 4, T_w reaches up to 379 ^oC when the flame temperature greater than 1580 ^oC. That's make up many troubles in the rotary kiln in this case the red spot (hot spot) through the rotary kiln will be occurs., in which the coating will be start to collapse that leading to decrease the thermal resistance that allowable to increase the external wall surface temperature (T_w) reaches up to 450 ^oC which is known in cement industries as red spot.

As shown in Figure 4, the deviation between two lines are clear when the flame temperature increased above 1580 ^{o}C, this due to the values obtained by model are perfectly but as a matter of fact field data refers to all the materials inside kiln is burnet and any increase in the flame temperature causes too much liquid to form and can result in a serious loss of coating. This behavior may be also noted in Figure 5, in which this mode leading to increase the heat losses, due to increase the difference temperatures between inner and outer wall surfaces temperature.

4. Conclusion

The results obtained show that, the predicted data using a mathematical model satisfied with industrial data for burning zone of rotary kiln. The simulation done on the process showed that, the predicted external wall surface temperature is ranged from (267.85-327.85 ^oC) without problem occur (hot spot formation) in the rotary kiln. So, the optimum flame temperatures recommended to used are ranged (1200-1600 ^oC) in cement industry by dry process.

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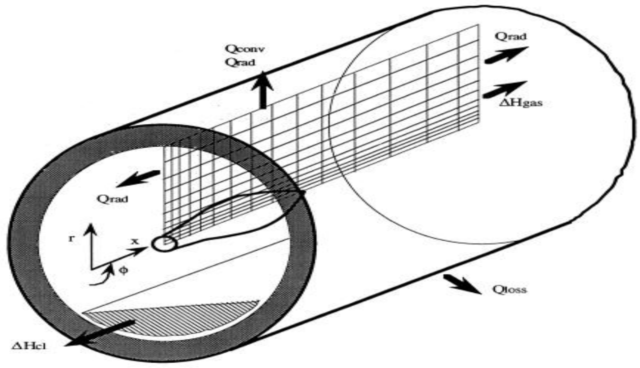

Figure 1: Schematic indication of the heat transport in cement rotary kiln [1].

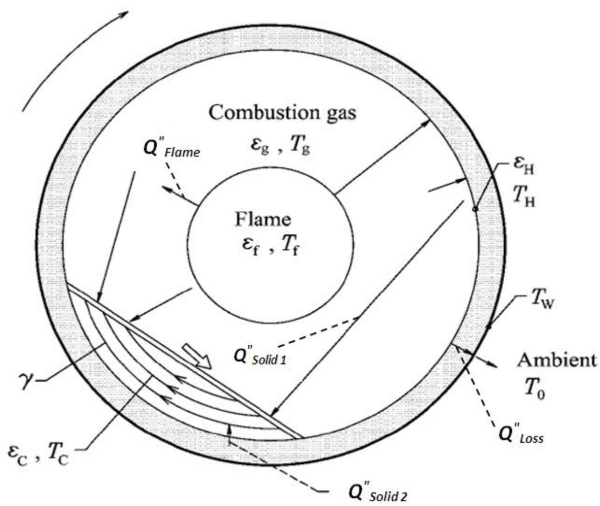

Figure 2: Model of heat transfer mechanism in the combustion and heating region.

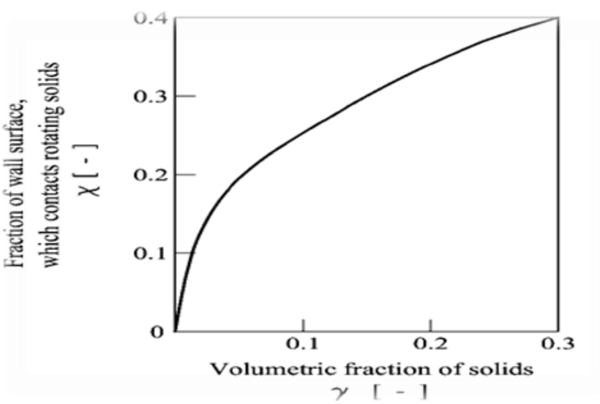

Figure 3: Fraction of wall surface area which contacts rotating solids [7].

