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Energy Analysis Using Matlab Graphical User Interface of Cement Rotary Kiln for Alburge Cement Plant: A Case Study

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ABSTRACT

Cement manufacture has been one of the most energy intensive industries in the world. In order to produce clinker, rotary kilns are widely utilized in cement plants. This work deals with the energy analysis of a rotary kiln system working in a cement plant in Alburge Cement Plant (ACP), at Arab Union Cement Company (AUCC), Zliten city, Libya. The kiln has a capability of producing 4200 ton-clinker per day. The main objective of this study is to examine heat loss of various components of the rotary kiln system. In the present study, a Matlab program with a graphical user interface (GUI) has been used for energy auditing of ACP as a case study. The GUI inputs and outputs showed through the paper as an interface widows. Result shows that 30% of the total energy is being lost. An amount of 20.54% missed through hot flue gas, 5.25% across cooler stack, and 4.56% by kiln shell convection plus radiation.

***Keywords*:**
Energy audit.
Rotary kilns.
Cement plant.
Graphical user interface.

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1 INTRODUCTION

Cement is a vital element that can accomplish the basic needs in our daily life. It is a basic material for all types of construction, including hospitals, schools, housing, roads, and may even be used in decorative items such as tables and bookcases. In Libya, like the other countries, the cement production plants consume large amount of energy. Nearly 11% of the total energy consumption in the industries related to cement industry [1]. The calcination process considered as a large energy consumer process in the cement industry plants [2]. Heat loss is the major type of energy that can be recovered and utilized in the cement production. Therefore, to improve the energy efficiency of the cement plant, heat loss from cement plant equipment should be evaluated and reduced. This heat loss occurs due to distribution of the temperature, rotational speed, thermal stability and resistance of a refractory lining inside the kiln, and characteristics of the process that occurs inside the kiln [3]. The heat loss could be recovered using heat exchangers or by fixing an isolating shell around the kiln [4, 5].

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The energy audit has arisen as one of the most useful ways for a successful energy managing method and it has received great attention among researchers working in this area [6]. For instance, Karellas and coworkers [7] have carried out energetic and exergetic analysis of waste heat recovery systems. Two different cycles have been investigated; an organic Rankin cycle (ORC) with isopentane as the working fluid and a water-steam cycle.

NOMENCLATURE

Symbols	Notation	Units
W_A	Fuel rate, as fired	kg/kg-Clinker
A_J	Heat value of fuel	kJ/kg
CJ	Specific heat	kJ/kg ^oC
T_F	Temperature of fuel as fired	^oC
W_{df}	Dry feed rate	kg/kg-Clinker
T_C	Temperature of feed entering kiln	^oC
W_t	Total air flow into cooler	kg/kg-Clinker
H_{AL}	Percent of aluminum oxide	%
H_{Mg}	Percent of magnesium oxide	%
H_{Ca}	Percent of calcium oxide	%
H_{Si}	Percent of silica oxide	%
H_{Fe}	Percent of ferric oxide	%
m_{eg}	Kiln exhaust gas flow rate	kg/kg-Clinker
$C_{P\text{-}eg}$	Specific heat of exit gas	kJ/kg ^oC
T_{eg}	Temperature of kiln exhaust gas	^oC
W_2	Weight of dust exit from cooler	kg
$W_{Clinker}$	Weight output clinker	kg
T_{st}	Temperature of cooler exit gas	^oC
K_l	Flow rate of dust and moisture in the kiln exist gas	kg/kg-Clinker
T_{Be}	Temperature of dust kiln exist gas	^oC
	Boltzman constant	W/m^2K^4
	Emissivity of kiln shell	N/A

A_{kiln}	Kiln surface area	m^2
$m_{Clinker}$	Clinker flow rate	kg/s
T_S	Temperature of kiln surface	^oC
T_∞	Environment temperature	^oC
h_{nconv}	Heat transfer coefficient normal convection	$W/m^2.^oC$
Kair	Thermal conductivity of air	W/m.k
Nu	Nussle number	-
D_{Kiln}	Kiln diameter	m
Pr	Pranttle number	-
Ra	Relagh number	-
g	Standard Acceleration	m/s^2
ν	Kinematic viscosity	m^2/s

The water steam cycle outperforms the ORC in terms of energy and exergy, with a system efficiency of 23.58 percent compared to 17.56 percent for the ORC. Morteza and colleagues [8] have performed an energy audit in the Momtazan cement plant in Kerman, Iran. They proposed a decision-making procedure to help the decision maker to choose the best strategy in order to reduce energy loss. Another energy auditing study conducted by Engin and Ari [4]. They indicated that with an input heat of 3686 kJ/kg of clinker (kJ/kg-cl) (95.47 %), the energy utilized for clinkering was 1795 kJ/kg-cl with an efficiency of 48.7 % with almost around 40 % of the total input energy being lost through hot flue gas (19.15 %), Cooler stack (5.61 %) and kiln shell (15.11 % convection plus radiation).

