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Energy and Exergy Analysis of Cement Production Process in the context of Waste Heat Recovery and reduction of CO_2 Emission

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Abstract**—***Cement industry ranks 2nd in energy consumption among the industries in India. It is one of the major emitter of* CO_2*, due to combustion of fossil fuel and calcination process. The main objective of the research work is to assess the energy consumption and energy conservation of the Indian cement industry and to predict future trends in cement production and reduction of* CO_2 *emissions. In order to achieve this objective, a detailed energy and exergy analysis of a typical cement plant in MP was carried out. The data on fuel usage, electricity consumption, amount of clinker and cement production were also collected from selected cement industry and the* CO_2 *emissions were estimated. The energy and exergy analysis of the raw mill of the cement plant revealed that the exergy utilization was worse than energy utilization. The energy analysis of the kiln system showed that around 38% of heat energy is wasted through exhaust gases of the preheater and cooler of the kiln system. The cement industry will remain one of the critical sectors for India to meet its* CO_2 *emissions reduction target. India's cement production will continue to grow in the near future due to its GDP growth. The control of population, improvement in plant efficiency and use of renewable energy are the important options for the mitigation of* CO_2 *emissions from Indian cement industries.*

Keywords:— *Cement industry, energy and exergy analysis, Raw Mill, Kiln System, waste heat recovery system,* CO_2 *emissions.*

1. INTRODUCTION

Cement is produced worldwide in virtually all countries as an important building material. With the Government of India giving boost to various infrastructure projects, housing facilities and road networks, the cement industry in India is currently growing at an enviable pace. The Indian cement industry is the second largest producer of cement in the world just behind China, but ahead of the United States and Japan. The production of cement clinker from limestone and chalk is the main energy consuming process in this industry. The most widely used cement type is Portland cement, which contains 95% cement clinker. Cement production is an energy-intensive process in which energy represents 20 to 40% of total production costs. Most of the energy used is in the form of fuel for the production of cement clinker and electricity for grinding the raw materials and finished cement. In short, the main environmental challenges facing the cement manufacturing industry are releases to air of oxides of nitrogen, sulphur dioxide, particulates and carbon dioxide, use of resources, especially primary raw materials and fossil fuel and generation of waste.

1.1. Research Problem

Cement production accounts to nearly 2% of the world's total energy demand. The high intensity of CO_2 reduces the reflectivity of the surface and allows greater absorption of solar radiation, thus cause global warming. The possibility of such significant changes demonstrates the need to study the effect of cement production due to its large amount of CO_2 emissions. Numerous studies have been conducted in energy conservation and CO_2 mitigation actions are reported in many countries. The forecasting of CO_2 emissions from this sector becomes essential because of the production growth rate due to higher demand. Now, recently some researchers have done forecasting models in Indian scenario, but none of them with real time plant data and result validation. This research concept of forecasting of CO_2 emissions and with mitigation options from the cement industries on system dynamic approach will be outstanding support as a reference for upcoming research since the analysis have been carried on with dynamic condition.

1.2 Objectives of Research

- To conduct energy and exergy analysis of the cement industry.
- To identify the area in which energy conservation opportunities are in the cement industry.
- To collect data on fuel usage, electricity consumption and amount of clinker and cement production from the major cement industries in India.
- To estimate CO_2 emissions of the selected cement industry of MP.
- Energy conservation management scenario was also discussed. The projection of this scenario states that recovery of waste heat and also using renewable energy in the cement industries will help to reduce CO_2 emissions.

2. REVIEW OF LITERATURE

Sogut (2012) examined exergetic efficiency of Turkish cement production and CO_2 emissions caused by the sector due to exergetic losses and environmental effects

Madlool et al (2012) reviewed exergy analysis, exergy balance, and exergetic efficiencies for cement industry. It is found that the exergy efficiency for cement production units ranges from 18% to 49% as well as the exergy losses due to the irreversibility from kiln are higher than other units in cement production plant.

Wang et al (2012) studies the current strategies of energy efficiency improvement, CO_2 capture in cement production and fly ash blended cement and concrete. This paper will serve as a guide for the technology improvement, energy policy making and environmental protection in cement production.

