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ENERGY AND EXERGY ANALYSIS OF CEMENT ROTARY KILN

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Abstract — *In this study, the rotary kiln of cement industry is taken as the control volume having the length of 75 m, diameter of 4.35 m and capacity of 4400 MTD. The average operational data for the rotary kiln is collected for the winter period in the December month of the 2015 for the rotary kiln situated at Gujarat Sidhee Cement Ltd, Morasa, Gir-Somnath, Gujarat, India for the numerical calculations. This paper reviewed mass and energy balance and analysis, exergy analysis for the dry process cement industry. The energy lost from the kiln shell is about 6.4 MW. The results for the analysis show that the 33.63% of the total exergy is still wasted to the environment though the pre calcining and pre heating of the raw material. The overall kiln exergy analysis show the irreversibility of 61.71% and the first and second law efficiency for the rotary kiln of GSCL is 51.90% and 38.29% respectively.*

Keywords *- Energy, Exergy, Cement, Rotary kiln, Dry process*

I. INTRODUCTION

Cement production is one of the most energy intensive industries in the world. The cement industries consume approximately 12–15% of total industrial energy use. Energy accounts for 30-40% of total production cost in the cement industry. Reduction of the production cost is very much important. As energy analysis fails to indicate both the energy transformation and the location of energy degradation, in recent years, emerged a growing interest in the principle of special ability to measure different types of energy to work and popularly known as exergy.

The production of cement is also emits a lot of CO2, due to the decomposition of CaCO3. Cement production accounts for about 8% of total CO2 emissions from all human activities. It is beneficial from both an environmental and an energy point of view to optimize or redesign this process to improve its efficiency [5]. The main purpose of exergy analysis is to detect and assess quantitatively the thermodynamic imperfections' causes of thermal and chemical processes. The exergy method of thermodynamic analysis is based upon both the first and the second laws of thermodynamics together, while the energy analysis is based upon the first law only. It is a feature of the exergy concept to allow quantitative assessment of energy degradation [7].

Firstly the mass balance of the rotary kiln system is analyzed. Then, enthalpies going into and leaving the rotary kiln are calculated according to the first law of thermodynamics. Furthermore, exergy analysis is made based on the second law of thermodynamics. Finally efficiencies depending on both the first and second laws are compared which are also shown in the Grassman diagrams of the same. The schematic for the analysis is shown in the ***Figure 1***.

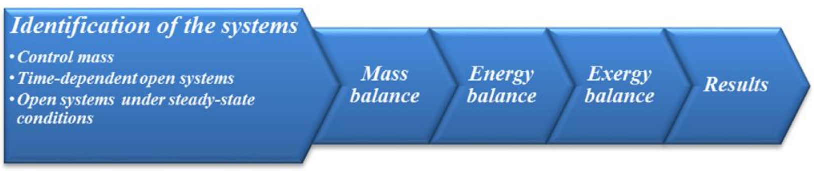

Figure 1 Specific method for the analysis of rotary kiln

II. SYSTEM DESCRIPTION

The system of the cement production mainly includes following steps and the brief description about them is also explained.

1) **Raw material extraction:** The raw material i.e. lime stone is excavated from the mines using the earthmover like surface miner.

2) **Limestone crushing:** The lime stone, in terms of boulders is crushed in single impact rotor crusher upto 75mm (about 95%) long lumps.
3) **Limestone storage & pre-homogenization:** The lime stone after the crushing is stored in terms of piles, stacked by the twin boom stacker and homogenization is done by bridge type reclaimer and dispatched to the grinding process of limestone to the Vertical Raw Mill (VRM).
4) **Raw material grinding, blending & storage:** The lime stone then grinded upto the 90 micron powder (about 20-25%) and stored in the C.F.S. (Continuous Flow Silo) in which the blending continuously occurs by air which is blown by the blowers.
5) **Clinkerisation:** This raw meal then fed into rotary kiln from silo for the final product i.e. clinker through the pro processing section i.e. P.H. (Pre Heater) & P.C. (Pre Calciner) where 90-95% calcination is done. After that the clinker goes for cooling in the grate cooler and sent to the grinding section for the final product production.
6) **Clinker grinding:** The clinker with necessary amount of gypsum (which is used to manage settling time of cement, about 13-15%, in case to produce OPC - Ordinary Portland Cement) and fly ash (about 30-40%, in case to produce PPC - Pozzolana Portland Cement) are grinded in ball mills upto 30 micron (about 40%) fineness to produce the cement.
7) **Cement storage, packing & dispatch:** Again the cement is stored in the silos and as per the requirement it is packed in the bags by electronic packers and dispatched directly to the carriers.
   The over view of complete cement production system can be found in the following ***Figure 2*** to understand the same.

