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Energy Audit and Heat Recovery on the Rotary Kiln of the Cement Plant in Ethiopia: A case study

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Abstract— *This study deals with the energy audit and heat recovery on the rotary kiln taking a cement factory in Ethiopia as a case study.The system is a dry type rotary kiln equipped with a five stage cyclone type preheater, pre-calciner and grate cooler. The kiln has a capacity of 2,000 tons/day.Mass and energy balance has been performed for energy auditing. The energy lost from the kiln shell is about 4.3 MW. By using secondary shell on the rotary kiln about 3.5MW could be recovered safely.This energy saving reduces fuel consumption (almost 9%) of the kiln system, and increases the overall system efficiency by approximately 2–3%.*

Keywords*— *Rotary kiln; Energy audit; Heat recovery; Secondary shell.

I. INTRODUCTION

Cement production is an energy consuming process and requires about 4 GJ per ton of cement product. In order to produce one ton of clinker at least 1.6 GJ heat is needed [1]. However, now days, it is about averagely2.95 GJ energy is consumed per ton of cement for advanced kilns, but in some countries, the consumption exceeds 5 GJ/ton. For example, the average energy requirementof Chinese key plants to produce clinker is 5.4 GJ/ton [2].

The energy audit is the most effective procedures for good and well energy management program [3]. The main purpose of energy audits is to give an accurate account of energy requirement and use analysis of different components and to provide the detailedinformation needed for determining the possible opportunities for energy conservation. There are potential ways to improve overall kiln efficiency likewaste heat recovery from hot gases and hot kiln surfaces[3,4]. However, it is difficult to make a detailed thermal analysis of rotary kiln systems in the open literature. This study focuses on the energy audit and heat recovery of a horizontal rotary kiln system, by usingMessebo Cement Plant line-1 in Ethiopia. First a detailed thermodynamic analysis of the kiln system is made and then, mechanismof heat recovery from the kiln shell heat loss sources are discussed.

II. PLANT AND PROCESS DESCRIPTION

Rotary kilns are refractory lined tubes and have a diameter up to 6 m. Rotary kilns are generally rotates with a speed of1–2rpm and inclined at an angle of 3–3.5^0. By using cyclone type pre-heaters raw materials are preheated before enters the kiln intake. Pre-calcination is started in the pre-heaters, and almost one third of the raw material would be pre-calcined at the end of pre-heating in the current dry rotary kiln system[5].

The physical appearance of our rotary kiln is refractory lined tubes with a diameter of 3.8m and 57 m length and has a capacity to produce 2,000 tons/day. It is dry process rotary kiln equipped with five stage cyclone preheaters and pre-calciner kilns and grate coolers. The system of the cement production mainly includes following steps:

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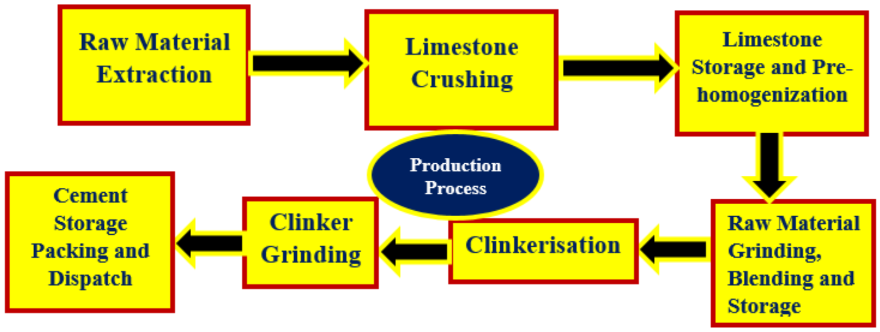

Fig.1: The overview of cement production process

III. THERMODYNAMIC ANALYSIS AND HEAT RECOVERY OF ROTARY KILN

3.1 Assumptions

The following assumptions are made toanalyze the rotary kiln thermodynamically

a) The systemis steady state, steady flow and open.

b) Ambient temperature are constant throughout the study i.e. $T_0 = 297K$.

c) The composition of raw material and coal material and feed rate of both are constant.

e) The velocity of atmospheric air is < 3 m/s.

f) The temperature of kiln shellis constant throughout the study.

g) Consider the gases inside the kiln as an ideal gas.

