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Thermal Energy Assessment of Indian Cement Plant Specially Related to Rotary Kiln

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ABSTRACT : *This work is basically, a modeling of rotary cement kiln where objective is to optimize fuel and air consumption. The study aims to optimize on air and fuel quantities at kiln considering design parameters of the cement plant by keeping adequate safety factors at each level of calculations to assure that neither production rate nor quality of clinker vary. The data obtained from industry show that the first law efficiency and the second law efficiency of the kiln system are 50.41% and 61.39% respectively. Irreversibility of the system was found to be about 20%, which is due to the conversion from chemical to thermal energy. Theoretical energy requirement of this plant is 1720 kJ/kg of clinker whereas actual energy supplied is 2286 kJ/kg of clinker .The energy difference is 566 kJ/kg of clinker. Keeping allowance for losses and unaccounted figure still we can reduce actual supply energy up to 2000 kJ/kg of clinker. The study suggests that there is still scope of energy saving up to 12%. This can be achieved by direct and indirect methods i.e. through air optimization, fuel optimization and reduction of losses through kiln wall. Thermal energy consumption reduces from 3.2 GJ/ton of clinker to 3.0 GJ/ton clinker at J. K. Laxmi. Air consumption reduces from 98 TPH to 88 TPH. It saves electrical consumption upto 17% Thus total thermal and electrical energy saving is quantified in terms of rupees that is coming in the range of rupees 18 to 27 million.*

Keywords *- Cement Industry, Thermal Energy, Rotary Kiln, Heat transfer modeling; Energy conservation*

I. INTRODUCTION

Cement industry is considered as one of the large energy consuming industry. It consumes about 4 GJ/t cement produced. Indian cement industry accounts for 10.3% of total fuel consumption in the manufacturing sector. The energy costs account for about 26% of the manufacturing cost of cement. Where, on an average, 25% electrical energy and 75% thermal energy is used as an input energy. The best practice in India for specific energy consumption is reported as 3.06 GJ/t while in some other countries it is even lower than 2.95 GJ/t. for this study heat modeling and thermal performance assessment of kiln is taken up.

II. PLANT DATA

Communication has been taken up with various Indian cement plants whose daily thermal requirement is more than 3 GJ/t of clinker. J.K.Laxmi plant at Sirohi, Rajasthan is selected for further study as they have also attempted blending of coal with waste derived fuel in the past. The plant uses a dry process with a series of cyclone type pre-heaters and an incline-kiln. The kiln is 4.2 m in diameter and 61.17 m long. The average daily production capacity is 4200 TPD, and the specific energy consumption has been estimated to be 3.2 GJ/t of clinker. Figure 1 presents simple schematics of the pyroprocessing showing flow of solid, air and fuel.

III. MASS BALANCE

The following input data i.e. composition of raw meal, ultimate analysis of the fuel, dust content in the exhaust gas, loss of ignition(LOI) and exhaust gas composition in the suspension pre heater were used for the mass balance calculation. The mass balance of the kiln system is summarized in Table 1. All gas streams are assumed to be ideal gases at the given temperatures.

IV. HEAT BALANCE

In order to analyze the kiln system thermodynamically, following assumptions are made:

1. Steady state working conditions.
2. The change in the ambient temperature is neglected.
3. Cold air leakage into the system is negligible.
4. Raw material and coal compositions do not change.
5. Averaged kiln surface temperatures do not change.
6. Feed rate of raw material and coal are considered as constant.

The complete energy balance for the system is calculated and presented in Table 2. Since most of the heat loss sources have been considered, there is only a 397 kJ/kg-clinker of energy difference from the input heat. This difference is nearly 12% of the total input energy and can be attributed to the assumptions and nature of data. The distribution of heat losses to the individual components exhibits reasonably good agreement with reference plant.