Vedat Ari (2011) presented energetic and exergetic analyses of an existing rotary kiln system and first and second law efficiencies are calculated. The results showed that the energy and exergy efficiencies of the existing system are 54.9 and 28.1%, respectively. With the cogeneration, these exergy efficiencies have been obtained to be 70.6% for the use of waste heat recovery steam generator (WHRSG) and 81.5% for the use of heat to pre-heat the raw material, respectively.

Moya et al (2011) performs a cost-effectiveness analysis of some of the best available technologies (BAT) that can contribute to decreasing the energy consumption and CO2 emissions in the European Union's (EU27) cement industry.

Ahmet Kolip (2010) presented an alternative method to investigate the irreversibility in thermal systems by applying in a cement plant. Energy and exergy balances were calculated for whole system and its sub-units, which consist of clinker cooling, rotary kiln, calciner and preheater cyclone units. In the analyses, irreversibility sources are considered as combustion, chemical reaction, and heat transfer to raw material during mixing in the system, and heat transfer between the system and its environment.

Al-Ghandoor et al (2010) analyzed the energy and exergy utilizations in the U.S. manufacturing sector by considering the energy and exergy flows. Detailed end-use models for fourteen intensive industries are established using scattered data from the Manufacturing Energy Consumption Survey (MECS).

Rosen et al (2009) discussed the concepts of exergy analysis and the linkages between exergy and environmental impact. Several issues regarding the exergies of waste emissions are addressed.

Abdul Khaliq (2009) proposed a conceptual tri-generation system based on the conventional gas turbine cycle for the high temperature heat addition while adopting the heat recovery steam generator for process heat and vapour absorption refrigeration for the cold production.

Sogut et al (2008) determined the actual energy losses by performing energy and exergy analyses and to evaluate energy and exergy efficiency in each process for the cement factory.

Zafer et al (2006) performed energy and exergy analysis of a raw mill (RM) and raw materials preparation unit in a cement plant in Turkey using the actual operational data.

Balkan et al (2005) evaluated the performance of a triple-effect evaporator with forward feed system by using exergy analysis based on actual operational data. It is expected that the analysis presented here should provide a designer with a better, quantitative grasp of the inefficiencies and their relative magnitudes in the design, simulation and operation of multiple-effect evaporators.

Dincer (2004) suggests that exergy losses, particularly due to the use of non-renewable energy forms, should be minimized to attain sustainable development. It is concluded that the potential usefulness of exergy analysis in addressing sustainability issues and solving environmental problems is substantial.

3. ENERGY AND EXERGY ANALYSIS OF THE RAW MILL

Traditional methods of thermal system analysis are based on the first law of thermodynamics. These methods use an energy balance of the system to determine heat transfer between the system and its environment. The first law of thermodynamics introduces the concept of energy conservation, which states that energy entering a thermal system with fuel, electricity, flowing streams of matter, and so on, is conserved and cannot be destroyed. By contrast, the second law of thermodynamics introduces the useful concept of exergy in the analysis of thermal systems. Exergy is a measure of the quality or grade of energy and it can be destroyed in the thermal system. The second law states that part of the exergy entering a thermal system with fuel, electricity, flowing streams of matter, and so on is destroyed within the system due to irreversibility. The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems.

3.1 About the Cement Production Process

Limestone, the principle raw material is mined mechanically from the captive mine. The material is then crushed in two stage crushing at the mines and is conveyed to the plant site by mono cable aerial rope way. In the plant, the material is blended in the stacker re-claimer system for pre-homogenization. The limestone and other additives (sweetener grade limestone and laterite) are ground in closed circuit raw mill. The raw meal thus prepared is blended in huge blending silos and stored in storage silos. The preheated raw meal is then fed to coal fired rotary kiln. In the kiln, the material is then burned at 1280^{0}C and clinker is formed. It is then cooled down in grate cooler and stored in clinker stockpile. In the ordinary portland cement (OPC) the clinker and gypsum ratio is 95:5, for portland pozzalana cement (PPC) the mixture consists of clinker, dry fly ash and gypsum in the ratio of 65:25:5 and portland slag cement (PSC) the clinker, slag and gypsum are mixed in the ratio of 65:25:5. The grounded OPC, PPC, PSC are stored in separate silos. From the silos, it is fed into the packing house and the packing is done by electronic packing machines. After packing the products as per requirement, they are dispatched through rail or road.

