Studies on Heat Transfer Behaviour in a Magnesite Kiln and its Assessment.

B.K.Chakrabarti

Department of Materials & Metallurgical Engineering,
National Institute of Foundry & Forge Technology,
Ranchi-834003. India.

(Received January 9, 2002; final form February 8, 2002)

ABSTRACT

The challenges of improving sintered MgO raw materials with special high temperature properties from the user's viewpoint have made dead burning an energy intensive process. High temperature requirements and the dimensions of the kiln lead to enormous heat loss through the surface of the kiln by radiation and convection. In the present work an attempt was made to evaluate and assess the amount and the trend in the heat transfer through the kiln surface. Data were collected from the industries and the same were utilized for the work. Some measures were recommended with a view to making the process more energy economic. An attempt was also made to find out the possible fuel saving through reutilization of the heat at the burning zone of the kiln.

Key-words: Magnesite kiln, heat transfer, radiation & convection, economy.

1. INTRODUCTION

The proper utilization and conversion of energy plays an important role in the energy management of any system. The economics of energy use seems to be one of the most vital global issues. Energy analysis is a technique for examining the way in which energy sources are harnessed to perform useful functions. The dead burning of magnesite due to its variable factors causes the consumption of an alarming amount of energy, where the thermal energy constitutes an important part of the manufacturing costs.

These industries /1,2,3/ have been specially affected by heavy increases in the cost of energy, raw materials and fuels. The manufacturing cost factor has led the manufacturers to restrict the consumption of fuel by many improvements in installations and has led scientists to investigate the use of new materials in order to obtain compositions and additives /3,4,5/ that reduce energy consumption, mainly by decrease in the firing temperature of the refractory products, or by changing the process parameters, or by recovery of the waste heat energy. A necessary prerequisite for energy conservation programmes in these industries is the conducting of a plant's internal energy audit. An energy audit serves to inform the management of the critical areas wherein conservation measures could be implemented. A plant's energy audit serves the management in the following critical areas:

- To identify all the energy streams in a facility and to quantify energy use.
- To identify the costs of energy, where and how it may be used.
- To provide a base from which results can be measured and a programme can be further developed.
- To consider it as one amongst the other management functions.

- To provide data and appropriate information to the management about how the units have been functioning.

The main objective of the present work was to assess the heat expenditures in the process through the kiln shell in the form of radiation and convection. In addition to the above, the significance of this work was also to study the various aspects of the rotary kiln on the dead burning process when the kiln had equilibrated by running for over 4 months, with due consideration for utilizing the results for the study of heat balance of the process. The investigations and the measuring procedure of the rotary kiln systems for dead burning of magnesite yield a large quantity of operating data. In view of the large numbers of variable factors the present work has been limited to:

- Measurement of heat loss through radiation over the entire length of the kiln.
- Measurement of heat loss through convection over the entire length of the kiln.
- Calculation and evaluation of the recoverable heat loss through different zones along the kiln length.
- Discovering the possible fuel savings through reutilization of the heat loss at the 0-33metre length of the kiln.
- Studying the behaviour and patterns of the surface temperature and heat loss to assess the complexities inside the kiln.
- Suggesting measures in regard to the economy of the process.

2. METHODOLOGY

The present work aims at the acquisition of data and utilization of the same for evaluation of the radiative and convective heat transfer through the surface of the kiln and assessment of the same. Heat transfer coefficient, heat loss etc. were evaluated at each 3metre length of kiln surface using standard formulations /8/. The kiln shell temperatures were measured at each 3 metre length of the surface for the entire 84 metres by an Infrared thermometer (CHINO, made in Japan,