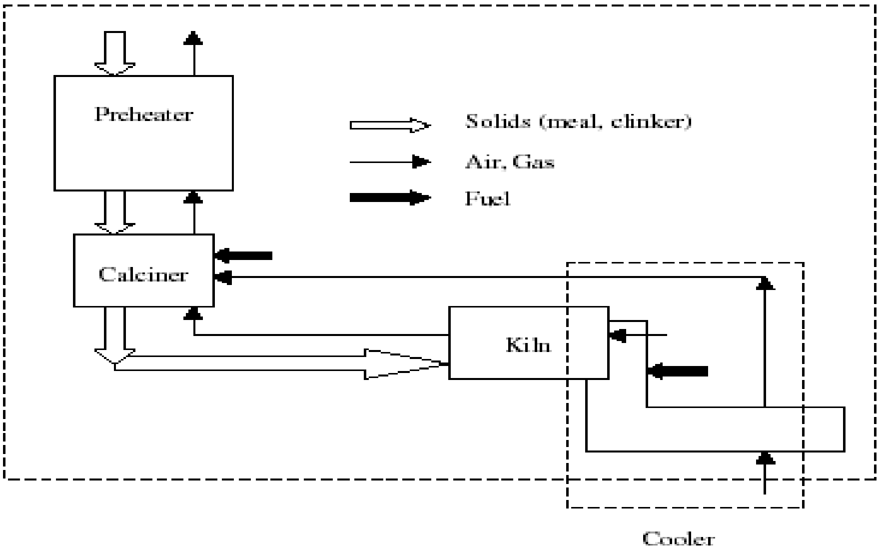


Fig.1 Preprocessing displaying flow of solid, air and fuel.

Table 1: Mass Balance

	Input (Kg/Kg of Clinker)	**Output (Kg/Kg of Clinker)**
Raw material	01.81	-
Cooling air	01.68	-
Coal	00.11	-
Preheater exhaust	-	01.8
Clinker	-	01.00
Cooling dust	-	00.007
Cooler - hot air	-	01.10
Dust from preheater	-	00.048

V. THEORETICAL HEAT REQUIRED (TER) TO PRODUCE ONE KG CLINKER

From K. E. Peray, Cement Manufacturers Handbook following formula is taken to calculate TER and composition of different ingredient is taken from plant data.

$$TER = 4.11 \times H_{Al} + 6.48 \times H_{Mg} + 7.646 \times H_{Ca} - 5.116 \times H_{si} - 0.59 H_{Fe}$$

$$= 411.27 \text{ kcal/kg} = 1719.09 \sim 1720 \text{ kJ/kg of clinker.}$$

Table 2: Heat/Energy Balance

Stream	**Flow rate kg/kg of clinker**	**Sp.Heat kJ/kg ^oC**	**Temp.^oC**	**Enthalpy kJ/kg of clinker**	**Percentage**
Entering the system					
Combustion of coal	0.108	CV=30160*[1]		3016*[1]	93.95
Raw feed	1.81	0.9	80	130.32	4.05
Ambient air	1.68	1.0	35	58.8	1.83
Coal	0.108	0.9	50	4.86	0.15
Total				**3210**	**100**
Leaving the system					
Reaction energy	-	-	-	1657.11*[2]	51.62
Clinker	1.00	0.8	220	176	5.48
Preheater exhaust	1.80	1.0	325	585	18.22
Hot air from cooler	1.10	1.0	340	374	11.65
Heat loss by dust	0.05473	1.09	340	20.28	0.63
Losses	-	-	-	397.59	**12.39**
Total				**3210**	**100**

*[1] Calorific Value (CV) = 80.8 x C + [(287 x $H_2 - O_2 / 8$)] + 22.45 x S – 6 x H_2O kcal/kg.

*[2] Reaction energy = 17.196 x Al_2O_3 + 27.112 x MgO + 32 x CaO – 21.405 x SiO_2 – 2.468 x Fe_2O_3 kJ/kg clinker.

VI. HEAT TRANSFER MODELING OF ROTARY CEMENT KILN

After estimating TER, modeling for actual thermal energy requirement for rotary kiln has been taken up. Heat transfer modeling of rotary kiln are analyzed and discussed here.

6.1 Heat generation due to combustion of fuel within the kiln

Heat generated is transferred to various components within the kiln and its transmission takes place to the material at relatively lower temperature. Mode of this heat transfer is very complex, as it not only involves the gas and solid but also the rotating kilns. Further, complexity is caused due to the presence of dust, flames in the gas and cyclic temperature variation at the inside wall as it repeatedly gets covered and exposed by the bed of material. Moreover, heat utilization in the process depends on the heat generated due to combustion, heat gained by incoming flue gas, heat lost through the reactor wall and heat carried away by the outgoing flue gas. The coal and air consumption rate is decided by the constituent energy balance requirement of the process.

6.2 Total heat requirement

Combustion of flue gas over bed at selected locations and fuel within the bed of material increases the temperature of flue gas and bed respectively. Table 3 indicates the temperature of the flue gas, solid and wall at seven equidistant locations in the kiln.

6.3 Estimation of total heat requirement at any stage

The estimation of total heat requirement consists of the following steps.

