

Heat Balance Analysis in Cement Rotary Kiln

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Abstract: The purpose of this study is optimizing the 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 the clinker vary. Analysis of Heat balance was used to determine the sources of heat loss from the kiln system. Based on the collected data, an energy balance is applied to the kiln system. The physical properties and equations can be found in Perry's handbook. The reference enthalpy is considered to be zero at 0°C for the calculations. The kiln has a capacity of 1000 ton-clinker per day. It found that the major heat loss is Heat losses by the kiln exhaust gas (2.33%), hot air from the cooler stack (7.28%), Radiation from kiln surfaces (11.71%). Some possible ways to recover the heat losses are introduced and discussed and they are Electricity generation, Heat recovery from kiln surface and Pre-heating raw material before the clinkering process.

Keywords: Rotary Kiln, Design Parameters, Exhaust Gas, Radiation

1. Introduction

Heat balance on a kiln can offer extremely useful information on the thermal performance of the system [1]. Heat balance show where or how the fuel heat is consumed based on the simple principle of $input = output$ [2, 3]. Unnecessary energy losses can be easily detected, the principle of heat balance may be easily transferred to another system such as preheater, cooler, and drying system. Therefore the use of this study can be extended to another system than cement kiln [3].

Various reasons or circumstances may cause a need for a heat balance measurement. The following situations may justify a heat balance:

1. Performance test,
2. Recoding of kiln performance before/after a modification,
3. Unusually high heat consumption or abnormal kiln operational data,
4. Kiln optimization campaign.

Although the specific heat consumption proper could also be determine by measuring nothing but fuel heat and clinker production, a complete heat balance does offer to considerably more information and security [5]. The consistency of the measured data is proved much better, and

the balance shows clearly where the heat is consumed. A heat balance is obviously a very efficient tool assessment of thermal efficiency [6].

A heat balance does not only mean calculation of heat balance items. The complete procedure usually includes the following steps:

1.1. Preparation

The extent of works to be done depends on the completeness and reliability which is desired. A careful planning and preparation are recommendable. The following basic items must be clarified:

1. What has to be measured (kiln and location of measuring/sampling points).
2. Duration of test?
3. The frequency of measurements (continuous recording, spot measurements, time intervals, etc)?
4. Necessary log sheets for manual recording ready?
5. Data recording system (electronic, pen recorder etc) available?
6. The flow of information among the test team?
7. Calibration and checks of instruments and scales done (flowmeters, orifice plates, ventures,do-cell, thermocouples, etc.?)
8. Temporary measuring equipment available? Complete?

Correct span? Functioning properly?

9. For example:

- Pitot tube
- U-tube manometer
- Mobile thermometer
- Radiation pyrometer
- Orsat / gas analyzer
- Sampling equipment for gas
- Sampling procedure for solids (e.g meal, dust, clinker) clarified?

1.2. Execution

An important precondition for a good test is steady kiln operation. The test should only be started if the system has reached a constant equilibrium state. During the test, variations of operating parameters should be avoided. For the measuring techniques, reference is made to the corresponding paper.

It is recommended to check completeness and reliability of measurements already during the test, afterward missing or uncertain information may create problems at the final evaluation.

1.3. Evaluation

This step is the scope of this paper. Evaluation of data means to establish a heat balance calculation according to the principle “input = output”

1.4. Discussion

A heat balance is such must bring some practical

conclusions otherwise it would be only of academically interest. The following items may be considered:

- Acceptable (normal) heat consumption?
- Are heat balance items normal for given kiln system?
- Measures in order to improve the heat economy of the system?

The last item can become quite an extensive work and the economic feasibility must be considered as well. Such subject, however, is beyond the scope of this paper. Summarizing, it is obvious that the 3rd step “evaluation” is only a limited part in the whole context [7].

2. Methods of Testing Calculations

2.1. Assumptions

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

- The system is assumed to be steady state, steady flow & open.
- Kinetic & Potential energy changes of input and output materials are negligible.
- Ambient conditions are constant throughout the study i.e. $T_0 = 301 \text{ K}$.
- Raw material and coal material composition do not change & feed rate of both are constant.
- The natural convection is taken into account as the velocity of atmospheric air is $< 3 \text{ m/s}$.
- Average kiln surface temperature does not change throughout the study.
- The gases inside the kiln are assumed to be ideal gases.