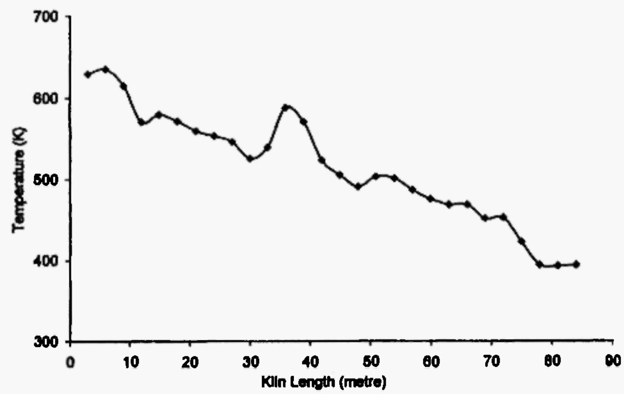

Fig. 1: Surface temperature vs kiln length

temperature range, 323-773°C). Figure 1 shows the trend in change of surface temperature along the kiln length. The data were collected for the kiln, which was running for the 128th day. In order to assess and identify the lining materials the brick samples were subjected to chemical composition analysis and density measurement.

2.1. Description of the kiln and data acquisition:

Process	:	Dry process.
Type	:	Rotary.
Kiln Length	:	84 metres.
Kiln Diameter	:	O.D = 2.575 metres
Rotational Speed	:	1 rpm.
Fuel Type	:	LSHS (Low sulfur heavy stock) preheated to 423 ^{0}K.
Calorific Value of the Fuel	:	45.22 MJ/kg.
Fuel Consumption	:	947.92 Kgs / hr.
Inclination	:	3 %
Raw Magnesite Input	:	9679.59 Kgs / hr.
Dead Burnt Magnesite (DBM) output:		5129.17 Kgs / hr.
Fuel / DBM	:	0.185.
Exit gas temperature	:	608 ^{0}K.
Dead burning temperature	:	1923 ^{0}K.

3. EVALUATION OF AVAILABLE HEAT

3.1. Calculation of radiation heat transfer:

Radiative heat transfer coefficient, hr = $\varepsilon \sigma (Ts^4 - Ta^4) / (Ts - Ta)$

where ε = Emissivity of the surface

σ = Stefan-Boltzmann constant = 5.676×10^{-8} W/m^2.K^4.

Ts and Ta = Surface and atmospheric temperatures respectively, in °K.

Rate of radiative heat loss per unit area (qr) = hr. (Ts- Ta). W/m^2

Radiative heat loss from an area A, (Qr) = hr. A. (Ts – Ta). Watt.

[where A= π d l;

d = outer diameter of the kiln = 2.575 m, l = length of the kiln.]

Assigning an appropriate emissivity is an important task in this type of work. Emissivity capacity varies with temperature. As per the work of V.W. Kuhle /6/ the emissivity for the steel surface coated with dust in the temperature range of $373^0K < t_1 < 773^0K$ varies as,

$$\varepsilon = 0.96 - 5.20 \times 10^{-4}(t_1 - 100),$$

where, t_1= surface temperature. However, for the sake of simplicity of work an approximation was made, and an average of ε=0.8 was assigned and utilized for the calculation of radiation heat transfer coefficients. Temperatures were measured setting the surface emissivity at 0.8. Figure 2 shows the trend in change in the emissivity (ε) with temperature. The radiative heat loss was calculated for the area of each 3 metre length and then summed up for the total 84 metre length for calculating total heat loss.

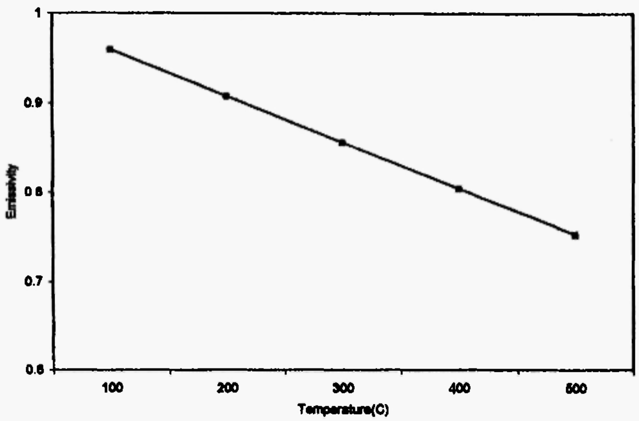

Fig. 2: Emissivity vs Temperature

3.2. Calculation of convection heat transfer:

In calculating and evaluating loss by convection, some uncertainty was encountered. As a general guideline, if the kiln is housed in an enclosed hall the coefficient for free convection is usually applied, and if it is in the open air the coefficient for forced convection is applied. The forced convective heat transfer coefficient (h_{fc}) and Reynolds number have been determined using the following equations. Standard data /8/ of density and viscosity of air at different temperatures were utilized.