6.4 Heat gained by the bed of material

$$Q_s = M_s C_s (t_{sm} - t_{s\infty}) \qquad (1)$$

Where, Q_s is heat transfer rate kJ/h to solid ,M_s is solid material feed rate (TPH),C_s is specific heat of the soild kJ/kg ^{o}C [13], t_{sm} is the maximum temperature (°C) of solid inside the kiln and $t_{s\infty}$ is the ambient temperature (°C) of the solid.

Table 3: Measured inside temperature (°C) at various location of kiln

Kiln capacity, TPH, kiln size, D(m), L(m)	**t_{g1}, t_{s1}, t_{w1}**	**t_{g2}, t_{s2}, t_{w2}**	**t_{g3}, t_{s3}, t_{w3}**	**t_{g4}, t_{s4}, t_{w4}**	**t_{g5}, t_{s5}, t_{w5}**	**t_{g6}, t_{s6}, t_{w6}**	**tg7 ts7, t_{w7}**
175	1050	1140	1250	1380	1950	2080	1350
4.217	940	980	1030	1100	1260	1370	1300
61.14	820	828	836	850	863	900	871

6.5 Heat lost through the kiln wall and refractory

$$Q_{lk} = (t_{ki} - t_{ko})/[(1/ h_{ri}A_{ri})+(1/2\pi\ k_rL).\ \ln(D_{si}/ D_{ri})+1/(2\ \pi\ k_sL).\ln(D_{so}/ D_{si})+(1/ h_{\infty} A_{so}) \qquad (2)$$

Where, Q_{lk} is rate of heat loss (kJ/h) through kiln/reactor wall, t_{ki} and t_{ko} are inside and outside temperatures (°C) of the kiln shell respectively, h_{ri} and h_{∞} are heat transfer coefficients (W/m^{2}°C) of rotary kiln at inside refractory and at the outer shell respectively. A_{ri} and A_{∞} are areas (m^{2}) of rotary kiln at inside the refractory and at the outer shell respectively, L is length (m) of the rotary kiln, K_r and K_s are thermal conductivities (W/m°C) of refractory and kiln shell respectively, D_{si} and D_{ri} are inside diameter (m) of kiln shell and inside diameter (m) of the refractory respectively. D_{so} is outside diameter (m) of the shell.

Actual heat lost through wall includes not only the heat lost through kiln shell but also through shells of inlet hood, outlet hood of rotary kiln, preheater surface and inlet area of cooler. Outer combined areas as mentioned is almost twice then that of the kiln and therefore Q_{lt} is taken as two times the $Q_{lk.}$

6.6 Heat required for the calcinations process to continue is as follows

Major chemical reaction were considered in the present model, are:

$CaCO_3 = CaO + CO_2$ 43740 kcal/kmol (3)
$CaO + SiO_2 = C_2S$ -33240 kcal/kmol (4)
$Cao + C_2S = C_3S$ 470 kcal/kmol (5)
$3CaO + Al_2O_3 = C_3A$ - 5800 kcal/kmol (6)
$4CaO + Al_2O_3 + Fe_2O_3 = C_4AF$ -12000 kcal/kmol (7)

Reaction (3) indicates that a great amount of heat is required for desired calcination/ transformation to takes place. Q_p is calculated in kJ/h (8)

Total heat required Q_t for the process at any stage:

$$Q_t = Q_s + Q_{lt} + Q_p \quad .... \text{kJ/h} \qquad (9)$$

The values of Q_s, Q_{lt}, Q_p and Q_t are estimated for the plant and presented in following Table4

Table 4: Estimated heat requirement against heating of bed of material, heat loss

Capacity (TPH),	**D (m),**	**L (m)**	**Q_s kJ/h Eq.1 (I)**	**Q_{lt} kJ/h Eq.2 (II)**	**Q_p kJ/h Eq.8 (III)**	**Q_t kJ/h (IV= I+II +III)**
175	4.217	61.14	4399×10^5	7.4×10^5	5942×10^5	10348×10^5

6.7 Mechanism of Heat transfer

The mechanism of heat transfer is very complex because it involves not only the gas and solid, but also wall of rotating kiln. Apart from the conduction through kiln wall, entire heat transfer involves four following steps.

- Gas - to - solid by radiation and convection (Q_{gs})
- Gas - to - wall by radiation and convection (Q_{gw})
- Exposed wall - to - solid by radiation (Q_{wes})
- Covered wall - to - solid by radiation and convection (Q_{wcs})

Estimation of above mentioned heat transfer steps are carried out using optimistic operational data on temperature along the various locations of the kiln using following empirical relations.