Table 1. Equations used to calculate the rotary kiln Heat balance.

Heat Output	
Heat of Formation	$Q = 2.2 A + 6.48 M + 7.646 C - 5.1165 S - 0.59 F$
Heat in Preheater Exit Dust	$Q_d = m_d * C_{p,d}(t_d - t_r)$
Heat in Preheater Exit Gases	$Q_e = m_e * C_{p,e}(t_e - t_r)$
Heat in Clinker from Cooler Discharge	$Q_c = m * C_{p,c}(t_c - t_r)$
Heat in Cooler Exhaust Air	$Q_{ce} = m_{ce} * C_{p,ce}(t_{ce} * t_r)$
Heat in Evaporation of Raw Meal Moisture	$Q_{er} = m_{mr} * L$
Heat Input	
Heat of fuel Combustion	$Q = CV * X$
Heat in Kiln Feed	$Q = m_f * C_{p,f}(t_f - t_r)$
Heat in Cooling Air	$Q = m_{co} * C_p (t_{co} - t_r)$
Heat in Primary Air	$Q = m_p * C_p (t_p - t_r)$
Sensible Heat of Fuel	$Q = m_{fuel} * C_p (t_{fuel} - t_r)$

2.2. Basic data

2.2.1. Kiln Dimensions

Diameter (m):	3.4
Length (m):	63

2.2.2. Preheater4Stage Cyclone with Calciner

Feed temperature (°C):	50
Raw Meal Feed rate (tph):	70
Raw Meal Moisture (%):	0.5
Gas after preheater (°C):	320
Orsat measurements :	CO ₂ (%): 28

O ₂ (%):	3.5
CO(%):	0.01

Dust from cyclones (ton/hour):	10
Pitot measurements, kg/sec:	24.94
Production (tonne per day) based on clinker weight.	

2.2.3. Firing System

i. Fuel: Gasoline	
Calorific value (kcal/kg):	8000
ii. Kiln primary air	
Temperature (°C):	40
Pitot measurements (kg air/kg clinker):	0.073

iii. Calciner primary air
 Temperature (°C): 40
 Flow rate (kg air/kg clinker): 0.009

2.2.4. Grate Cooler

i. Exhaust air:
 Temperature (°C): 240
 Pitot measurements (kg air/sec): 11.34
 ii. Clinker from cooler
 Temperature (°C): 140
 iii. Cooling air
 Flow rate, kg/kg clinker: 2.4
 Temperature (°C): 37

2.3. Analysis of Clinker

Table 2. The chemical composition of clinker sample.

Component	Percentage%
CaO	64.40
SiO ₂	21.46
Al ₂ O ₃	04.85
Fe ₂ O ₃	04.79
MgO	03.63
SO ₃	00.50
L.O.I	00.79
K ₂ O	00.50
Na ₂ O	00.26

Mean specific heats between 0 and T°C

$$C_p = A + B * T * 10^{-6} + C * T^2 * 10^{-9} \text{ kcal/kg.}^\circ\text{C}$$

Table 3. Values of coefficients.

Component	A	B	C
CO ₂	0.196	118	-43
H ₂ O	0.443	39	28
N ₂	0.244	22	0
O ₂	0.218	30	0
Air	0.237	23	0
Raw Meal	0.206	101	-37
Clinker	0.186	54	0
Coal	0.262	390	0

Table 4. Heat for evaporation of water: kcal/kg.

Temp.°C	0	20	100
Heat Evaporation kcal/kg	597	586	539

3. Results

3.1. Basis

- 1kg of clinker
- Reference Temperature 0°C

3.2. Heat Outputs

3.2.1. Heat of Formation

Considering loss free clinker as loss-free meal feedstock under equilibrium condition