3.2 Mass Balance

It is usually more convenient to define mass/energy data per kg clinker produced per unit time.

Table.1: Raw materials and clinker components and their percentages

Component	Raw Material (%)	Clinker (%)
SiO_2	13.4	21.1
Al_2O_3	3.2	4.08
$Fe_2 O_3$	2.4	4.01
CaO	42.35	66.44
MgO	1.71	2.42
SO_3	0.4	1.15
K_2O	0.27	0.5
Na_2O	0.09	0.3
H_2O	0.01	---
Organics	0.8	---
Ignition loss	35.4	---
Total	100	100

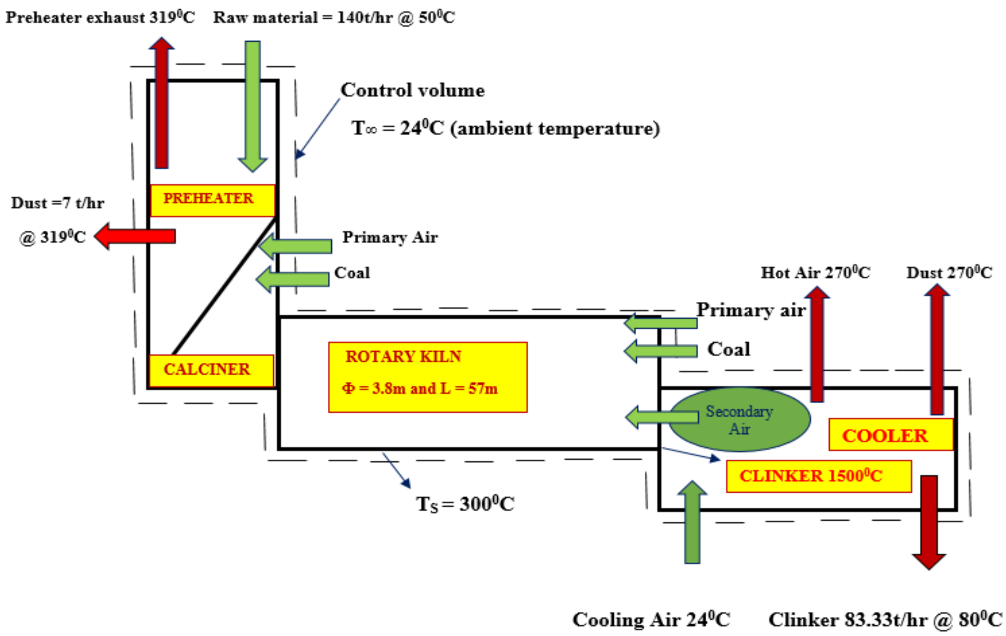

Fig.2: Control volume, various streams and components for kiln system.

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3.3 Energy Balance

Based on the collected data,the energy balance is applied to the kiln system. By using Zur-Strassen equationthe energy used for clinker formation can be found [6,7].

Clinker formation energy = 17.196(Al_2O_3) + 27.112(MgO) + 32(CaO) - 21.405(SiO_2) - 2.468(Fe_2O_3)

By using Dulong's formula the GCV (Gross Calorific Value) of the coal is found [8].

GCV = 337 x C + 1442 (H – O/8) + 93 x S

Table.2: Percentage composition of Coal

Element Content	Percentage (%)
C	73
H	3.5
O	6
N	1.75
S	1.59
Ash	3.01
Moisture	0.309
Volatile	4.67
Fixed Carbon	9.05