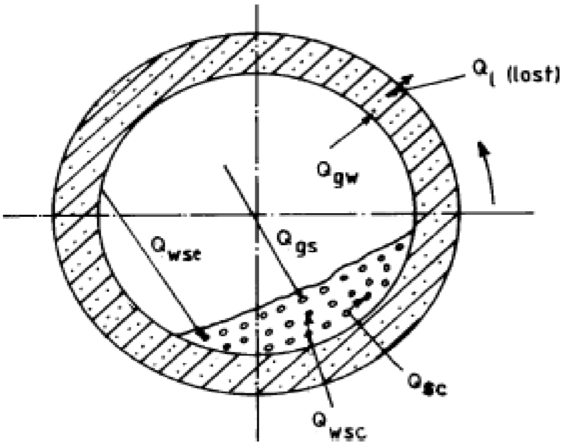


Fig. 2 Heat flow path in a rotary kiln

Fig.2 represents heat flow path in a rotary kiln.

6.8 Gas - to – solid

The equation governing the heat transfer from gas to solid is

$$Q_{gs} / A_{se} = \{\sigma / [(1/\varepsilon_g + 1/\varepsilon_s - 1)]\}(T_g^4 - T_s^4) + h_{gs} (T_g - T_s) \qquad (10)$$

Where, A_{se} is the exposed solid surface, s is Stefan-Boltzman constant (kW/m^{2}K^4), ε_g and ε_s are emissivity of gas and solid respectively. Solid and gas emissivity are taken as 0.9 and 0.4 respectively. Tg and Ts are the fourth power average temperature (K), Tg and Ts are the arithmetic average temperatures of gas and solid respectively, and subscript gs is used for gas to solid, se for solid exposed, g for gas and s for solid. h_{gs} is convective heat transfer coefficient (W/m^2°C) from gas to solid.

$$\text{Also,} \quad T_g = \Sigma T_{gi} A_i / \Sigma A_i \; ; \; T_g^4 = \Sigma T_{gi}^{\ 4} A_i / \Sigma A_i \qquad (11)$$

6.9 Gas - to – wall

The equation governing the heat transfer from gas to wall is

$$Q_{gw} / A_{we} = \{\sigma / [1/\varepsilon_g + 1/\varepsilon_w - 1]\} (T_g^4 - T_w^4) + h_{gw} \{T_g - T_w\} \qquad (12)$$

Where, A_{we} is the exposed wall surface, subscript gw is gas to wall and we is wall exposed. The wall emissivity may be assumed as 0.9.

6.10 Exposed wall - to - solid

The equation governing the heat transfer from exposed wall to solid is

$$Q_{wes} / A_{se} = \{\sigma /[(1/\varepsilon_w)+(1/\varepsilon_s)-1]\} \{T_{wes}^4 - T_s^4\} \qquad (13)$$

where, T_{wes} is temperature (K) of exposed surface of the kiln wall and subscript wes is exposed wall to solid, se is solid exposed, w is wall and s is solid.

6.11 Covered wall - to -solid

The equation governing the heat transfer from covered wall to solid is

$$Q_{wcs} / A_{sc} = \{\sigma /[1/\varepsilon_w+1/\varepsilon_s-1]\} \{T_{wcs}^4 - T_s^4\} + h_{ws} (T_{wcs} - T_s) \qquad (14)$$

Where, wcs is covered wall to solid and T_{wcs} is temperature (K) of covered surface of the kiln wall and $Q_{ws} = Q_{wcs} + Q_{wes}$, taking $T_w \sim T_{we}$, A_{se} is unexposed/covered solid surface, A_{sc} is covered solid surface and $A_s = A_{se} + A_{sc}$.

Plant wise estimation of above mentioned heat transfers is carried out and presented in table 5.