Loss-free feedstock composition:

$$\text{SiO}_2 = 21.46\%$$

$$\text{Al}_2\text{O}_3 = 4.85\%$$

$$\text{Fe}_2\text{O}_3 = 4.79\%$$

$$\text{CaO} = 64.4\%$$

$$\text{MgO} = 3.63\%$$

$$Q = 2.2 A + 6.48 M + 7.646 C - 5.1165 S - 0.59 F$$

$$Q = 2.2 * 4.85 + 6.48 * 3.63 + 7.646 * 64.45 - 1165 * 21.46 - 0.59 * 4.79$$

$$Q = 413.75 \text{ kcal/kg clinker}$$

3.2.2. Heat in Preheater Exist Dust

1. Gross dust loss=8.5tph

2. Clinker output rate= 42tph

Dust in Preheater Exit Gas = 12/1000

$$= 0.24 \text{ kg dust/kg clinker}$$

Mean Specific heat:

$$C_{p_d} = A + B.T.10^{-6} + C.T^2.10^{-9} \text{ kcal/kg}^\circ\text{C}$$

From table 3:

$$A = 0.206, B = 101, C = -37$$

Therefore:

$$C_{p_d} = 0.2305 \text{ kcal/kg}^\circ\text{C}$$

$$t_d = 330^\circ\text{C}$$

$$t_r = 0^\circ\text{C}$$

$$Q_d = m_d * C_{p_d} * (t_d - t_r)$$

$$Q_d = 0.24 * 0.2305 (330 - 0)$$

$$= 18.25 \text{ kcal/kg clinker}$$

3.2.3. Heat in Preheater Exist Gases

$$Q_e = m_e * C_{p_e} * (t_e - t_r)$$

Pitot measurements of kiln exit gases = 24.94 kg/sec

Clinker Production = 1000tpd

$$= 11.6 \text{ kg/sec}$$

$$m_e = 24.94 / 11.6$$

$$= 2.15 \text{ kg/kg clinker}$$

Exit gas composition:

$$\text{O}_2 = 2.8\%$$

$$\text{CO}_2 = 26.3\%$$

$$\text{CO} = 0.03\%$$

Assuming balance gases as N₂

$$\text{N}_2 = 70.87\%$$

Table 5. Determination of gases weight fraction.

Gas	vol.fraction	WT.fraction	WT.%
O ₂	0.028	0.028*32/22.4=0.04	2.77
CO ₂	0.263	0.263*44/22.4=0.516	35.77
CO	0.0003	0.0003*28/22.4=0.000375	0.026
N ₂	0.7087	0.7087*28/22.4=0.8859	61.434
Total	1.0	1.4422	

The specific heat of exist gas is the sum of specific heats of individual gas composition. Considering that waste gases in terms of weight percentage comprise of 2.77% O₂, 35.77% CO₂ and 61.46%N₂.

$$C_{p_e} = (2.77/100)(0.218 + 30*269 * 10^{-6}) + (35.77/100)(0.196 + 118 * 269 * 10^{-6}) - (43 * 2692 * 10^{-9}) + (61.46/100)(0.244 + 22 * 269 * 10^{-6})$$

$$= 0.2402 \text{ kcal/kg}^\circ\text{C}$$

Heat in preheater exist gas

$$Q_e = 2.15 * 0.2402 * (330 - 0) \\ = 170.42 \text{ kcal /kg clinker}$$

3.2.4. Heat in Clinker from Cooler Discharge

$$Q_c = m * C_{p_c} * (t_c - t_r) \\ m = \text{wt. of clinker} \\ C_{p_c} = \text{mean specific heat of clinker, kcal/kg}^\circ\text{C} \\ t_c = \text{temperature of clinker, } = 120^\circ\text{C} \\ C_{p_c} = 0.186 + 54 * 140 * 10^{-6} \\ = 0.1935 \text{ kcal/kg}^\circ\text{C} \\ Q_c = 1 * 0.1935 * (140 - 0) \\ = 27.1 \text{ kcal/kg clinker}$$

3.2.5. Heat in Cooler Exhaust Air

$$Q_{ce} = m_{ce} * C_{p_{ce}} * (t_{ce} - t_r) \\ \text{Pitot measurement of cooler exhaust air} = 11.34 \text{ kg/sec} \\ \text{Clinker output rate} = 11.6 \text{ kg/sec} \\ m_{ce} = 11.34 / 11.6 \\ = 0.98 \text{ kg air / kg clinker} \\ t_{ce} = 340^\circ\text{C} \\ C_{p_{ce}} = 0.237 + 23 * 240 * 10^{-6} \\ = 0.2425 \text{ kcal/kg}^\circ\text{C} \\ Q_{ce} = 0.98 * 0.2425 * 240 \\ = 57.041 \text{ kcal/kg clinker}$$