Reynolds number, $Re = V\rho D/\mu$

where V= velocity of air, m/s

ρ= density of air, kg/m^3

μ= viscosity of air, Pa.s

D= diameter of the kiln, metre.

Convective heat transfer coefficient, $h_{fc} = \kappa B.Re^n/D$ w/m^{2}K

where κ = thermal conductivity of air, w/m^{0}K

D = diameter of the kiln, metre

Re = Reynolds number(dimension less)

The values of B and n for applicable ranges of Reynolds number were utilized as established by Hilpert/7/, other values as per Todd and Ellis /8/.

Heat loss through forced convection in a area A,

$q_{fc} = h_{fc}$. A. (Ts-Ta) watt.

Air velocity plays an important role in the convection of heat. The effects of air velocity on heat transfer coefficient and on heat loss were evaluated at different air velocities, keeping all other parameters (viz, density, viscosity, etc) constant. The trend of change in heat loss with air velocity can be seen in Fig. 3. However, as the periodic data of air velocity at different time intervals was not available, a different model was considered for the evaluation of the heat transfer coefficient and the heat loss.

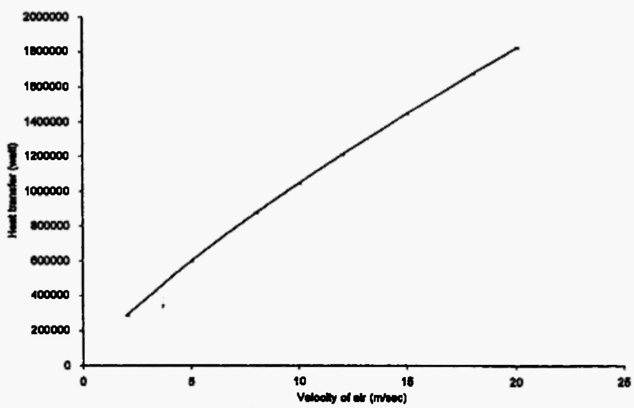

Fig. 3: Effect of air velocity on the heat transfer

The factor of wind velocity in this particular calculation was not considered. As air is often involved in free convection calculations, simplified equations have been developed /8/ for air to facilitate the determination of convective heat transfer coefficient (hc).

Convective heat transfer coefficient (hc) for air at atmospheric pressure, in contact with the surface of horizontal cylinder of diameter more than 0.6 metre is expressed /8/ as:

$$hc = [C_2\, k\, \alpha 1/3].\ \Delta T\ 1/3 \quad w/m^2 K \qquad C.1.$$

where

C_2 = Dimensionless factor that evaluates the effect of the solid surface configuration.

k = Thermal conductivity of air, w/m.K.

α = Free convection modulus. $1/m^3.K$

$\Delta T = (Ts - Ta)$

where

Ts & Ta are the temperatures of the surface and atmosphere respectively.

If we consider $C_2\, k\, \alpha^{1/3} = f$, then the equation C.1 stands as,

$$hc = f.\ \Delta T^{1/3} \quad w/m^2 K \qquad C.2$$

f depends on the temperature Tav, where Tav = (Ts + Ta) / 2 ^{0}K

Rate of convective heat loss per unit area (qc) = hc (Ts – Ta) w/m^2.

Convective heat loss in an area A (Qc) = hc. A. (Ts – Ta) w/m^2.

Total radiative and convective heat in an area A (Qt) = [Qr + Qc] watt.