In this paper, energy audit of the ACP in Zliten, Libya performed. This analysis considered an important step in any cement plant before conducting heat recovery in order to improve overall efficiency. Since the Calculations to achieve energy, analysis would be time and effort consuming. Therefore, (GUI) in Matlab software was proposed to achieve these calculations in easy way for users. It will also reduce the error of calculation and the time of complex calculation. The other benefit of using GUI in energy auditing is that it can be used for other different cement plants by only changing the input data related to the studied plant.

2 PROCESS DESCRIPTION

The reference cement plant is Alburge Cement Plant (ACP), is one of the plants followed to (AUCC). The average daily production capacity is 4200 ton of clinker and the used fuel is heavy oil. The process based on the dry type kiln, which consists of a five-stage cyclone preheater, pre-calciner, rotary kiln and clinker cooler. First, the raw material entered to milling process where homogenizing and grinding actions performed. The grounded material is stored, as raw meal, in storage silos. Second, the raw material came from the silos entered into cyclones (five stage preheaters) from the top. Flue gases came from the rotary kiln used to heat up the raw meal. After that, the raw material then transferred to rotary kiln. Rotary kiln is refractory lined tubes with a diameter up to 4.35 meter and 75 m long. It is inclined with an angle of 3-3.5°, and it rotated with speed of 1-2 rpm. Cyclone pre-heaters usually used to preheat the raw materials before it enters the kiln. In this process, the pre-calcination step gets started in the preheaters. At the end of preheaters, the temperature of the raw material would be around 850 °C. After that, the materials enters the rotary kiln and passes towards the flame. At the first zone of the kiln where the temperature around (700 - 900 °C), calcination and initial combination of alumina, ferric oxide, silica, and lime takes place. In the second zone where the temperature is around 900 – 1200°C, clinker and $2CaO.SiO_2$ will be formed. At the final zone of the rotary kiln, $3CaO.SiO_2$ will be formed at temperature of 1250 °C. The product out of the rotary kiln enters the clinker cooler where the air at 30°C used to cool down the product. During the cooling stage, where the molten phase of $3CaO.Al_2O_3$ formed, the cooling should be fast to improve the product quality. Figure 1 represent simple schematic diagram of cement manufacturing process.