3.2.6. Heat in Evaporation of Raw Meal Moisture

$$Q_{er} = m_{mr} * L \\ \text{Raw meal feed rate} = 70 \text{ tph} \\ = 1.66 \text{ kg/kg clinker} \\ \text{Moisture in Raw Meal} = 0.5\% \\ \text{Therefore, wt. of moisture} = 1.66 * 0.5 / 100 \\ = 8.3 * 10^{-3} \text{ kg water/kg clinker} \\ \text{Heat of evaporation of moisture} = 597 \text{ kcal/kg} \\ \text{Therefore, Heat of evaporation of raw meal moisture} \\ Q_{er} = 8.3 * 10^{-3} * 597 \\ = 4.95 \text{ kcal/kg clinker}$$

3.2.7. Radiation and Conventional Losses

$$\text{Kiln} 45.7 \text{ kcal/kg clinker} \\ \text{Preheater} 40.7 \text{ kcal/kg clinker} \\ \text{Cooler} 5.2 \text{ kcal/kg clinker} \\ \text{Total heat loss by radiation and convention:} \\ Q = 91.6 \text{ kcal/kg clinker}$$

3.3. Heat Input

3.3.1. Heat of Fuel Combustion

$$Q = CV * X \\ \text{Where } X = \text{fuel consumption,} \\ = 0.118 \text{ kg fuel/kg clinker} \\ CV = 8000 \text{ kcal /kg} \\ \text{Therefore, Heat of fuel Combustion} = \\ 8000 * 0.118 = 944 \text{ kcal / kg clinker}$$

3.3.2. Heat in Kiln Feed

$$Q = m_f * C_{p_f} * (t_f - t_r) \\ m_f = \text{amount of kiln feed} \\ = 70 \text{ tph} \\ = 1.66 \text{ kg/kg clinker} \\ t_f = \text{temp. of kiln feed} \\ = 50^\circ\text{C} \\ C_{p_f} = 0.206 + 101 * 50 * 10^{-6} + (-37) * 50 * 10^{-9} \\ = 0.211 \text{ kcal/kg}^\circ\text{C} \\ Q = 1.66 * 0.211 * (50 - 0) \\ = 17.51 \text{ kcal/kg clinker}$$

3.3.3. Heat in Cooling Air

$$Q = m_{co} * C_p * (t_{co} - t_r) \\ m_{co} = \text{amount of cooling air} \\ = 27.84 \text{ kg/sec} = 2.4 \text{ kg/kg clinker} \\ t_{co} = \text{temp. of cooling air} \\ = 37^\circ\text{C} \\ C_p \text{ air at } 37^\circ\text{C} \\ = 0.237 + 23 * 37 * 10^{-6} \\ = 0.238 \text{ kcal/kg}^\circ\text{C} \\ Q = 2.4 * 0.238 * (37 - 0) \\ = 21.12 \text{ kcal/kg clinker}$$

3.3.4. Heat in Primary Air

$$Q = m_p * C_p * (t_p - t_r) \\ m_p = \text{total primary air (kiln \& calciner)} \\ \text{Primary air to kiln} = 0.073 \text{ kg/kg clinker} \\ \text{Primary air to Calciner} = 0.009 \text{ kg/kg clinker} \\ m_p = \text{Total Primary Air} \\ = 0.082 \text{ kg/kg clinker} \\ t_p = \text{Temperature of Primary air} \\ = 40^\circ\text{C} \\ C_p = 0.237 + 23 * 40 * 10^{-6} \\ = 0.238 \\ Q = 0.082 * 0.238 * (40 - 0) \\ = 0.8 \text{ kcal/kg clinker}$$

3.3.5. Sensible Heat of Fuel

$$Q = m_{fuel} * C_p * (t_{fuel} - t_r) \\ \text{Mean } C_p \text{ of gasoline} = 0.53 \text{ kcal/kg}^\circ\text{C} \\ Q = 0.118 * 0.53 * (55 - 0) \\ = 3.44 \text{ kcal/kg clinker}$$

3.4. Total Heat Inputs and Outputs

$$\text{Total Heat Inputs} = 986.87 \text{ kcal/kg clinker} \\ \text{Total Heat Outputs} = 783.11 \text{ kcal/kg clinker} \\ \text{Calculation of Heat loss} \\ \text{Total Heat Input} = \text{Total Heat Output} \\ \text{Heat loss} = 986.87 - 783.11 \\ = 203.76 \text{ kcal/kg clinker}$$