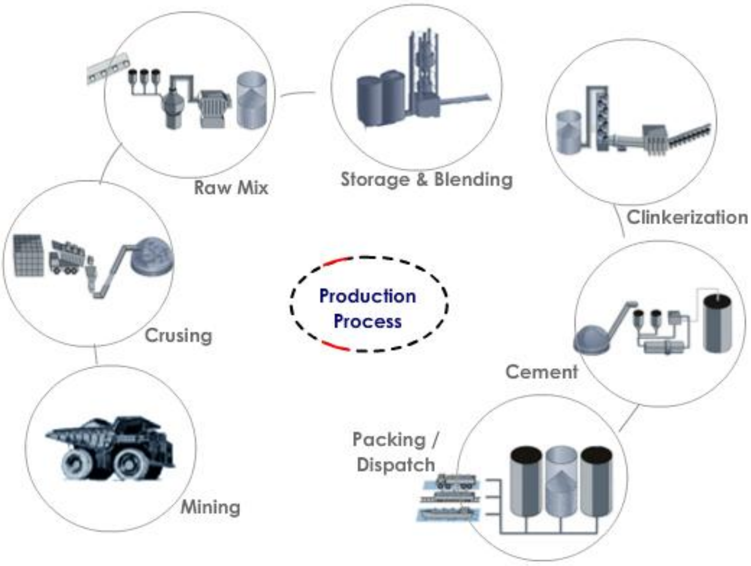

Figure 2 Cement production process

III. THERMODYNAMIC ANALYSIS OF ROTARY KILN

3.1. Assumptions

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

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

3.2. Mass balance

The mass balance for an open system operating under steady state conditions is expressed as:

$$\sum m_{in} = \sum m_{out} \quad \text{………. (1)}$$

The schematic for the mass balance of the kiln system is shown in the ***Figure 3*** and the mass balance is shown in the ***Table 1***.

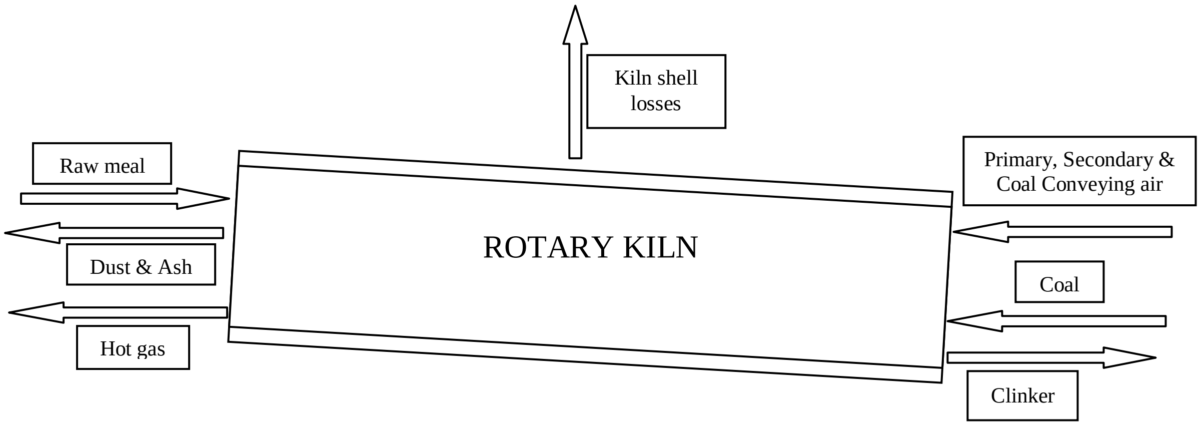

Figure 3 Schematic for the mass balance of the rotary kiln

Table 1 Mass balance of the rotary kiln

Type of material	Mass flow rate, m (kg/sec)	Total
Input		
Raw meal	60.27	91.27
Coal	2.55	
Primary air	2.31	
Coal conveying air	0.72	
Secondary air	25.42	
Output		
Clinker	51.31	91.27
Hot gas	37.78	
Dust & ash	2.18	