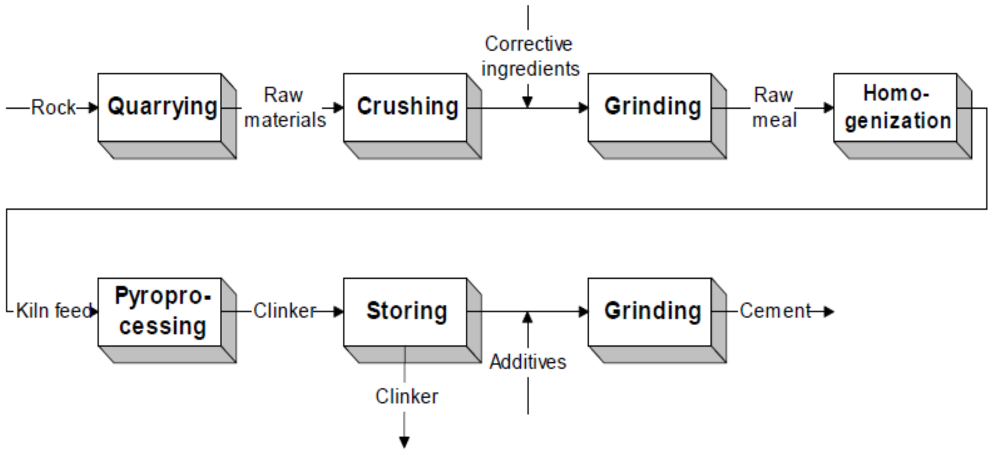


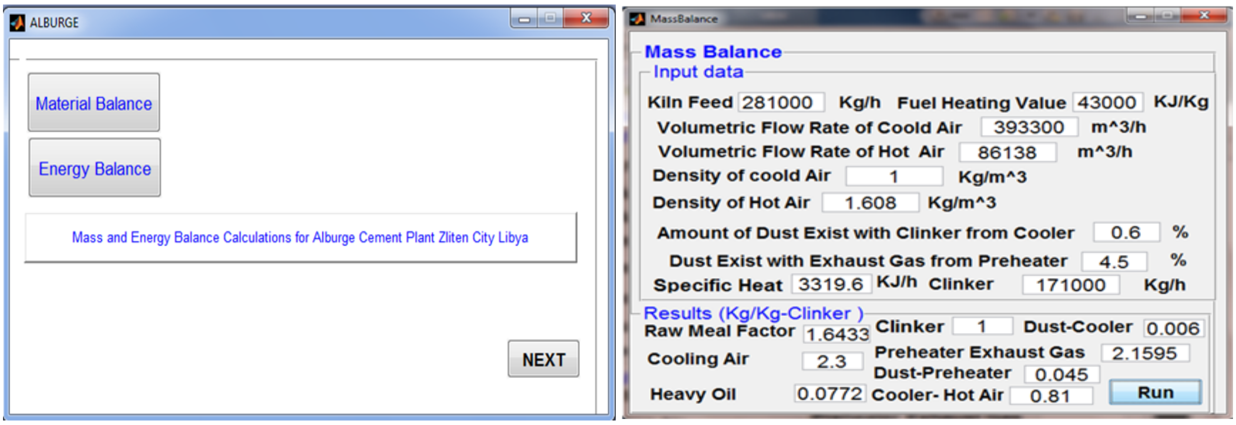
Figure 1. Schematic diagram of cement manufacturing process [9].

3 ENERGY AUDITING

Thermal energy balance in cement plant is a practical method for determining the energy consumed during the process by various equipment operational activities, as well as the source of losses. Considering design parameters of the cement plants by keeping adequate safety factors of calculation and the physical properties of equipment can be found in Perry's handbook [10]. It covers mass and energy balances.

3.1 Mass Balance

The mass balance developed for the clinker produce and across the boundary of the kiln system, which involve the preheater, kiln and cooler. Figure 2 shows the main building block of development mass and energy balance (figure 2a) as well as the GUI input data required for mass balance (figure 2b). The input data, including composition of raw meal, ultimate analysis of the fuel, and dust content in the exhaust gas, loss of ignition (LOI) and exhaust gas computations in the suspension preheater employed for the mass balance computation. Based on the heavy oil configuration, the net heat value rate has been found to be 43000kJ/kg-fuel. It is typically more suitable to express mass/energy data per kg clinker produced yielded per unit time.



(a) *(b)*

Figure 2. A graphical User Interface (GUI) screens: a) main menu; b) input data for material balance

The mass balance of the kiln system summarized in figure 3. All gas streams are assumed to be ideal gases at the given temperatures [4]. While the raw material and clinker compositions have been taken from the operation datasheet of (ACP) and listed in table 1

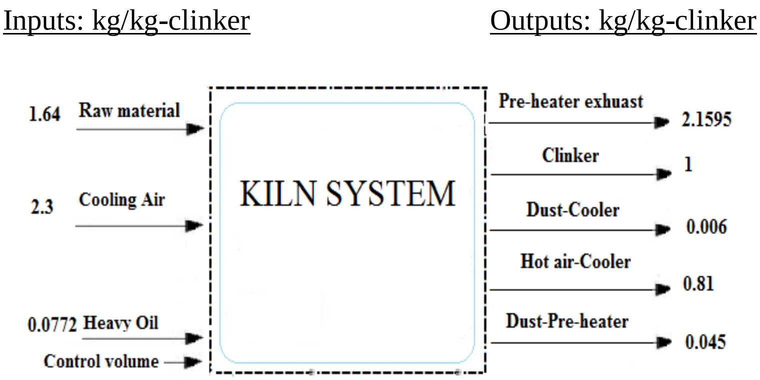


Figure 3. Mass balance of the kiln system.