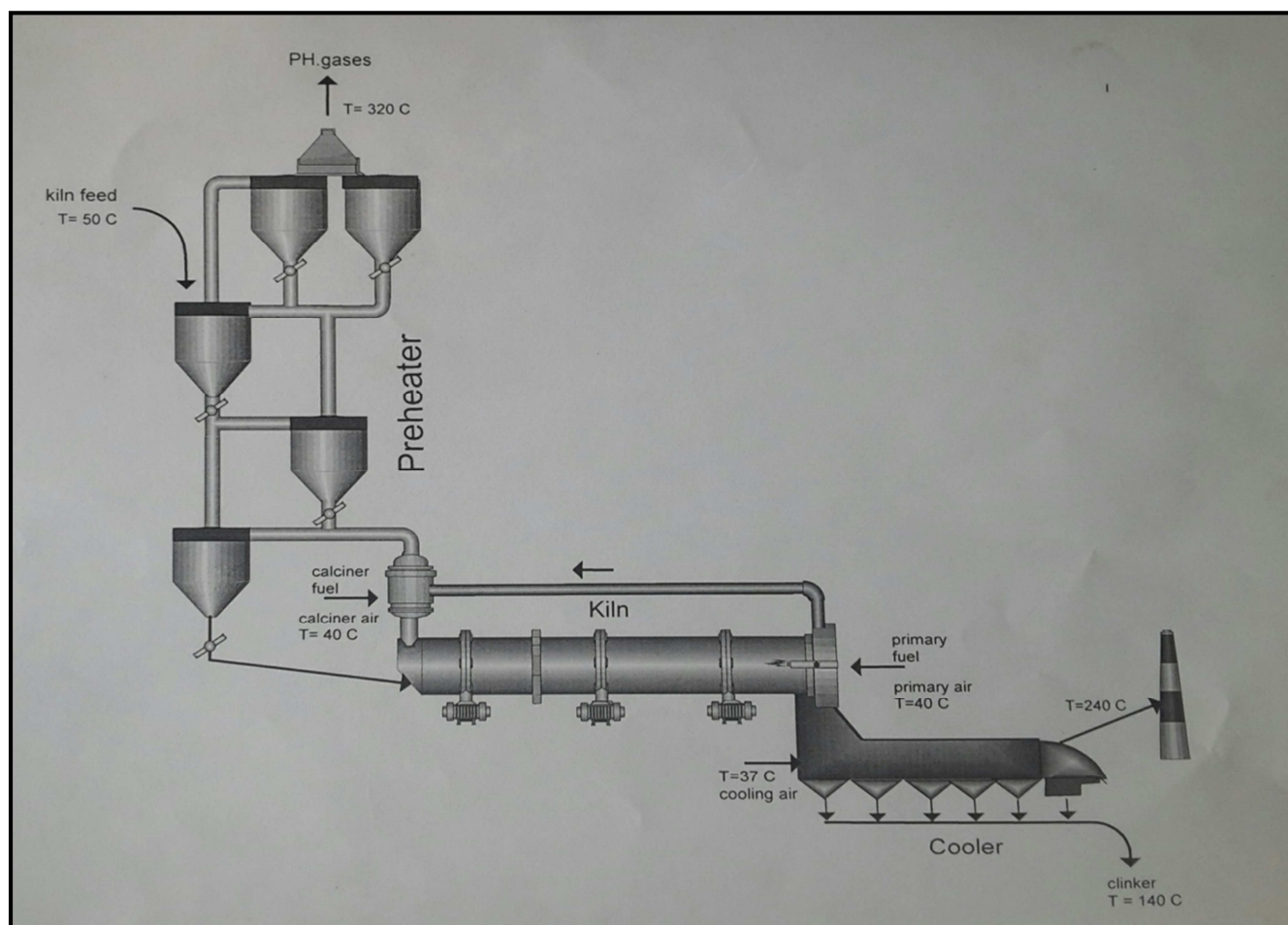


Figure 1. Flow diagram show the kiln and preheater system.

Heat balance of kiln
Clinker output: 1000tpd

Table 6. Summary of total heat balance of kiln.