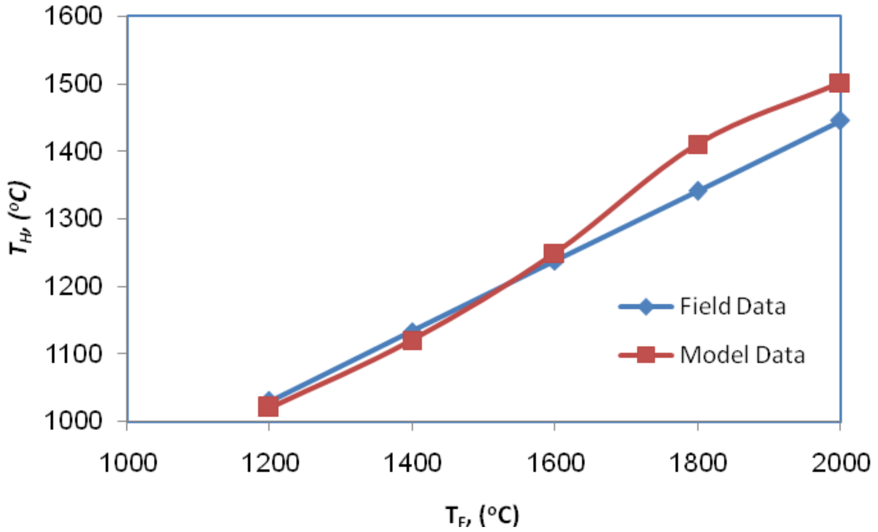

Figure 4: Comparison between field and model data of internal wall surface temperatures for burning zone (with coating)

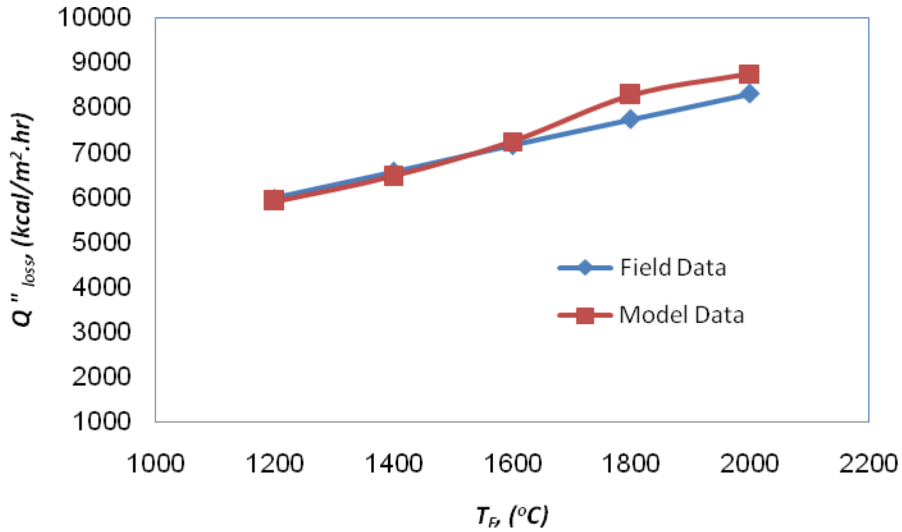

Figure 5: Comparisons between field and model data of heat losses from external surface of kiln for burning zone (with coating)