The values of 'f' for the horizontal cylinder or rotary kiln with a diameter of more than 0.6 metre can be obtained by multiplying the values in Table 1 by 0.8125 as stated by Todd and Ellis /8/. Thus the values of 'f ' at various Tav values stand as in Table 1.1. The values of Table 1.1 were utilized for making a graph

Table 1

Dependence of 'f' on Tav for a large vertical flat plane in air

Tav (°K)	$f(w/m^2.K^{1.33})$
253	1.711
273	1.649
293	1.587
313	1.525
333	1.463
353	1.400
373	1.338
393	1.269

Table 1.1

Dependance of 'f' on Tav for a horizontal cylinder of diameter over 0.6 metre in air

Tav (°K)	$f(w/m^2.K^{1.33})$
253	1.3902
273	1.3398
293	1.2894
313	1.2391
333	1.1887
353	1.1375
373	1.0871
393	1.0311

and fitted into an MS Excel package. Figure 4 shows the change of 'f 'with Tav. With the help of the MS Excel package an equation could be formulated which is linear in nature, as represented below:

$$f = -0.0026\, Tav + 1.341 \qquad C.3.$$

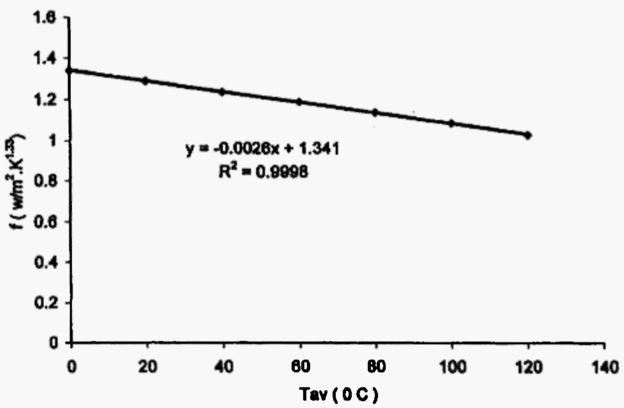

Fig. 4: "f" vs Tav

Utilizing the equation C.3, 'f' was calculated at different Tav values, corresponding to various kiln shell temperatures. The 'f' values so obtained were utilized for further calculations.

3.3. Recovery of heat from the burning zone of the rotary kiln:

A run around mechanism may be recommended to recuperate the heat available in the burning zone of the kiln. Assuming at least 50 % efficiency of the system, the equivalent fuel savings in a year were calculated and presented as follows:

Total operating hours of the kiln in a year	:	7300 hrs.
Heat available at the burning zone (see Table 2)	:	6.050 x 10^9 Joules/hr.
The total heat recovery by the proposed run around system	:	3.025 x 10^9 Joules/hr.
Calorific value of the fuel	:	4.521 x 10^7 J/kg.
Equivalent fuel savings	:	66.91 kgs/hr.
Equivalent fuel savings per year	:	4.884 x 10^5 kgs/year.

It is recommended that the amount of heat around the burning zone of the kiln could effectively be utilized either to preheat the furnace oil or to preheat the primary air.

4. RESULTS AND DISCUSSION

The most important aspect of this type of work was to assign appropriate boundary conditions. In order to streamline the method of evaluation and to facilitate the assessment process the heat transfer was found with certain boundary conditions (as mentioned in the methodology section). For better understanding of the results heat transfer coefficients, heat loss etc. (viz. hr, hc, qr, qc etc.) were determined at each 3 metre length of the kiln.