Items	Kcal/kg clinker	Percentage%
Heat input		
Heat through fuel combustion	944	95.66
Sensible heat in kiln feed	17.51	1.77
Sensible heat in fuel	3.44	0.35
Sensible heat in air (cooling air and primary air)	21.92	2.22
Total heat input	986.87	100
Heat output		
Heat in ph exit gases	170.42	21.76
Heat in dust in ph exit gases	18.25	2.33
Theoretical heat of reaction	413.75	52.83
Heat in cooler exhaust air	57.04	7.28
Heat in clinker leaving cooler	27.1	3.46
Heat in evaporation of moisture rawmeal	4.95	0.63
Radiation and convection losses		
1. kiln 45.7 kcal/kg clinker		
2. preheater 40.7 kcal/kg clinker	91.6	11.71
3. cooler 5.2 kcal/kg clinker		
Total heat output	783.11	100

Net specific heat of fuel combustion = 1000 kcal/kg clinker

4. Discussion

Based on the collected data, an energy balance is applied

to the kiln system. The reference enthalpy is considered to be zero at 0°C for the calculations. The complete energy balance for the system is shown in Table 6. It is clear that the total

energy used in the process is 986.87 kJ/kg-clinker, and the main heat source is Gasoline, giving a total heat of 944 kJ/kg-clinker (95.66%). Also, the energy balance given in Table 6 indicates relatively good consistency between the total heat input and total heat output. Since most of the heat loss sources have been considered, there is only a 203 kJ/kg-clinker of energy difference from the input heat. This difference is nearly 20% 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 some other key plants reported in the literature.

4.1. General Remarks

1. It was found that the gases out at a high temperature of 330°C caused damage in the filter bags.
2. Radiation affects the performance of workers near the kiln.

4.2. Heat Recovery from the Kiln System

The overall system efficiency can be defined by $\eta = Q_6/Q_{\text{total input}}$, $\eta = 413.75/986.87 = 0.42$ or 42%, which can be regarded as relatively low. Some kiln systems operating at full capacity would declare an efficiency of 55% based on the current dry process methodology. The overall efficiency of the kiln system can be improved by recovering some of the heat losses [9]. The recovered heat energy can then be used for several purposes, such as electricity generation and preparation of hot water. There are a few major heat loss sources that would be considered for heat recovery.

These are heat losses by (1) preheater exhaust gas (21.76%), (2) hot air from the cooler stack (7.28%) and (3) radiation from kiln surfaces (11.7%). In the following section, there are some possible ways for recovering this wasted heat energy:

4.2.1. Electricity Generation

There are many ways in which heat wasted to the environment is captured and utilized for preheating and electricity generation. One of the most accessible and in turn the most cost-effective heat losses available are the kiln exhausts gas and cooler discharge. The exhaust gas from the kilns is on average, 330°C, and the temperature of the air discharged from the cooler stack is 240°C. These streams are directed into the waste heat recovery generator which will convert the available energy into electricity. Thus this, in turn, reduces the electrical demand of the plant [10, 11].

4.2.2. Pre-heating

Apart from power production, one of the most effective methods of waste heat recovery is to preheat the raw material before the clinking process. Preheating is usually achieved by directing gas streams into the raw material just before the grinding mill, which helps in increasing the temperature of the raw material and also lead to more efficient grinding process [12].

4.2.3. Heat Recovery from Kiln Surface

The hot surface of the kiln is another source of waste heat recovery, in which heat loss occurs by convection and radiation which is about 11.71% of the input energy. The use of the secondary shell on kiln surface can significantly reduce this loss which will reduce fuel consumption and increase the overall system efficiency by approximately 5-6% [13].

5. Conclusions

A detailed energy audit analysis, which can be directly applied to any dry kiln system, has been made for a specific key cement plant. The distribution of the input heat energy to the system components showed good agreement between the total input and output energy and gave significant sights about the reasons for the low overall system efficiency.

According to the results obtained, the system efficiency is 42%. The major heat loss sources have been determined as preheater exhaust gas (21.76% of total input), cooler exhaust (7.28% of total input) and combined radioactive and convective heat transfer from total kiln surfaces (11.71% of total input).

For the first two losses, a conventional West heat recovery steam generation system (WHRSG) system is proposed. For the kiln surface, a secondary shell system has been proposed and designed.

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