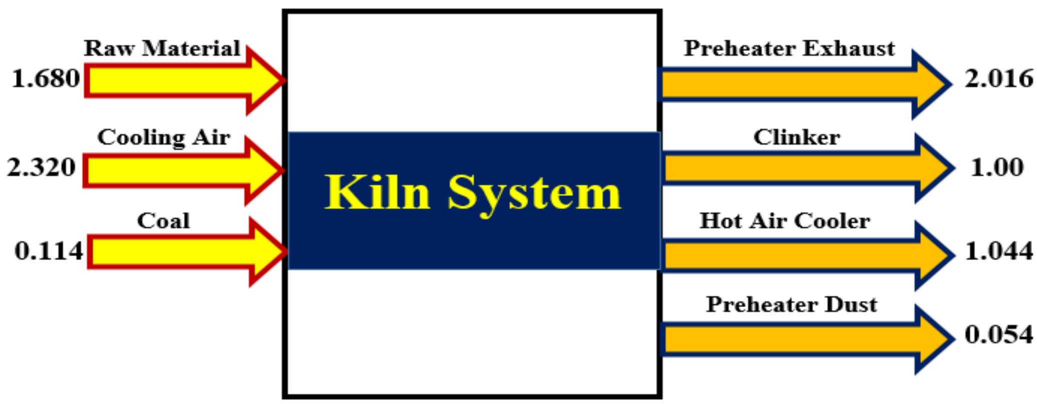

Fig.3: Mass balance of the kiln system.

Note: All the above data are taken from CCR (Central Controlling Room) from Messebo Building Material Production (MBMP) Line-I, Mekelle (Ethiopia) when the plant is under working condition by using averages and interpolation.

Heat Inputs

1. Combustion of Coal (95.22%)
   $Q_1 = M_c H_c = 3358.25$ kJ/kg-clinker M_c=0.114kg/kg-clinker H_c=29,458.32kJ/kg
2. Sensible heat by coal (0.19 %)
   $Q_2 = M_c H_c = 6.9$ KJ /kg-clinker, H_c= CT C=1.15kJ/kg^{0}C T=50^{0}C
3. Heat by Raw material (2.05%)
   $Q_3 = M_{Rm} H_{Rm} = 72.24$ kJ /kg-clinker, H_{Rm}= CT C=0.86kJ/kg^{0}C T=50^{0}C
4. Organics in the kiln feed (0.54%)
   $Q_4 = FKh_{or}$= 18.93 kJ /kg-clinker, F=0.10, K=0.009, h_{os} =21,036 kJ/kg (Ref. [6])
5. Heat by cooling air (2%)

$Q_5 = M_{ca} H_{ca}$ = 70.5 kJ /kg-clinker, H_{ca} = 30 kJ/kg

6. Total heat inputs
   $Q_T = {}_{i=1}\sum^5 Q_i$= 3526.82kJ/kg (100%)

Heat Outputs

1. Kiln exhaust gas (19.53%)
   $Q_6 = M_{ex} C_{ex} T_{ex}$= 688.76kj/kg-clinker C_{ex}

=1.071 kJ/kg^{0}C, T =319^{0}C

2. Heat loss by dust (0.42%)
   $Q_7 = M_D h_D$= 14.85kj/kg-clinker $h_{dust;ave}$= 275 kJ/kg (Ref. [6])
3. Hot air from cooler (16.22%)
   $Q_8 = M_{Ha} h_{Ha}$= 571.87kj/kg-clinker h_{Ha}=547.77kJ/kg(@T=270^{0}C)
4. Clinker discharge (2.02%)
   $Q_9 = M_{clinker} h_{clinker@80^0C}$ = 71.09kj/kg-clinker
5. Clinker formation (51.04%)
   Q_{10}=1800kj/kg-clinker
6. The combined effects of conduction, convection and radiation on the kiln shell is calculated below and has the heat lost from kiln surface (5.27%)
   Q_{11}=4.3MW=185.94kj/kg-clinker
7. Radiation from pre-heater surface (0.23%)
   $Q_{12} = \sigma \varepsilon A_{ph}(T_s^4 - T_\infty^4) / 1000 M_{clinker}$ = 8.11kj/kg-clinker

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σ=5.67 $*10^{-8}$ W/m^2 K^4, $\mathcal{E}$=0.78, A_{ph} =264m^2, T_{PHs} =393K, T_∞=297K,

8. Natural convection from pre-heater surface (0.3%)

$Q_{13}=h_{ncon}A_{ph}(T_s-T\infty)/1000M_{clinker}$ = 10.61kj/kg-clinker

$h_{ncon}=K_{air}*Nu/L_{ph}$; Ra=5.35*$10^{13}$, Nu=0.1$(Ra)^{1/3}$ Nu=3768.06 (Ref. [8]), T_f=72^{0}C (film temp.)