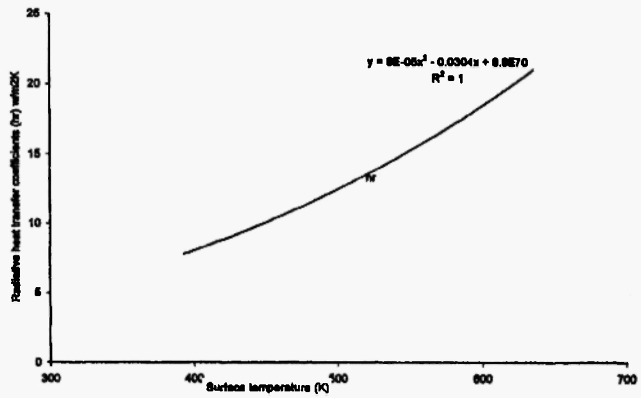

Fig. 5: Effect of surface temperature on heat transfer coefficients

It was observed that surface temperature had a marked effect on the radiative heat transfer coefficients (hr), which can be seen in Fig. 5. The change in the value of hr with surface temperature follows a second order polynomial equation. The respective equation is also presented in the figure. The scattered values of surface temperatures and heat loss (Qr & Qc) along the kiln length as shown in Figures 1 & 6 respectively are indicative of the variant complex factors inside the kiln which may be ring formation by the fused magnesia, thinning of the brick layer due to abrasion and spalling, etc. The distribution pattern of the heat transfer along the kiln surface as shown in Fig. 6 clearly hints at the complexities inside the kiln, which was running for the 128^{th} day. The sudden fall in surface temperature and heat loss in kiln length of 12 metres, 30 metres and around 50 metres as can be seen in Figs. 1 and 6 may be attributed to the ring formation of fused magnesia of different thickness. Thermal conductivity of magnesia decreases /9/ at higher temperatures. The bigger trough in the heat loss pattern may be attributed to the thicker fused magnesia ring. Ring formation is considered as the hazard to the smooth functioning of the kiln and output also becomes affected. A sudden rise in surface

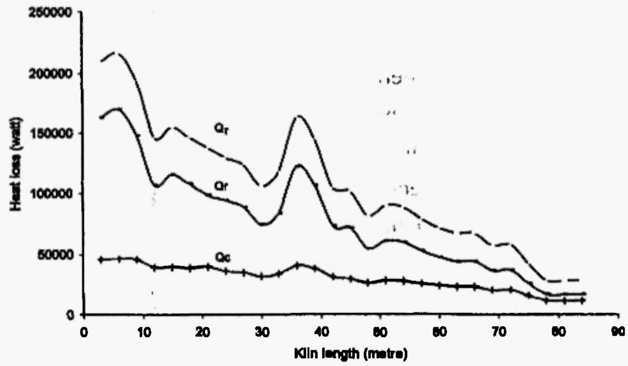

Fig. 6: Heat loss through radiation and convection along the kiln length

temperature and Q_T in the kiln length around 35-40 metres may be due to thinning of the brick layer by abrasion and spalling. Even falling of the brick lining could not be ruled out as the kiln under investigation was on its 128th day of operation.

It was observed that the radiative heat loss is more sensitive toward the surface temperature as compared to convective heat loss, which can be visualized in Fig. 7.

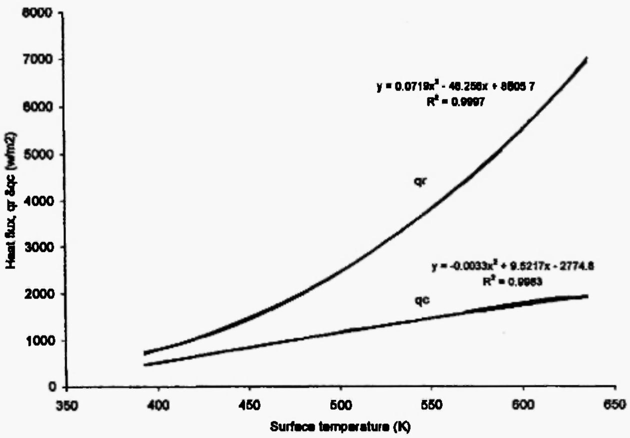

Fig. 7: Effect of surface temperature on heat transfer

In order to correlate the change in heat transfer per unit area with the surface temperature, data were fed into a Microsoft Excel package to develop simplified equations. The equations thus developed for radiation and convection heat transfer are as follows.

$$Y = 0.0719X^2 - 48.256X + 8605.7$$
$$[\text{where, } R^2 = 0.9997]. \qquad (A)$$

$$Y = -0.0033\,X^2 + 9.522\,X - 2774.8$$
$$[\text{where } R^2 = 0.9983] \qquad (B)$$

Radiative heat transfer follows second order polynomial equation A, and convective heat transfer follows the relationship as in equation B.