3.3. Energy analysis

The energy balance for the open system operating under steady state condition is expressed as:

$$\sum Q_{in} = \sum Q_{out} \quad \text{………… (2)}$$

$$\text{Where, } Q = m \times C_p \times \Delta T \quad \text{………… (3)}$$

All the energies, coming in and going out is to be calculated by using above equation. The energy used for the formation of the clinker can be found using the Zur-Strassen equation [14].

Clinker formation energy = 2.22 [Al_2O_3] + 6.48 [MgO] + 7.66 [CaO] – 5.116 [SiO_2] – 0.59 [Fe_2O_3] ………… (4)

Also the GCV (Gross Calorific Value) of the coal and pet coke is found using Dulong's formula [7].

$$GCV = 337 \times C + 1442\,(H - O/8) + 93 \times S \quad \text{………… (5)}$$

Also because of the temperature difference between outer and inner surface of the rotary kiln, the heat transfer from the rotary kiln shell to the environment occurs. And this heat transfer is due to the conduction, convection and the radiation. This heat transfer is considered as the loss of heat that can be conserved somehow. The heat transfer between kiln shell and surrounding can be calculated from the following equation [11] [12].

$$Q_{TOTAL} = \frac{T_{in} - T_{out}}{R_{total}} \quad \text{………… (6)}$$

Where,

$$R_{TOTAL} = R_{cond1} + R_{cond2} + \frac{R_{conv} \times R_{rad}}{R_{conv} + R_{rad}} \quad \text{........... (7)}$$

$$R_{cond} = \frac{\ln\left(\frac{r_{out}}{r_{in}}\right)}{2 \times \pi \times L \times k} \quad \text{........... (8)} \qquad R_{conv} = \frac{1}{A \times h} \quad \text{........... (9)} \qquad R_{rad} = \frac{1}{A \times E} \quad \text{...... (10)}$$