Table 1. Composition of raw material and clinker [11]

Component	Raw Material (%)	Clinker (%)
SiO_2	13.8	22.279
Al_2O_3	3.38	5.268
Fe_2O_3	2.38	3.176
CaO	42.03	64.499
MgO	1.21	2.961
SO_3	0.10	0.183
K_2O	0.62	1.070
Na_2O	0.08	0.150
H_2O	0.006	-
Organics	0.9	-
Ignition loss	35.46	0.55
Total	99.966	100.136

The mass balance obtained based on the following assumptions [3]:

- The raw material factor is equal to the amount of raw material which enter to the boundary kiln system per hour/clinker produced per hour.
- Amount of the required fuel to produce 1 Kg of the clinker is equal to the ratio of specific energy to the heating value of fuel.
- Amount of air required for cooling the clinker to 110 ^{o}C is equal to the air volumetric flow rate times density of the air divided by the clinker produced per hour.
- The amount of dust exist with the clinker from the cooler are 0.6%.
- The amount of hot air exit from the cooler is equal to the ratio of the product of the hot-air volumetric flow rate and the hot-air density at 220 ^{o}C to the clinker produced per hour.
- Amount of dust exist with exhaust gas from the preheater are 4.5%.

3.2 Energy Balance

To achieve the energy balance in the cement plant, information about some parameters such as temperature, amount of fuel, fuel heating value, fuel heating capacity, and energy consumption of the utility equipment is required (Figure 4).

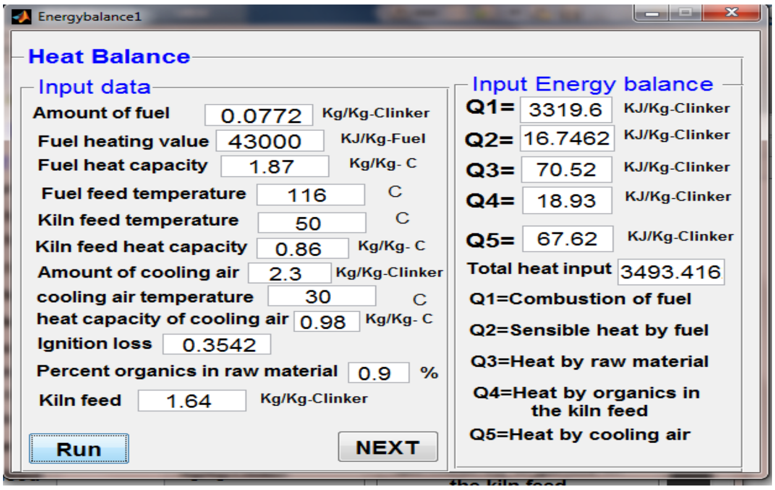


Figure 4. Input data for energy balance

The kiln system considered for the energy auditing summarized in figure 5. All gas streams are assumed to be ideal gases at the provided temperature. The control volume for the system includes the pre-heaters group, rotary kiln and cooler. The streams coming to and from the control volume and all measurements indicated in the Figure 5.