Results of the calculations corroborate that the heat loss through the 0-33 metre length of the kiln surface was maximum, which amounts to about 56% of the total heat loss through the entire kiln surface (Q_T). The next segment of the kiln, i.e, 33-54 metre, had a heat transfer of about 26% of Q_T. It was determined that the surface heat loss Q_T decreases along the kiln length. Distribution of heat loss at different segments of the kiln can be seen in Fig. 8. The results in Table 2 give

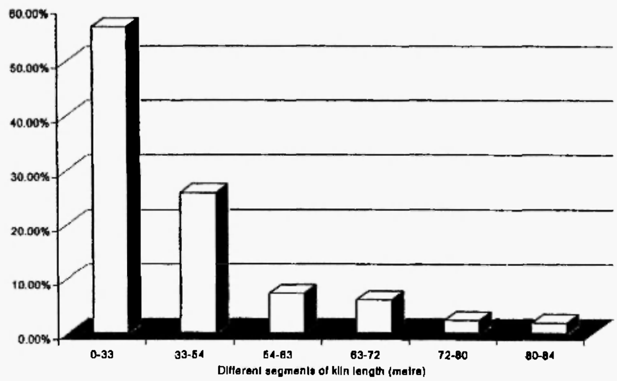

Fig. 8: Heat loss at different segments of the kiln

information on the heat loss at each segment of the kiln, where the brick linings were different in each segment. The results in Table 2 also describe the total heat loss (Q_T), total heat received through fuel burning (Qrecv.) and percentage of total heat loss $\%Q_T$ & %Qrecv. at each segment of the kiln. It was observed that heat loss at the 1st segment of the kiln (0-33metre) equals about 14% of the heat received through fuel burning. Quality and composition of lining materials played an important role as far as heat loss through the kiln shell was concerned. The brick lining materials were subjected to chemical analysis and sp. gravity measurement; the results can be seen in Table 3.

The calculation of recoverable heat from the 1st segment (0-33metre) of the kiln and its equivalent fuel savings yielded the results that if a run around system

Table-2
Distribution of heat along the kiln length.

Heat received from fuel (Qrecv.) (watt)	Total heat loss through the kiln shell (Q_T) (watt)	Kiln length (metre)	Heat loss at each segment (watt)	% Q_T	% Qrecv.
11.9881×10^6	2.9806×10^6	0-33	1.6806×10^6	56.39 %	14.02 %
		33-54	0.7732×10^6	25.93 %	6.45 %
		54-63	0.2174×10^6	7.29 %	1.81 %
		63-72	0.1821×10^6	6.11 %	1.52 %
		72-80	0.0752×10^6	2.37 %	0.59 %
		80-84	0.0568×10^6	1.91 %	0.47 %

Table-3
Composition of lining materials along the kiln length.

Kiln length (metre)	Lining materials and dimensions	Sp. gravity (gms/cc)	Chemical composition						
			L.O.I.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Cr_2O_3
0-33	Magnesia chrome bricks	3.06	0.40	4.52	2.51	7.51	2.45	74.5	8.11
33-54	High alumina bricks	3.2	0.93	18.84	72.45	4.55	2.30	0.93	-
54-63	Molar insulation bricks	2.2	1.03	78.47	9.45	5.67	1.26	4.12	–
63-72	Abrasive bricks	3.0	0.06	46.17	43.25	3.56	3.90	3.06	–
72-80	Cross zone (heat exchangers, chains, etc.	–	–	–	–	–	–	–	--
80-84	Abrasive bricks	3.0	0.06	46.17	43.25	3.56	3.90	3.06	–

could be assumed which had at least 50% recuperative efficiency, then possible fuel saving per year would be about 4.88×10^2 tons.

5. CONCLUSIONS

The present study reveals that a large amount of heat is generated and wasted through the kiln surface, as a consequence of the high temperature required for the dead burning of magnesite for achieving properly sintered magnesia (at a temperature of 1923°K or more) with an appropriate periclase growth. Results obtained in the work were the outcome of a systematic approach towards data acquisition and utilization of the same. However, while comparing the results it has to be borne in mind that the kiln can be judged only after considering the approximations and boundary conditions which were applied in calculating the results. The investigations revealed that the heat loss depends on many items. The following have a major influence on heat loss.