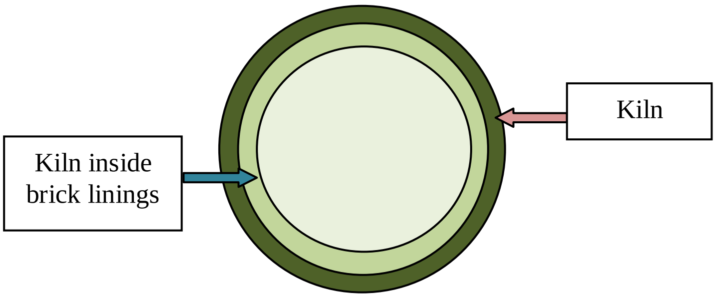

Figure 4 Transverse cross section of rotary kiln shell

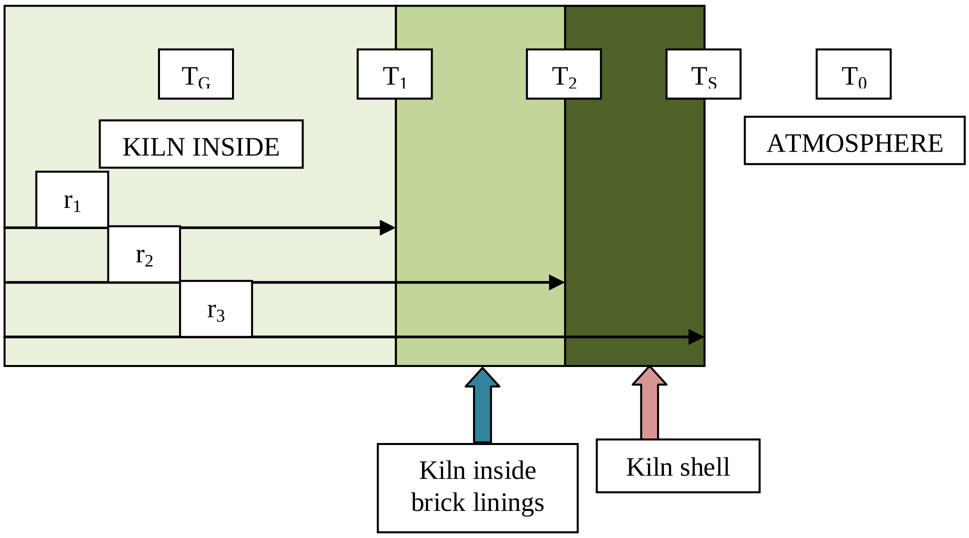

Figure 5 Longitudinal cross section of rotary kiln shell

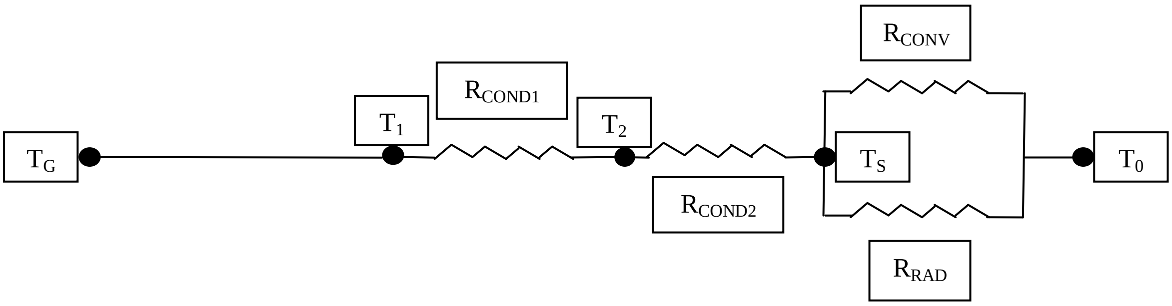

Figure 6 Equivalent circuit of kiln shell resistance

In the above equations 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 75m and the dia. is 4.35m, k is the thermal conductivity of bricks lining (2.7-1.5 W/mK) [17] and kiln shell (27 W/mK) [16], h is the natural convective coefficient, E is the radiative heat transfer and can be found by the following equation [12].

In general, the natural convective heat transfer can be correlated with the Grashof number (Gr), which is defined as

$$Gr = \frac{g \times \beta \times \Delta T \times d^3}{\nu^2} \qquad \text{........... (11)}$$

Where β is the volumetric expansion coefficient (=1/T for ideal gases as used in this study), ΔT is the temperature difference between the heated surface and the surrounding fluid, g is the gravitational acceleration, and ν is the fluid kinematic viscosity, ΔT is the characteristic temperature and is equal to $(T_s – T_o)/2$.

The heat transfer coefficient (h) is scaled to a non dimensional number, Nusselt number (Nu),

$$h = \frac{Nu \times k}{d} \qquad \text{........... (12)}$$

When Gr = 10^4~10^7, the flow is laminar, and the correlation is
$Nu = 0.48(GrPr)^{(0.25)}$ .... (13)

When Gr = 10^7 ~ 10^{12}, the flow is turbulent, and the following equation should be used:
$Nu = 0.125(GrPr)^{(0.333)}$ .... (14)

And E = Heat flux = $\sigma \times \varepsilon \times F_{12} \times (T_S^2 + T_0^2) \times (T_S + T_0)$ .... (15)

Where, 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 into account the radiative heat flux effectively transferred between two surfaces (=1).

Thus, the first law efficiency of the thermodynamics can be expresses as per below equation:

$$\eta_I = \frac{\sum Q_{out}}{\sum Q_{in}}$$

$$\eta_I = \frac{\sum (Q_{clinker} + Q_{gas} + Q_{dust})}{\sum Q_{in}} \qquad \text{........... (16)}$$

The detailed energy analysis of the material is shown in the ***Table 2***.