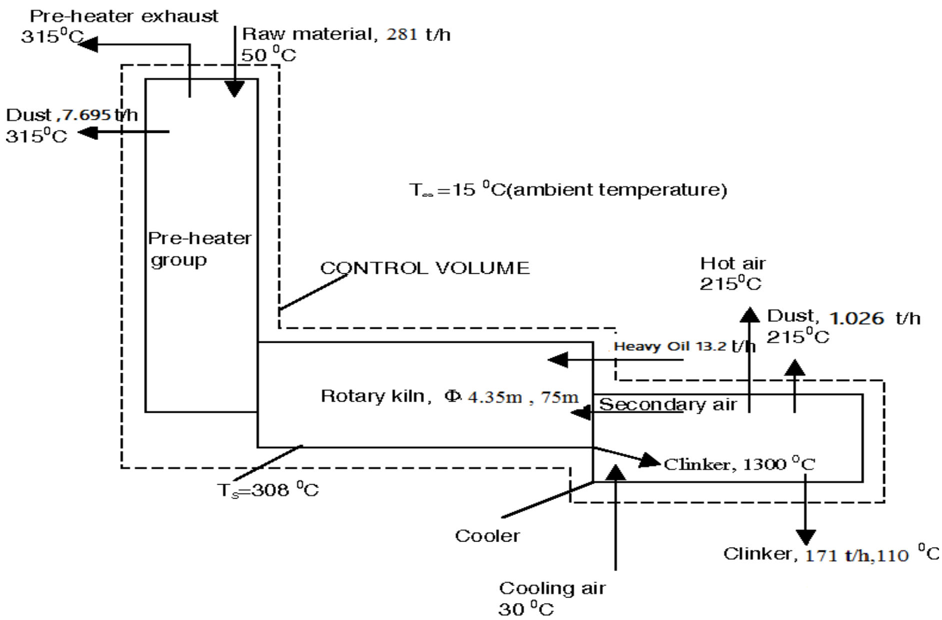


Figure 5: The boundary of kiln system control volume.

To analyze the kiln system thermodynamically, steady state working conditions assumed with neglecting the change in the ambient temperature and cold air leakage into the system. Also, raw material, heavy oil composition, and average kiln surface temperature assumed to be unchanged.

According to collected data [11], an energy balance submitted to the kiln. All equations used for energy input and output calculations summarized in table 2. While equations regards calculations heat loss from various equipment such as rotary kiln, cyclones, cooler, air duct, and precalciner presented in table 3.

Table 2. Equations for energy input and output calculations

Heat Input Equations		Heat Output Equations	
$Q_{(\text{Combstion of fuel})}=W_A \times A_J$	(1)	$Q_{(\text{formation of clinker})} = 4.11H_{Al_2O_3} + 6.48H_{Mgo} + 7.646H_{Cao} - 5.116H_{Sio_2} - 0.59Fe_2O_3$	(6)
$Q(\text{Sensible heat by fuel}) = W_A \times C_J \times T_F$	(2)	$Q_{(\text{Kiln Exhaust gas})} = W_{eg} \times C_{peg} \times T_{eg}$	(7)
$Q(\text{ Heat by Raw Material}) = W_{df} \times C_J \times T_C$	(3)	$Q_{(\text{Moisture in Raw matrial})} = W_{\text{Total }(H_2O)} \times 2500.8$	(8)
$Q(\text{ Organics in the kiln feed}) = g \times C_C/100 \times (21036)$	(4)	$Q_{(\text{Clinker discharge})} = C_j \times T_{\text{Clinker}}$	(9)
$Q(\text{ Heat by Cooling Air}) = W_A \times 1/W_{\text{clinker}} \times C_J \times F_T$	(5)	$Q_{(\text{Heat loss at cooler stack})} = W_2/W_{\text{clinker}} \times C_j \times T_{st}$	(10)
		$Q_{(\text{Heat losses due to dust in the kiln exist gas})} = K_1 \times C_j \times T_{eg}$	(11)

Table 3. Equations for heat loss from various equipment

Heat Losses From Rotary Kiln	
$Q_{(\text{Radition from Kiln surface})} = \sigma \epsilon A_{\text{kiln}}\left(T_s{}^4 - T_\infty{}^4\right)/\,(1000 \times m_{cl})$	(12)
$Q_{(\text{convection from Kiln surface})} = h_{\text{nconv}} A_{\text{kiln}} (T_s - T_\infty)/(1000 \times m_{cl}$	(13)
$h_{\text{nconv}} = k_{air} \times Nu/D_{\text{Kiln}}$	(14)
$Ra = \frac{g\beta(T_s - T_\infty)d^3}{\nu^2} \times Pr$	(15)
$Ra = G_r P_r$	(16)

$$N_u^{0.5} = 0.60 + 0.387 * \left[\frac{G_r P_r}{\left[1 + \left(\frac{0.559}{P_r}\right)^{\frac{9}{16}}\right]^{\frac{16}{9}}}\right]^{\frac{1}{6}} \quad (17)$$

$$N_u = ((0.6 + 0.387(\mathrm{Ra})^{\frac{1}{6}})/(1 + (.559/.6877)\text{^}(9/16)\ )\text{^}(8/27))^2 \quad (18)$$