The different stages of cement production in the plant are given as follows.

- Mining.
- Raw meal preparation.
- Clinkerisation and coal grinding.
- Cement grinding and packing.

3.1.1 Mining

The main raw material, limestone is in the form of hard rocks. These rocks are drilled and blasted. This limestone of 25 mm size is transported to the factory through a ropeway system. Limestone received in the plant is stacked in the stockpile.

Raw meal preparation

The raw materials such as limestone, sweetener limestone and laterite are extracted from their respective hoppers through weigh feeders in correct proportion. The material thus extracted moves through a common belt conveyor into the raw mill. A part of the kiln exhaust gas is used for drying the raw meal. In raw mill the raw materials are ground to the required fineness. The ground raw meal is then transported to turbo air separator for separating the raw meal into fine and coarse particles. The fine particles are then transported to blending silo through an air slide and bucket elevator while coarse particles are returned to the mill through a screw conveyor for further grinding.

3.1.3 Clinkerisation and Coal grinding

The raw meal, from raw mill is lifted to the top of the preheater by bucket elevator. The material thus moves through the preheater cyclone down to the rotary kiln. Hot gas from the kiln moves upwards as a result of which heat transfer takes place between raw meal and hot gas and raw meal gets partly calcined. The partly calcined raw meal then moves to the rotary kiln. Kiln is fired from the other end using pulverized coal. Due to rotation of the kiln the raw materials exposed to hot gases and in its course, it gets fully calcined.

3.1.4 Cement grinding and packing

Clinker from the clinker stockpile is extracted through belt conveyor to clinker hopper. Gypsum is also extracted through the same belt conveyor to gypsum hopper from gypsum shed. From these hoppers clinker and gypsum is extracted according to pre-set conditions to cement mill for grinding.

3.2 Raw mill

The raw mill is a cylindrical shell consists of two sections which are called drying section and grinding section. Input material after being mixed in the drying section is taken into the grinding section. Raw materials contain small amount of water. So the raw material must be heated up before it is fed into the grinding section. This is done by taking heat from the exhaust gas of rotary kiln in the drying chamber of the raw mill. After the heat treatment, it is fed into the grinding section, where it is ground into the required size.

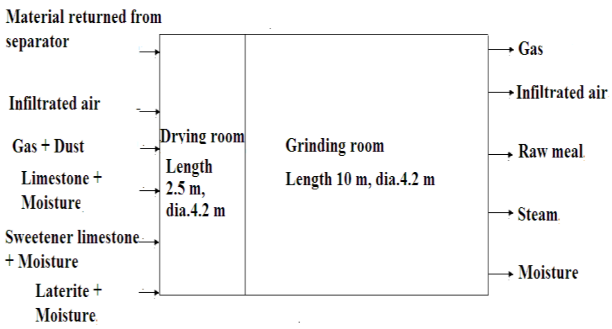

Figure 1: Schematic diagram of raw mill

3.3 Raw mill analysis

The raw mill is considered as the control volume for energy and exergy analysis in this section. The energy and exergy modeling technique is applied to the RM for two different operating conditions as follows.

3.3.1 Production rate of 117 tones per hour

Temperature of hot gas from the kiln system at the inlet of the raw mill and the temperature of hot gas leaving the mill are continuously measured by the probes which are installed on the system.

Table 1: Operation data for the production rate 117 tones per hour

Ambient temperature	30°C
Raw meal production rate	171 TPH
Temperature of raw meal	88°C
Limestone feed	98.36 TPH
Sweetener limestone feed	12.71 TPH
Laterite feed	5.96 TPH
Temperature of feed	30°C
Temperature of gas at mill inlet	360°C
Temperature of gas at mill outlet	88°C
Flow rate of gas at mill outlet (mill fan inlet)	100450 Nm2/hr
02 present in raw mill outlet gas	9%
02 present in raw mill inlet gas	6%
Recirculation load	67% of material in the separator
Dust concentration in hot gas supplied to the mill	37 g/Nm³
Surface temperature of drying room	72°C
Surface temperature of grinding room	82°C

3.3.2 Production rate of 121 tones per hour

When the production capacity of the plant is increased there is a chance to decrease the temperature of the product and thereby increased moisture content in the product (raw meal). In order to prevent this effect the hot gas supplied to the mill with increased temperature compared to lower feed operation. Accordingly in this operating condition the temperature of the gas at inlet is maintained at 362^0C in order to keep minimum moisture in the product (0.5%). The raw meal production rate in this operating condition is 121000 kg/hr with a temperature of 88^0C.