3.4. Exergy analysis

Exergy is the maximum work potential of a system, stream of matter, or a heat interaction as the datum state in relation to the reference environment [11]. Most thermal systems are supplied with exergy inputs derived directly or indirectly from the consumption of fossil fuels. Accordingly, avoidable destructions and losses of exergy represent the waste of these resources. By devising ways to reduce such inefficiencies, better use can be made of fuels. The exergy balance can be applied to determine the locations, types, and true magnitudes of energy resource waste, and thus can play an important part in developing strategies for more effective fuel use [13]. Moreover, exergy can be defined as the maximum theoretical work obtainable from an overall system consisting of a system and the environment as the system comes into equilibrium with the environment (passes to the dead state) [8].

Environment
For thermodynamic analysis involving the exergy concept, it is necessary to model the atmosphere used. The resulting model is called the exergy reference environment, or simply the environment. From a theoretical standpoint, the environment must be in thermodynamic equilibrium, and therefore with no usable energy, but in fact it is not, as its intensive properties vary from place to place and from time to time. Owing to high activation energy, many reactions - thermodynamically spontaneous - that lead to thermodynamic equilibrium are kinetically blocked. The intensive properties of the environment do not change significantly as a result of any process under consideration and the environment is free of irreversibilities.

Dead state
When the pressure, temperature, composition, velocity or elevation of a system is different from the environment, there is an opportunity to develop work. As the system changes state toward that of the environment, the opportunity diminishes, ceasing to exist when the two, at rest relative to one another, are in equilibrium. This state of the system is called the dead state.

The four components of the exergy [15] are Potential exergy, Kinetic exergy, Physical exergy and Chemical exergy.

Potential & kinetic exergy

The kinetic energy, E_K and potential energy, E_P of a stream of substance are ordered forms of energy and thus fully convertible to work. Therefore, when evaluated in relation to the environmental reference datum levels, they are equal to kinetic and potential exergy respectively. Thus:

$$E_K = m\,v^2/\,2 \text{ and } E_P = mgZ$$

Physical exergy

Physical exergy, E_{PH} is equal to the maximum amount of work obtainable when the stream of substance is brought from its initial state to the environmental state defined by P_0 and T_0, by physical processes involving only thermal interaction with the environment. The physical exergy of a closed system at a specified state is given by expression,

$$E_{PH} = (U-U_0) + P_0\,(V-V_0) - T_0\,(S-S_0)$$

Chemical exergy

Chemical exergy may be defined formally as the maximum work that can be obtained when the considered system is brought into reaction with reference substances present in the environment. Chemical exergy is equal to the maximum amount of work obtainable when the substance under consideration is brought from the environmental state to the dead state by processes involving heat transfer and exchange of substances only with the environment.

The assumptions are steady state and steady-flow process. The following equations represent the exergy balance for the rotary kiln.

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \dot{E}x_{dest}$$

$$\sum\left(1-\frac{T_0}{T_s}\right)\times Q - W_{out,net} + \sum m_{in}\Psi_{in} - \sum m_{out}\Psi_{out} = \dot{E}x_{dest} \qquad \text{............ (17)}$$

Where Q is the heat transfer rate through the boundary of the rotary kiln at temperature T_s at location s.

As the maximum improvement in the exergy efficiency for a process is obviously achieved when the exergy loss or irreversibility is minimized. Higher exergy efficiency permits a better matching of energy sources and uses.

$\Delta h = \Delta u + v\,\Delta P$

Where, ΔP is a pressure change. Due to the negligible pressure change the enthalpy change is equal to the internal energy change.

$\Delta h = \Delta u$

$\quad = C_P\,\Delta T$

For ideal gases the entropy change is:

$$\Delta s = C_p \ln\left(\frac{T_{in-out}}{T_0}\right) - Rln\left(\frac{T_{in-out}}{T_0}\right)$$

Though the fluid in the rotary kiln is considered as incompressible fluid, the above equation can be written as:

$$\Delta s = C_p \ln\left(\frac{T_{in-out}}{T_0}\right) \qquad \text{............ (18)}$$

After obtaining the entropy and enthalpy values of the input and output materials, the exergy values of input and output materials in the rotary kiln are calculated from the following equations.