Heat Losses From Cyclones	
$Q_{(\text{Radition for cyclonI})} = \sigma\epsilon A_c(T_s{}^4 - T_\infty{}^4)/\ (1000\times m_{cl})$	(19)
$Q_{(\text{convection forcyclonI})} = h_{nconv} A_c (T_s - T_\infty)/(1000\times m_{cl})$	(20)
$\mathrm{Ra} = \frac{g\beta(T_s - T_\infty)d^3}{\nu^2} \times \mathrm{Pr}$	(21)
$N_u = 0.1(\mathrm{Ra})^{1/3}$	(22)
$h = k_{air} \times Nu/L_c$	(23)
Heat Losses From Cooler	
$Q_{(\text{Radition for cooler surface})} = \sigma\epsilon A_c(T_s{}^4 - T_\infty{}^4)/\ (1000\times m_{cl})$	(24)
$Q_{(\text{convection for cooler surface})} = h_{nconv} A_c (T_s - T_\infty)/(1000\times m_{cl})$	(25)
$\mathrm{Ra} = \frac{g\beta(T_s - T_\infty)d^3}{\nu^2} \times \mathrm{Pr}$	(26)
$N_u = 0.1(\mathrm{Ra})^{1/3}$	(27)
$h = k_{air} \times Nu/L_c$	(28)
Heat Losses From Air Duct	
$Q_{(\text{Radition for Tertiary Air Duct surface})} = \sigma\epsilon A_c(T_s{}^4 - T_\infty{}^4)/\ (1000\times m_{cl})$	(29)
$Q_{(\text{convection forTertiary Air Duct surface})} = h_{nconv} A_c (T_s - T_\infty)/(1000\times m_{cl})$	(30)
$\mathrm{Ra} = \frac{g\beta(T_s - T_\infty)d^3}{\nu^2} \times \mathrm{Pr}$	(31)
$N_u = ((0.6 + 0.387(\mathrm{Ra})^{\frac{1}{6}})/(1 + (.559/.6877)\text{^}(9/16)\ )\text{^}(8/27))^2$	(32)
Heat Losses From Precalciner	
$Q_{(\text{Radition for precalciner surface})} = \sigma\epsilon A_c(T_s{}^4 - T_\infty{}^4)/\ (1000\times m_{cl})$	(33)
$Q_{(\text{convection for precalciner surface})} = h_{nconv} A_c (T_s - T_\infty)/(1000\times m_{cl})$	(34)
$\mathrm{Ra} = \frac{g\beta(T_s - T_\infty)d^3}{\nu^2} \times \mathrm{Pr}$	(35)

$N_u=0.1(Ra)^{1/3}$ (36)

$h = k_{air} \times Nu/L_c$ (37)

Regarding the preheater group, there are five stages of cyclone difference in dimensions and outside temperature which are measured using infrared instruments. Table 4 shows the outside temperature and physical properties for the five cyclones.

Table 4. Outside temperature and physical properties for five cyclones

Properties	Cyclone I	Cyclone II	Cyclone III	Cyclone IV	Cyclone V
Ts(K)	312	362	412	462	396
T_∞(K)	288	288	288	288	288
T_f(K)	300	325	350	375	342
K_{air}(w/m k)	2.6	2.816	3.003	2.317	2.943
Pr	0.707	0.701	0.697	0.692	0.698
$\nu(m^2/s)$	1.5	1.8	2.05	2.3	1.97
Diameter, m	7.2	7.2	7.5	7.5	7.5
Length, m	14.396	9.025	9.445	10.645	10.645
Surface area, m^2	325.65	204.14	222.54	250.81	250.81

4 RESULTS AND DISCUSSION

4.1 Input and Output Energy of the Kiln System

The total heat input to the kiln system given in table 5. These include the total heat of the coal, the sensible heat of coal, raw material, and air. It is important to notice that the reference enthalpy is assumed to be zero at 0 ^oC for the calculations [3]. As indicated in table 5, all the energy employed in the process is 3493.416 kJ/kg-clinker. The key heat source is heavy oil, providing an overall heat of 3319.6 kJ/kg-clinker (95%).

Table5. Total heat input of the kiln system

Heat Input	Result (kJ/kg-clinker)	Percent
Combustion of fuel	3319.6	95.02
Sensible heat by fuel	16.746	0.48
Heat by raw material	72.67	2.08
Organics in the kiln feed	18.93	0.54
Heat by cooling air	67.62	1.93

Total heat inputs	3493.416	100

As clearly shown in Table 6, there is a consistency between the input and output energy. Since most of the heat loss sources have been considered, there is only a 274 kJ/kg-clinker of energy difference from the input heat. It is about 8% of the total input energy and could be attributed to the assumptions and nature of data. The heat loss calculations of each individual component exhibited a good agreement with other published reports [12,13].