9. Radiation from cooler surface (0.11%)

$Q_{14}=\sigma\mathcal{E}A_c(T_s^4-T\infty^4)/1000M_{clinker}$=3.8kj/kg-clinker

σ=5.67 $*10^{-8}$ W/m^2 K^4, $\mathcal{E}$=0.78 (oxidized surface, Ref. [8]), A_C=144m^2, T_{Cs} =383K, T_∞=297K, $M_{clinker}$ =23.15kg/s

10. Natural convection from cooler surface (0.07%)

$Q_{15}=h_{ncon}A_c(T_s-T\infty)/1000M_{clinker}$ = 2.6kj/kg-clinker

$h_{ncon}=K_{air}*Nu/L_C$, Ra=7.89*10^{12}, Nu=0.1$(Ra)^{1/3}$

Nu=1991, L_C =12, T_f=67^{0}C(film temp.)

11. Moisture in raw material and coal (0.69%)

$Q_{16}=m_{water}(h_{fg@50^0C}+h_{g@319^0C}-h_{g@50^0C})$=24.41kj/kg-clinker

$h_{fg@50^0C}$=2384kj/kg, $h_{g@50^0C}$=2591kj/kg, $h_{g@319^0C}$=2700kj/kg, m_{water}= 0.0098kg/kg-clinker

12. Unaccounted heat losses (4.1%)

Q_{17}=144.78kj/kg-clinker

13. Total heat output

$Q_T=\sum_{i=1}^{17}Q_i$=3526.82kj/kg-clinker (100%)

The heat is transferred from the rotary kiln shell to the surroundingdue to the temperature difference between inner and outersurface of the rotary kiln. This heat is transferred by three mechanisms such as conduction, convection and the radiation. These mechanismsare assumed as the heat loss that can be conserved somehow. The heat lost from the rotary kiln surface to the environment is determined from the following equation [9,10,11].

$Q_{total} = \frac{T_{in} - T_{out}}{R_{total}}$ where, $R_{total} = R_{cond\ I} + R_{cond\ II} + \frac{R_{conv}*R_{rad}}{R_{conv}+R_{rad}}$

$R_{cond} = \frac{\ln(\frac{r_{out}}{r_{in}})}{2\pi*l*k}$, $R_{conv} = \frac{1}{A*h}$, $R_{rad} = \frac{1}{A*E}$

Where: R_{total} is the total heat resistance,

A is the area of the rotary kiln = π x L x d while length of kiln is 57m and the diameter is 3.8m,

k is the thermal conductivity of bricks lining (2.7-1.5 W/mK) [12] and kiln shell (27 W/mK) [13],

h is the natural convective coefficient &E is the radiative heat transfer and is calculate below [10].