$\Delta\Psi = \Delta h - T_0\,\Delta s$

The second-law efficiency or exergetic efficiency may generally be defined as the rate of exergy output divided by the rate of exergy input:

$$\eta_{II} = \frac{\sum \Psi_{out}}{\sum \Psi_{in}} \qquad \text{............ (19)}$$

The detailed exergy analysis of the rotary kiln is shown in the ***Table 2***.

Table 2 Energy and exergy analysis of the rotary kiln

Material	Composition	%	m (kg/sec)	C_P[6] (kJ/kgK)	T_{in} (K)	T_{out} (K)	Δh (kJ/kg)	Δs (kJ/kgK)	∑mΔh (kW)	∑mΔΨ (kW)
Input										
Raw- meal	CaO	43.36	39.63	0.66	1230	301	575.98	0.873	22826.09	12412.51
	SiO_2	12.46	11.39	0.69	1230	301	641.01	0.971	7301.10	3972.15
	Al_2O_3	3.46	3.16	2.01	1230	301	1867.29	2.829	5900.64	3209.80
	Fe_2O_3	2.70	2.47	4.16	1230	301	3864.64	5.856	9545.66	5191.89
	H_2O	2.00	1.83	4.18	1230	301	3883.22	5.884	7106.29	3865.22
	MgO	1.25	1.14	0.37	1230	301	343.73	0.521	391.85	213.08
	SO_3	0.36	0.33	0.62	1230	301	575.98	0.873	190.07	103.36
	K_2O	0.25	0.23	4.31	1230	301	4003.99	6.067	920.92	500.90
	Na_2O	0.10	0.09	4.36	1230	301	4050.44	6.137	364.54	198.28
TOTAL		100.00	60.27						54547.16	29667.19
Pet-coke	C	75.10	0.766	0.03	343	301	1.26	$3.92x10^{-3}$	0.97	0.06
	H	4.20	0.043	14.32	343	301	601.44	1.871	25.86	1.64
	N	1.70	0.017	1.04	343	301	43.68	0.136	0.74	0.05
	S	3.00	0.031	5.64	343	301	236.88	0.737	7.34	0.47
	O	4.90	0.050	0.92	343	301	38.64	0.120	1.93	0.13
	Ash	11.10	0.113	1.30	343	301	54.60	0.170	6.17	0.38
TOTAL		100.00	1.020						43.01	2.73
Coal	C	85.60	1.310	0.03	343	301	1.26	$3.92x10^{-3}$	1.65	0.11
	H	12.20	0.187	14.32	343	301	601.44	1.871	112.47	7.21
	N	0.13	$1.989x10^{-3}$	1.04	343	301	43.68	0.136	0.08	~0
	S	0.27	$4.313x10^{-3}$	5.64	343	301	236.88	0.737	0.98	0.06
	O	0.70	0.011	0.92	343	301	38.64	0.120	0.43	0.03
	Ash	1.10	0.017	1.30	343	301	54.60	0.170	0.93	0.06
TOTAL		100.00	1.530						116.54	7.46
Combustion of pet-coke	-	-	1.02	1.15	1223	301	29810.00	1.612	31376.09	31188.20
Combustion of coal	-	-	1.53	1.19	1223	301	39500.00	1.668	70897.96	70129.79
Primary air	-	-	2.31	1.005	327	301	26.73	0.085	61.75	2.65
Conveying air	-	-	0.72	1.005	327	301	26.73	0.085	19.25	0.83
Secondary air	-	-	25.42	1.177	1350	301	1234.67	1.766	31385.39	17872.90
Electrical work	-	-	-	-	-	-	-	-	7488	
Output										
Clinker	CaO	65.35	33.53	0.618	1543	301	767.55	1.010	25736.15	15542.70
	SiO_2	21.45	11.00	0.743	1543	301	922.81	1.214	10150.87	6131.31
	Al_2O_3	5.90	3.03	2.167	1543	301	2691.41	3.542	8154.98	4924.57
	Fe_2O_3	4.52	2.32	4.426	1543	301	5497.09	7.234	12753.25	7701.61
	MgO	1.15	0.59	0.392	1543	301	486.86	0.641	287.25	173.41
	SO_3	0.82	0.42	0.887	1543	301	1101.65	1.450	462.69	279.39
	K_2O	0.70	0.36	4.779	1543	301	5935.52	7.811	2136.79	1290.39
	Na_2O	0.11	0.06	4.711	1543	301	5851.06	7.700	351.06	2112.00
TOTAL			51.31						60033.04	36864.99
Hot gas	-	-	37.78	1.177	1160	301	1011.04	1.588	38197.20	20138.82
Dust & ash	-	-	2.18	1.052	683	301	401.86	0.862	876.06	20449.26