Table 5Estimated value of various heat transfer rate

Capacity (TPH), & area, A_{we},A_{se}, A_{sc},A_c(m^2)	**Q_{gw}** kJ/h (I)	**Q_{gs} kJ/h (II)**	**Q_{ws} kJ/h (III)**	**Q_{cs} kJ/h (IV) = (I - II)**	**Q_s kJ/h (V) = (II+III + II)**	**Q_s kJ/h (VI)**	**%Error**
175 304,212 292,504	2454 x 10^5	1300 x 10^5	11195 x 10^5	- 8741 x 10^5	3754 x 10^5	4399 x 10^5	15.58

Based on the data of temperature of gas, wall and solid at various locations along the bed of material, heat gained by material (Q_s) from Eq.1, heat loss through the reactor system wall (Q_{lt}) from Eq.2, heat required (Q_p) from Eq.8 and the total heat rate required for the process to continue are calculated and tabulated in Table 4. Estimated values of Q_{gw}, Q_{gs}, Q_{ws} are mentioned in Table 5. Moreover Q_s, the estimated heat transfer to solid (Table 4), is found more than some heat rate estimated in Table 5. This difference however, is due to inadequate selection of various constants of the empirical relations. These are found to vary within 10-15% and hence the mentioned procedure may be utilized for design and estimation of the size of the rotary reactor.

VII. FIRST LAW, SECOND LAW AND IRREVERSIBILITY

From a thermodynamics perspective, all natural processes are irreversible. The phenomenon of irreversibility results from the fact that if a thermodynamic system of interacting molecules is brought from one thermodynamic state to another, the configuration or arrangement of the atoms and molecules in the system will change as a result of dissipative effects A certain amount of "transformation energy" will be used as the molecules of the "working body" do work on each other when they change from one state to another. During this transformation, there will be a certain amount of heat energy loss or dissipation due to intermolecular friction and collisions; energy that will not be recoverable if the process is reversed. Figure shows rotary kiln system under consideration for irreversibility calculation.

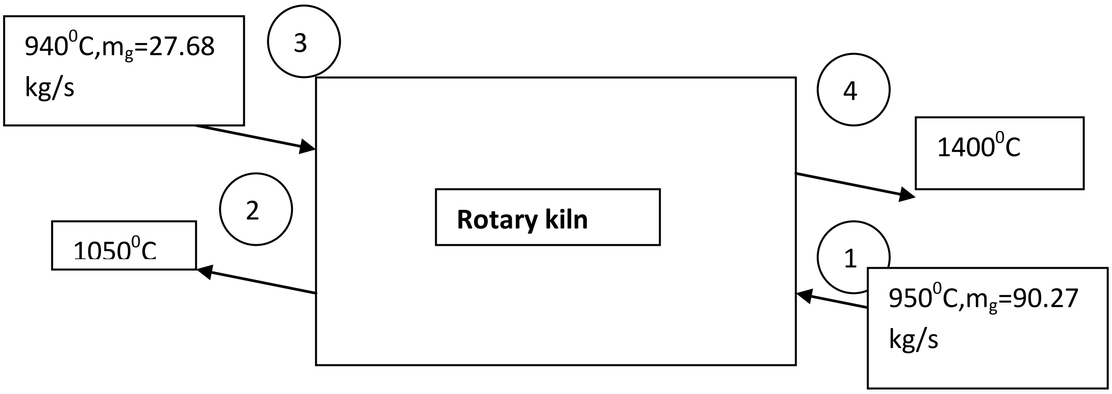


Fig. 3 Rotary kiln mass flow rate and temperature at inlet and outlet

$S_{gen} = m_m \times (S_4 - S_3) - m_g \times (S_2 - S_1)$
$= 23.912$ kJ/kg K

Irreversibity / Lost work = $T_\infty \times S_{gen} = 308 \times 23.912 = 7364.89$ kJ/kg

Now, efficiency is ratio of output upon input or simply a ratio of what we get and what we pay.

First law efficiency (η_I) = Reaction energy / heat supplied
= 50.41 %
Second law efficiency (η_{II}) = $(\eta_I) / (1 - T_\infty / T_H)$
= 61.39 %

VIII. FUEL AND AIR MASS OPTIMIZATION AT ROTARY

Thermal as well as electrical energy used currently can be reduced to optimum value without affecting the production rate and the quality of the clinker and subsequently of the cement. Each type of energy saving is described below:

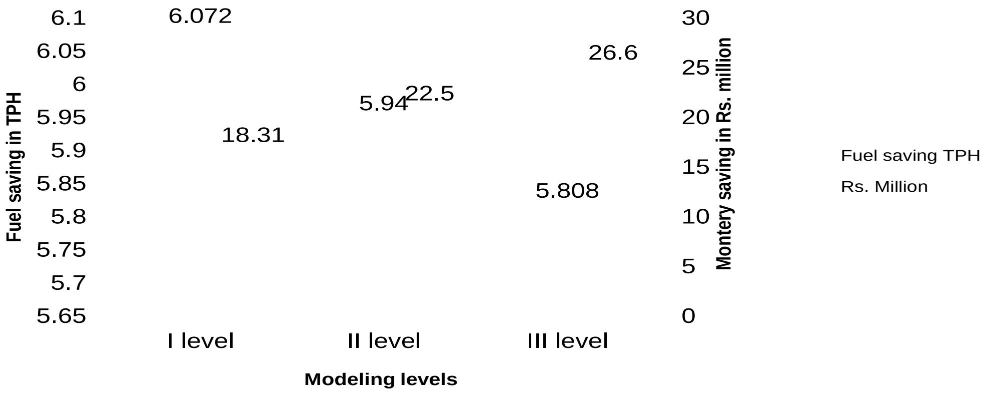
8.1 Thermal Energy

Actual fuel supplied at J.K.Laxmi cement plant is 18 TPH. Out of total fuel, 60% fuel is used in Precalciner and remaining 40 % is used in the kiln.Above value is taken as a reference for various modeling levels. It is tabulated in following Table 6.

Table 6: Fuel Consumption At Various Stage Of Modeling Taking Level 1 As 8% Saving; Level 2 As 10% And Level 3 As 12%

Level	**Fuel consumption at J.K.Laxmi cement plant**			**Difference in fuel consumption after modeling**	**% Saving**
	TPH	**TPD**	**TPA**		
Actual	6.6	158.4	52272	---	---
Level 1	6.072	145.73	48090.24	4181.76	8
Level 2	5.94	142.56	47044.8	5227.16	10
Level 3	5.808	139.39	45999.36	6272.64	12

From above table fuel saving is estimated in the range of 0.003 to 0.005 kg/kg clinker/hr. Taking cost of the fuel as Rs.4000 per ton .Saving in terms of rupees can be estimated.



8.2 Electrical Energy

From J. K. Laxmi cement plant it can be seen that the fixed carbon in the fuel used is 78.63% and hydrogen is 3.6%. It is an established fact that there is 21% oxygen and 79% nitrogen present in the air. It is found true even in the case of plant environment due to stringent pollution control**.**

To calculate excess air following correlations are used

Theoretical CO_2 generated = moles of CO_2 / total moles

= [6.5525 / 7.6409] x 100

= 85.75 %

Actual CO_2 generated = 36.52 %

% Excess air supplied = { [The. CO_2 / Act. CO_2] –1 } x 100

= 134.8 % Thus, 34 % excess air is supplied to the plant.

IX. RESULT AND DISCUSSION

From mass balance calculation 1.8 unit raw feed (kg/kg clinker) is required to produce 1 unit of clinker it is slightly more than other plant data where it is 1.5. TER is about 1600 kJ/kg clinker but in this case it is calculated and estimated as 1720 kJ/kg clinker which means specific energy consumption in Indian cement plant is more and the reason behind that is the harder raw material and poor quality of the fuel. Heat balance suggests that there are 12.6% of unaccounted losses. Thermal efficiency of plant is 50.41%. Second law efficiency comes around 61.39%. As fuel is used for combustion, a conversion of chemical energy into heat energy is associated with irreversibility. This can be calculated as lost work from entropy generation. It is estimated around 20% of the total heat supplied. To validate the results error analysis is carried out between actual heat gain by bed of material and different modes of heat transfer inside the kiln. Error between these two equations is 15.5% which is within acceptable limit .This level of error has probably occurred due to approximate values of different areas such as expose to the gas, wall etc. In Level 1 modeling 8% saving is achieved that results in thermal energy saved as 3.1 GJ/ton clinker and after fine tuning it comes up to 3 GJ/ton clinker in Level 2 and Level 3. This thermal energy saving is achieved by optimizing the fuel. As fuel requirement is reduced down, so air supply also reduces from 98 TPH to 86 TPH, which is around 17% of actual supplied air.

X. CONCLUSION

The outcome of the study confirms that there is a significant scope of thermal heat input reduction in the Indian cement industry. The study tried to reduce air and coal quantities at kiln considering design parameters of the J.K.Laxmi cement plant by keeping adequate safety factors at each level of calculations to assure that neither production rate nor quality of clinker varies. Thermal energy consumption reduces from 3.2 GJ/ton of clinker to 3.0 GJ/ton clinker. Air consumption reduces from 98 TPH to 88 TPH. It saves electrical consumption up to 17% Thus total thermal and electrical energy saving is quantify in terms of rupees that is coming in the range of rupees 18 to 27millions. This work has high replicability as similar heat transfer modeling can be applied to other cement plants globally.

Acknowledgements

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