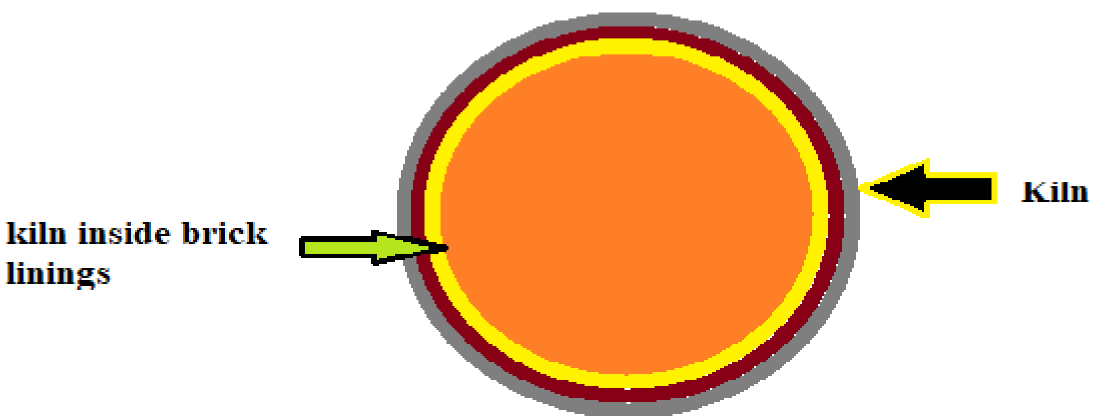

Fig.4: The rotary kiln transverse cross section

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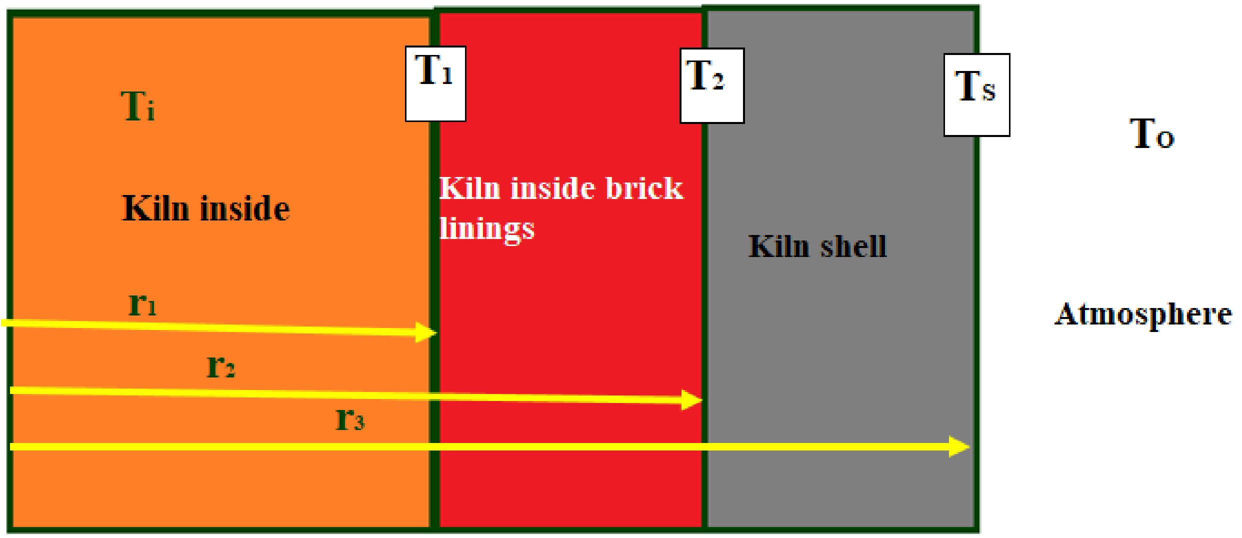

Fig.5: The rotary kiln shell longitudinal cross section

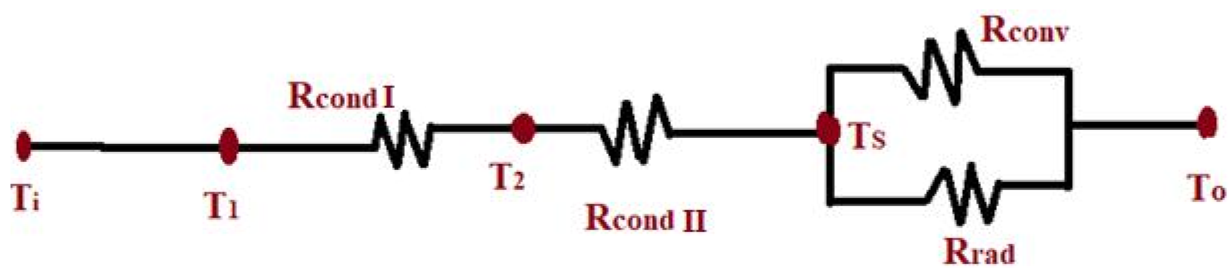

Fig.6: Kiln shell resistance equivalent circuit diagram

The heat transfers coefficient (h) and the heat flux (E) is given by:

$$h = \frac{Nu * K}{d}$$

$$E = \sigma * \varepsilon * F_{12} * ({T_S}^2 + {T_O}^2)(T_S + T_O)$$

Where, ε is the emissivity of the surface (0.78 for oxidized surface), and σ is Stefane-Boltzman constant as 5.67 x 10-8 W/m^2 K^4, F_{12} is View factor that takes (=1)and Nu is Nusselt number.