3.5. Result & discussion

From the equations (16) & (19), we can calculate that the first and the second law efficiency of the rotary kiln is 51.90% and 38.29% respectively. Moreover, the Grassman diagram of the energy and exergy analysis are represented in ***Figure 7*** and ***Figure 8***.

Table 3 Final results

Material	m (kg/sec)	Q (kW)	Ψ (kW)
Input			
Raw - meal	60.27	54547.16	29667.19
Pet-coke & Coal	2.55	159.56	10.20
Combustion of coal	-	102274.05	100706.45
Primary air	2.31	61.75	2.65
Coal conveying air	0.72	19.25	0.83
Secondary air	25.42	31385.39	17872.90
Electrical work	-	7488.00	7488.00
TOTAL	91.27	195935.16	156359.76
Output			
Clinker	51.31	60033.04	36864.99
Clinker formation	-	87745.72	-
Hot gas	37.78	38197.20	20138.82
Dust & ash	2.18	876.06	310.44
Kiln shell	-	6338.78	2570.18
Unaccounted loss	-	2744.36	-
TOTAL	91.27	195935.16	59881.43

The diagram shows that the 44.78% energy is not useful of total input while 2.7 MW is the unaccounted loss. The result shows that the greater portion of the energy is transferred through the kiln shell which is recoverable. Also it can be derived that it takes 87.75 MW for the formation of the clinker. Moreover the irreversibility of rotary kiln is about 61.71% that shows the destruction of the exergy into the system while 33.63% exergy is going with the hot gas which can be retrieved by some auxiliary arrangements. The resulting calculations of whole analysis are tabulated in ***Table 3***.