Table 6. Total heat output of the kiln system

Heat outputs	Result (kJ/kg-clinker)	Percent
Formation of clinker	1749.5	50.08
Kiln exhaust gas	717.713	20.52
Moisture in raw material	15.005	0.43
Clinker discharge	85.800	2.45
Heat loss at cooler stack	183.546	5.25
Heat losses due to dust in the kiln exist gas	16.993	0.48
Heat losses from rotary kiln	159.356	4.56
Heat losses from preheater group	32.373	0.92
Heat losses from cooler	12.438	0.35
Heat losses from tertiary air duct	22.714	0.65
Heat losses from precalciner	44.729	1.28
Heat losses from raw material and fuel	179.01	5.12
Unaccounted losses	274.239	8.00
Total heat outputs	3493.416	100

As depicted in table 6, there are a few major heat loss sources. Heat of formation of clinker was 1749.5 kJ/kg-clinker. It is in an acceptable industrial range where the major share of thermal energy in cement production is required for the endothermic chemical-mineralogical reactions forming cement clinker phases at temperatures up to 1450 °C with gas temperatures up to 2000 °C. It amounts to 1,590 to 1,840 kJ/kg-clinker, in the kiln dry type system. Heat of formation of clinker depending predominantly on the kiln feed chemical composition. The kiln feed considered as an indicator for soft or hard burning [14].

The energy output from the kiln exhaust gas was 717.713 kJ/kg-clinker, where the gases released are CO_2, NOx, and SO_2. Due to high carbon content in raw material, the most released gas is a carbon dioxide. The carbon dioxide emitted from calcination and combustion process increased by increasing calcium carbonate content. Increase in carbonate means increase in fuel consumption and results in increase in exhaust gases and consequently increase in heat losses [15].

Heat loss through the cooler stack was in an acceptable industrial range. It depends on the efficiency of cooling process and the efficiency of exhaust gas fan to drawing hot gases from cooler. In addition, the hot kiln shell outer surface is another significant heat loss source. The outer shell temperature depend on the coating formation inside the kiln and its optimum value should not exceed 350 °C. On the other hand, the use of a secondary shell on the kiln surface can significantly reduce this heat loss. Clinker discharge was 85.8 kJ/kg-clinker. Clinker temperature at the discharge of the cooler should be as low as possible because high temperatures endanger the transport equipment and waste valuable heat. However, fast cooling of the product (clinker) enables heat recovery from the clinker and improves the product quality. The tertiary air is a duct covered by certain insulation, used for transfer hot air from cooler to precalciner. Heat loss from tertiary can be reduced by using material with high insulation quality. Heat losses due to dust in the kiln exist gas was 17 kJ/kg-clinker. It depends on the efficiency of kiln filters (electric precipitate), that separate dust from kiln exhaust gases and recycle the dust to the kiln as cement kiln dust (CKD).

4.2 Heat Losses from Preheater Group

There are five stages of cyclone difference in dimensions and outside temperature, which measured by using infrared instrument. The total heat losses from preheater group are 32.373 kJ/kg-clinker. Figure 6 represents the heat losses from the preheater group. The main source of the heat, in this section of the cement production process, is came from the hot flue gases that are passes through the cyclones. The flue gases were been generated by burning of fossil fuel in the kiln. Consequently, the heat lost by radiation and convection to the ambient surroundings. As shown in this figure, the heat losses from the cyclones is not uniform. However, it is varies from one cyclone to another through the preheater group. This variation in the heat losses is due to position of the cyclones with regarding to kiln where the heat come from. The closer to the kiln, the more heat losses to surrounding.