- kiln size
- kiln feed rate
- air velocity
- proper refractory lining
- rotational speed of the kiln
- primary & secondary air etc.

A proper monitoring of the kiln is extremely essential so that the above factors may be regulated properly. This type of work provides data and appropriate information to the management of the company about how the units have been functioning.

Results of heat loss through the surface of the kiln show that in 0-33 metre length, the heat loss was maximum, which was about 56% of the total heat loss through the shell. This fact provides scope for more detailed study in this particular segment of the kiln with regard to its lining materials, surface temperature and factors responsible for heat loss. Results of heat loss in the other segments of the kiln and information about the corresponding lining materials in each segment can be seen in Tables 2 and 3. The knowledge of heat loss at each segment of the kiln and its lining materials would be a tool for the management for further developments and modifications as far as brick lining quality, dimensions and the design of the kiln are concerned.

The present study provides an idea about the probable complexities inside the kiln. It appears from the investigation that a periodic data base for a longer period may be compared to provide more conclusive predictions about the inner complexities of the kiln. However, this work opens up further avenues for studying the complexities of the structural behaviour inside the kiln with the help of the surface characteristics, while the kiln is in operation. It was also observed that an efficient run around mechanism could save substantial amounts of fuel.

NOMENCLATURE

Ts	kiln surface temperature, K.
Ta	atmospheric temperature, K.
Tav	average of Ts & Ta, K
hr	radiative heat transfer coefficient, w/m^2K.
h_{fc}	forced convective heat transfer coefficient, w/m^2K
hc	free convective heat transfer coefficient, w/m^2K.
ε	emissivity.
σ	stefan-boltzmann constant, w/m^2K.
C_2	dimensionless factor that evaluates the effect of solid surface configuration.
k	thermal conductivity of atmospheric air, w/mk
α.	free convection modulus, $1/m^3.K$.
qr	radiative heat loss, $w/m.^2$
q_{fc}	forced convective heat loss, $w/m.^2$
qc	free convective heat loss, $w/m.^2$
Qr	radiative heat loss over the area of 3 metre length, Watt.
Qc	convective heat loss over the area of 3 metre length, Watt.
Qt	total heat loss (Qr+Qc) over the area of 3 metre length, Watt
Q_T	total heat loss (ΣQt) over the entire kiln surface, watt.
A	surface area (πdl) along the kiln length, m^2

REFERENCES

1. John D. Morgan, and V.E. McKelvey. "Ceramics: Energy Update, a Report from the 79th Annual Meeting of the American Ceramics Society", *J. Am. Ceram. Soc. Bull.*, **56**, 586 (1977).
2. Clifford Storey. "Energy and the refractories industry", *Refractories Journal*, 6, 26-28 (1977).
3. I.K. Smithson. "Fuel and energy economy in industry", *Trans. Brit. Ceram. Soc.*, **74** (6), 203 (1975).
4. R.W. Rice. "Hot pressing of MgO with NaF", *J. Am. Ceram. Soc. Bull.*, **54** (4), 205-207 (1971).
5. S.G. Ampian and E.P. Flint. "Effect of silico fluorides on the formation of calcium silicates, aluminates and aluminoferrites", *J. Am. Ceram. Soc. Bull.*, **52**, 604 (1973).
6. V.W. Kuhle. *Zement-Kalk-Gips*, **23**, 263-268 (1970).
7. R. Hilpert. *Forschung a.d. Ingenieurwes*, **4**, 215 (1933).
8. James P. Todd and Herbert B. Ellis, *Applied Heat Transfer*, Harper & Row, New York, 1982; pp. 131, 140-141.
9. J.H. Chesters. *Refractories Production and Properties*, The Iron & Steel Institute, London, 1973; pp. 161, 438.
10. M.W. Thring. *The Science of Flames and Furnaces*, Chapman & Hall Ltd., London, 1962; p. 363.