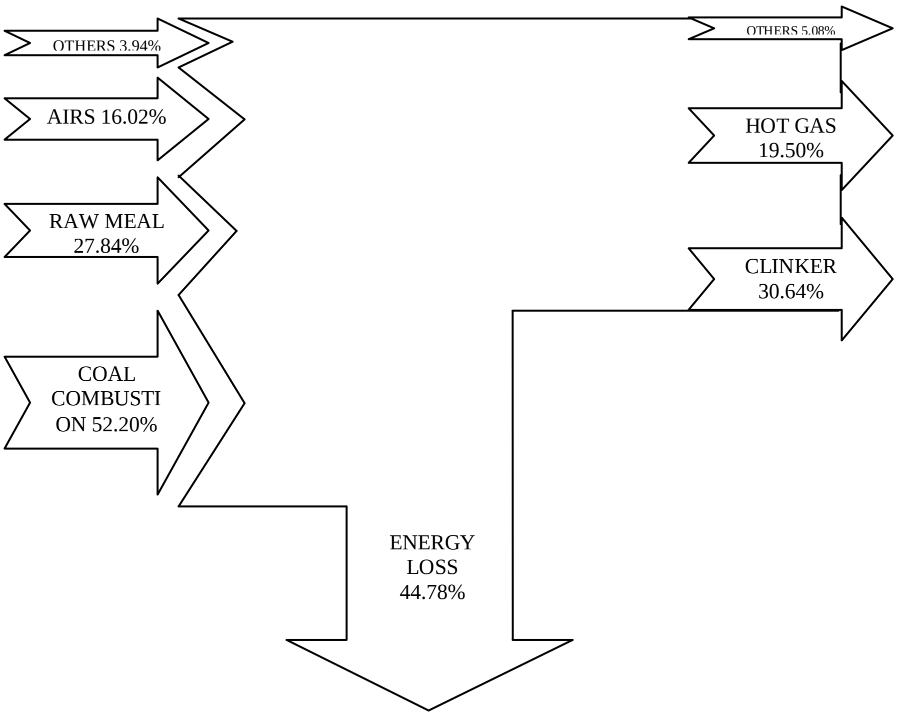

Figure 7 Grassman diagram of energy analysis of rotary kiln

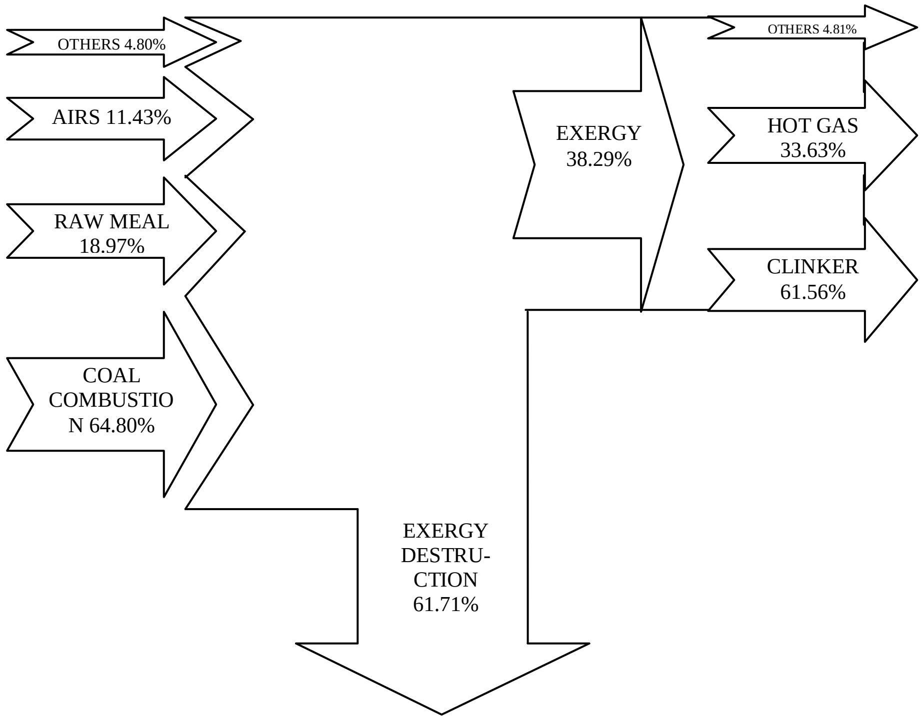

Figure 8 Grassman diagram of exergy analysis of rotary kiln

3.6. Conclusion

The following conclusions can be made from the energy balance-analysis and exergy analysis.

- It is found that the implementation of exergy analysis on the production line is a very efficient way for improving the performance of the system and reduction of energy costs.
- From the data taken and the numerical calculations, we can conclude that the first law and the second law efficiency of the rotary kiln of Gujarat Sidhee Cement Ltd. is 51.90% and 38.29% respectively. Also the exergy analysis shows that the rotary kiln has the irreversibility of 61.71%, which directly indicates the huge portion of availability for the upgradation of the system.
- The amount of O_2 and CO coming out from the rotary kiln hot gas are 7.29% and 0.38% respectively. The % of the O_2 shows that the amount of the oxygen coming out of the kiln hot gas is more than that of the normal that shows the unburnt oxygen is coming out of the rotary kiln, it shows that the excess air is supplied to the rotary kiln.
- The energy going with the hot gas is about 19.50% of the energy input (approximately 38 MW). Though after using this energy into the pre-calcination and pre-heating, the out let temperature of the hot gas is in order of 340^0C. For which an auxiliary circuit like WHRSG (Waste Heat Recovery Steam Generator) can be installed.
- In order to reduce the heat loss from the kiln shell the surface of the kiln should be painted having appropriate emissivity. Also the anzast layer inside the kiln bricks lining should be maintained upto the range so that it dead load of the kiln do not alter much.

Nomenclature

m	Mass flow rate
C_P	Specific heat
Q	Heat transfer
$\dot{E}$	Energy rate
T_0	Ambient temperature
T_S	Surface temperature
W	Work
s	Entropy
h	Enthalpy
Ψ	Exergy flow

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