Consider the thickness of the shell and brick linings is 25mm and 100mm respectively; hence,

$R_{cond\ I} = \frac{\ln(\frac{r_2}{r_1})}{2\pi * l * k} = 56.67 * 10^{-60}$C/W

$R_{cond\ II} = \frac{\ln(\frac{r_3}{r_2})}{2\pi * l * k} = 1.37 * 10^{-60}$C/W

$R_{conv} = \frac{1}{A * h} = 7.66 * 10^{-60}$C/W since the film temperature T_f=1035K and then

$h = \frac{Nu * K}{d}$ =191.84W/m^2 ^{0}C where NU=0.59(Ra)$^{1/4}$

$R_{rad} = \frac{1}{A * E}$ =9.17 $* 10^{-60}$C/W; $E = \sigma * \varepsilon * F_{12} * ({T_S}^2 + {T_O}^2)(T_S + T_O)$= 16.03W/m^2 ^{0}C

$R_{total} = R_{cond\ I} + R_{cond\ II} + \frac{R_{conv} * R_{rad}}{R_{conv} + R_{rad}}$=65.11 $* 10^{-60}$C/W

$Q_{total} = \frac{T_{in} - T_{out}}{R_{total}} = \frac{(300-24)\,0C}{65.11 * 10^{-6}0C/W}$ ≅4.3MW

IV. HEAT RECOVERY FROM THE KILN SYSTEM

The overall system efficiency is given by η=$Q_{10}/Q_{Total\ input}$ = 1800/3526.82 =0.5104 or 51.04% which is relatively low as compared to some kiln systems operating at full capacity that have an efficiency of 55% operated on the current dry process methodology. In order to improve the overallefficiency of the kiln system some of the heat losses should be recovered. The recoveredheat energy can be used for various purposes, like boilingof hot water as well aselectricity generation. There are some major heat losses butin this study we would like to recover the heat lost from rotary kiln surface by using secondary shell system due to effective cost and easy installation.

4.1. Heat recovery from kiln surface

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The heat loss through conduction, convection and radiation forced to account a waste energy of 4.3MW(5.27%) of the input energy. Hence, this heat losseffectively reduced byusing secondary shell on the kiln surface.In this case insulating the kiln surface is unnecessary since the kiln shellhave to be repeatedly seen by the controller to observe any local burning on the surface because ofrefractory loss inside the kiln. The workingprinciple of secondary shell system is shown in Fig. 7.

Consider our rotary kiln, D_{kiln} =3.8 m, and a diameter of D_{shell}=4.2 m. Hence;the distance between the kiln and shell is relatively small (40 cm), we have to estimate the temperature of the secondary shell which is close to the actual one i.e. T_2= 280^{0}C = 553 K. We have to selectgood secondary shellmaterial for our purpose. Stainless steel (AISI 316) is selected due to low surface emissivity and thermal conductivity. The heat transfer rate by radiation is determined by: [7,9]:

$$Q_r = \frac{A_{kiln}\sigma(T_1{}^4 - T_2{}^4)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{D_{kiln}}{D_{shell}}\right)} = 186\text{kW}$$

Where; σ=5.67 x 10-8 W/m^2 K^4, T_1=T_S=573K,ε_1 = 0.78 (for oxidized kiln surface) and ε_2 =0.35 (lightly oxidized stainless steel).

This heat lost is transferredto the secondary shell through the insulation. In order to determineinsulation thickness,considera reasonable temperature for the insulationouter surface.The thermal conductivityfor glass wool insulation, is taken as 0.04 W/mK. Hence, the insulation layer resistance is given by:

$$\text{Resistance of insulation} = \frac{\ln\left(\frac{D_{ins}}{D_{shell}}\right)}{2\pi L_{kiln} K_{ins}}$$

Considering a temperature difference of ΔT_{ins}= 250^{0}C (i.e. outer surface temperatureis 50^{0}C), D_{ins} can be determined:

ΔT_{ins}= Q * R_{ins}

$$250^0\text{C} = 187000 * \frac{\ln\left(\frac{D_{ins}}{4.2}\right)}{2\pi * 57 * 0.04} = \quad D_{ins} = 4.285\text{m}$$