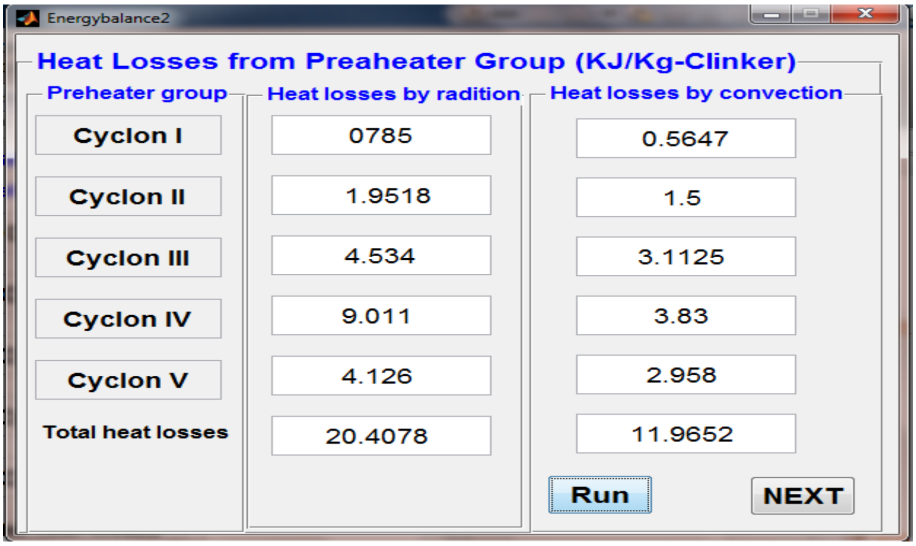


Figure 6. Graphical User Interface Matlab for Calculating heat losses from preheater group

4.3 Assessment of Energy Balance for the Kiln System

The overall system efficiency can be defined by $\eta = \frac{1749.5}{3493.416} = 0.500799$ or 50.08% . This is considered relatively low. Based on current dry process methodology, some kiln systems operating at full capacity would declared an efficiency of 55% [4]. By recovering some of the heat losses, the overall efficiency of the kiln system can be improved. The recovered heat energy can then be used for a variety of applications, including heating raw materials and generating electricity. The following are the primary heat loss sources that would be considered for heat recovery: (1) kiln exhaust gas (20.54%), (2) hot air from the cooler stack (5.25%), and (3) radiation from kiln surfaces (4.56%).

5 CONCLUSION

The GUI was used for energy analysis of ACP Rotary Kilns. After all data regarding the plant was collected and entered, GUI Matlab have been developed to help cement process engineers to calculate mass and energy balances. However, the distribution of the input heat energy to the system components exhibited good agreement between the total input and output energy and gave significant insights about the reasons for the low overall system efficiency. According to the results obtained, the system efficiency was around 50%. The total amount of heat input is 3493.416 kJ/kg-clinker, about 95% of this amount is obtained from fuel combustion (3319.6 kJ/kg-clinker). The major heat loss sources have been determined as kiln exhaust (20.54% of total input), cooler exhaust (5.25% of total input) and combined heat losses from raw material and fuel as well as radiative and convective heat transfer from kiln surfaces (9.68% of total input).The overall efficiency of the plant can be improved by reducing the heat losses. One way to reduce heat loss is by implementation of the annular duct type of the heat exchanger a secondary shell on the kiln surface. This will reduce fuel consumption and increase the overall system efficiency.

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تحليل الطاقة باستخدام واجهة المستخدم الرسومية للمتلاب لفرن الاسمنت الدوار لمصنع اسمنت البرج

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الملخص

صناعة الاسمنت هي أحد أكثر الصناعات في العالم استهلاكًا للطاقة لإنتاج الكلنكر، في مصانع الاسمنت الافران الدوارة مستخدمة بنطاق واسع. هذا البحث يقوم بتحليل الطاقة الحرارية لنظام الفرن الدوار العامل بمصنع اسمنت البرج وهو أحد المصانع التابعة لشركة الاتحاد العربي الواقع بمدينة زليتين بليبيا، ينتج هذا الفرن 4200 طن كلنكر لكل يوم. الهدف الرئيسي من هذا البحث هو اختبار وتحديد الطاقة المفقودة من الفرن وملحقاته. في هذا البحث تم تكوين واجهة المستخدم الرسومية للمتلاب لحساب توزيع الطاقة الحرارية لمصنع اسمنت البرج كنموذج خاص. أظهرت النتائج التي تم الحصول عليها ان حوالي % 30 من الطاقة تفقد على النحو التالي 20.45% تفقد مع الغازات الساخنة الخارجة من الفرن، 5.25% من الطاقة تفقد من المبرد و4.56% من الطاقة تفقد من الغلاف الخارجي للفرن على شكل طاقة حرارية بالحمل والاشعاع.

الكلمات الدالة:
حساب الطاقة.
الأفران الدوارة.
مصنع الاسمنت.
واجهة المستخدم الرسومية.

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