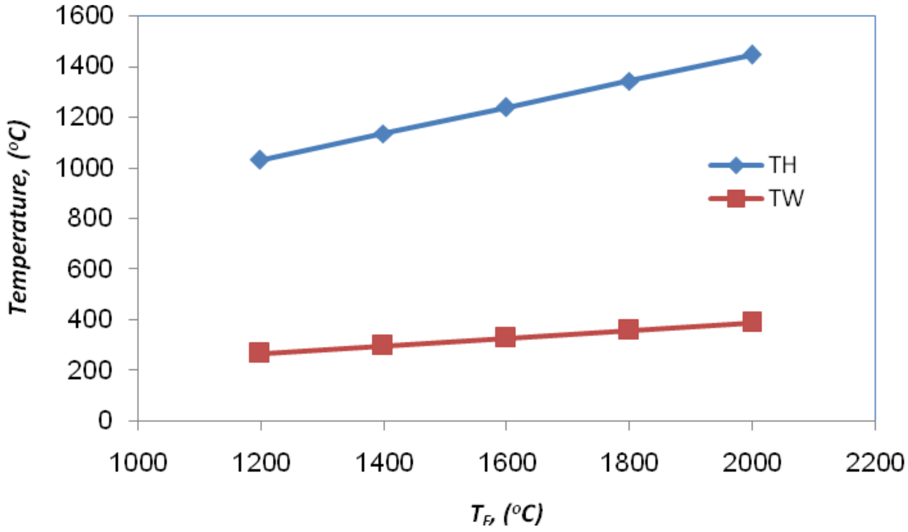

Figure 6: Predicted temperatures of inner and outer shell surface with coating

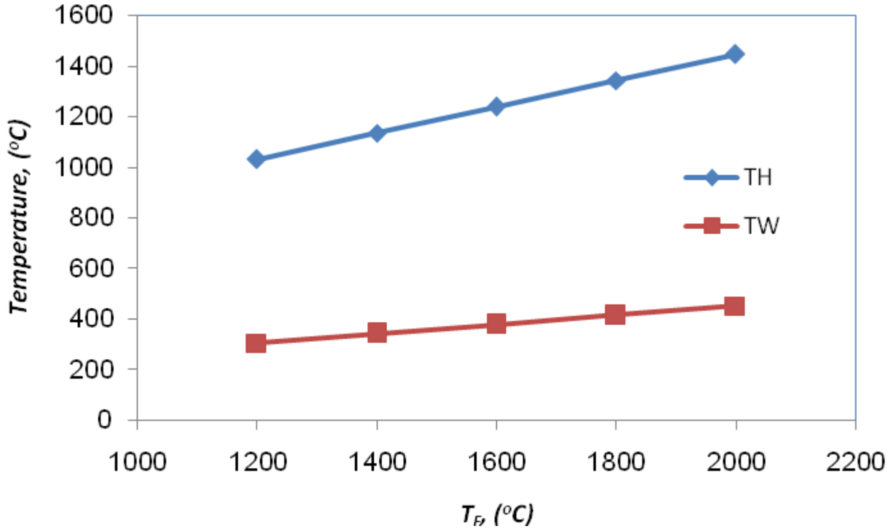

Figure 7: Predicted temperatures of inner and outer shell surface without coating

Table 1: Field data of the burning zone of cement rotary kiln [9]

Data	**Value**
Clinker temperature [T_c] , (^oC)	950
Average emissivity of internal surface and solid surface [ε_m]	0.8
Emissivity of solid surface [ε_c]	0.84
Emissivity of flame [ε_f]	0.7
Internal diameter of kiln with coating, (m)	4.2
Internal diameter of kiln without coating [d_{ti}], (m)	4.35
Flame diameter [d_f], (m)	1.4
Flame temperature [T_F], (^oC)	1200 - 2000

Table 2: Comparison between field and model data (with coating)

T_F, (^oC)	***T_H (^oC)***		***Q_{losses} (kcal/m^2.hr)***	
	Field data	***Model data***	***Field data***	***Model data***
1200	1029.8	1021	5990.41	5921.224
1400	1133.6	1120	6570.621	6463.698
1600	1237.4	1249	7150.83	7242.03
1800	1341.2	1410	7731.04	8271.945
2000	1445	1501	8311.25	8743.66

Table 3: Prediction of inner and outer shell surface temperatures <u>with coating</u>, Eqn. (16)\

T_F (^oC)	***T_H (^oC)***	***T_W (^oC)***	***h_{rg} (kcal/m^2.hr.^oC)***	***h_{rs} (kcal/m^2.hr.^oC)***	***h_p (kcal/m^2.hr.^oC)***	***Q_{loss} (kcal/m^2.hr)***
1200	1029.8	267.85	98.66	158.68	561.89	5990.41
1400	1133.6	297.85	133.06	179.76	561.89	6570.621
1600	1237.4	327.85	174.9	203.14	561.89	7150.83
1800	1341.2	357.85	224.95	228.95	561.89	7731.04
2000	1445	387.85	283.94	257.35	561.89	8311.25

Table 4: Predicted temperatures of inner wall and outer shell surfaces
<u>without coating</u> Eqn.(17)

T_F (^oC)	***T_H (^oC)***	***T_W (^oC)***	***h_{rg} (kcal/m^2.hr.^oC)***	***h_{rs} (kcal/m^2.hr.^oC)***	***h_p (kcal/m^2.hr.^oC)***	***Q_{loss} (kcal/m^2.hr)***
1200	1000	306.25	87.097	158.68	561.89	15956.55
1400	1045	342.65	117.64	179.76	561.89	16154.36
1600	1164	379.05	154.4	203.14	561.89	18054.19
1800	1311	415.45	198.58	228.95	561.89	20598
2000	1457	451.85	283.94	257.35	561.89	23118

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