The insulation thicknessbecomes:

Thickness = D_{ins}-D_{shell}=85mm

Theconvective and radiative heat transfer would become highly reduced when the secondary shell is applied onto the kiln surface. This is due to very low temperature difference in the gap. Hence, the total energy savings due to the secondary shell would become:

4300 -186 = 4114kW

Hence, we conclude that by using secondaryshell on the current kiln surface could save at least 3.5 MW safely, that is 8.4% of the total input energy. This high amount of energy saving leads as to reduce fuel consumption (almost 9%) of the kiln system, and increases the overall system efficiency by approximately 2–3%.

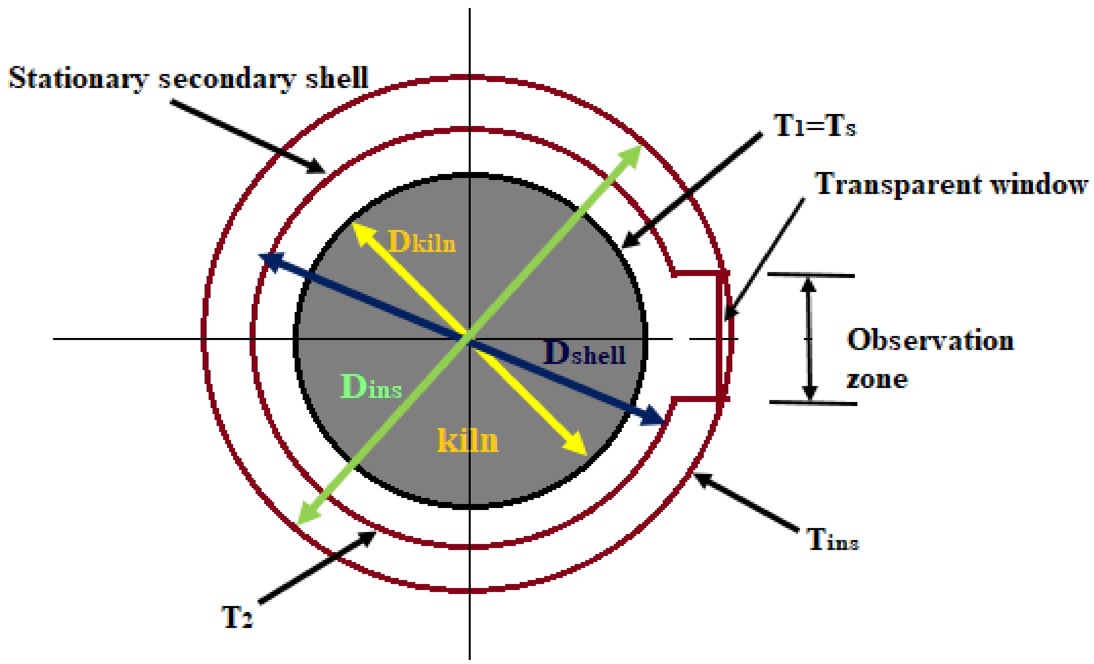

Fig.7: The working principle of Secondary shell to the current kiln surface.

V. CONCLUSION

It is found that the implementation of energy analysis on the rotary kiln is a very efficient and effective way for improving the efficiency of the kiln system and reduction of fuel consumption. There is some major energy lost with the hot gas through preheater andcooler stack is about 19.53% and is 16.22% of the energy input respectively. After using this energy into the pre-calcination and pre-heating although the out let temperature of the hot gas is very high. In this case an auxiliary circuit like WHRSG (Waste Heat Recovery Steam Generator) should be installed. In order to minimize the heat lost from the kiln shell,secondary shell system is applied and addedon to the kiln surface, the anzast layer inside the kiln bricks lining should have to be maintained and also the kiln surface should have to be painted for proper emissivity. By using these systems about 3.5 MW of energy is saved from the kiln surface which means 9% of the total input energy is recovered.Generally, in cement industry huge amount of energy is lost to the environment. Hence; there must be energy management department to study on the heat recovery system from the energy lost and on the alternative energy sources of the company.

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