Table 2: Operation data for production rate 121 tones per hour

Ambient temperature	30°C
Raw meal production rate	121 TPH
Temperature of raw meal	88°C
Limestone feed	101. 74 TPH
Sweetener limestone feed	13.14 TPH
Laterite feed	6.16 TPH
Temperature of feed	30°C
Temperature of gas at mill inlet	362°C
Temperature of gas at mill outlet	88°C
Flow rate of gas at mill outlet (mill fan inlet)	102800 Nm³/hr
02 present in raw mill outlet gas	9%
02 present in raw mill inlet gas	6%
Recirculation load	67% of material in the separator
Dust concentration in hot gas supplied to the mill	37 g/Nm³
Surface temperature of drying room	72°C
Surface temperature of grinding room	82°C

4. ENERGY AND EXERGY ANALYSIS OF THE KILN SYSTEM

In this section, the energy utilization efficiency for kiln system with different operating conditions was determined. Mass balance, energy and exergy utilization efficiency of the kiln system were analyzed using the actual operational data.

4.1 Kiln System

The rotary cement kiln is a long cylindrical steel shell lined on the interior with refractory bricks. Coal ground to fine power in the coal mill, is weighed in an electronic weight feeder and fired to the kiln through a burner pipe positioned almost concentric to the kiln at the outlet. This forms intense heat at the outlet end of kiln, imparting thermal energy for Clinkerisation. The pulverized coal is injected into the kiln with the help of primary air. Secondary air is drawn first through the cooler and then through the kiln for combustion of the coal. In the cooler the air is heated by the cooling clinker, so that it may be 800-950°C before it enters the kiln, thus causing intense and rapid combustion of the coal.

4.2 Kiln System Analysis

The energy and exergy analysis of the kiln system were conducted for two operating conditions given as follows.

4.2.1 Clinker production rate of 1400 TPD

The control volume for the study includes the pre-heaters, rotary kiln and cooler. The streams into the system are the raw meal, the air into the cooler and coal fired in the kiln. The streams leaving the system are clinker out from the cooler, the exhaust gas from the preheater and hot gases from the cooler. During this operating condition the various input and output gas volume at different locations are measured with pitot tube with manometer assembly. The temperatures of inlet and outlet gas are continuously measured by the online temperature probes which are installed on the system.

Table 3: Operation data of kiln system for the production rate of 1400 TPD

Ambient temperature	35°C
Present kiln capacity	1400 TPH
Required kiln feed	87 TPH
Temperature of feed	55°C
Raw meal/clinker factor	1.49
Coal consumption	11.08 TPH
Flow rate of preheater Exhaust gas	120666 Nm³/hr
Preheater exhaust gas temperature	384°C
02 % Preheater exit gas	4.20%
02 % Kiln inlet (junction between preheater and kiln)	1.80%
Flow rate of primary air	21508 Nm³/hr
Temperature of Primary air	71°C
Flow rate of cooler inlet air	185423 Nm³/hr
Excess air	10°C
Clinker discharge temperature from cooler	95°C
Flow rate of gas to coal mill	6157 Nm³/hr
Temperature of coal mill gas	330°C
Flow rate of cooler hot air	138542 Nm³/hr
Temperature of hot air from cooler	200°C
Temperature of secondary air	850°C
Dust concentration in Preheater exhaust gas	36.06 g/Nm³
Surface temperature of kiln	300°C
Surface temperature of preheater	80°C
Surface temperature of cooler	82°C

4.2.2 Clinker production rate of 1369 TPD

Table 4: Operation data of kiln system for the production rate of 1369 TPD

Ambient temperature	30°C
Present kiln capacity	1369 TPH
Required kiln feed	85 TPH
Temperature of feed	55°C
Raw meal/clinker factor	1.49
Coal consumption	10.83 TPH
Flow rate of preheater Exhaust gas	117113 Nm^3/hr
Preheater exhaust gas temperature	395°C
02 % Preheater exit gas	4%
02 % Kiln inlet (junction between preheater and kiln)	1.80%
Flow rate of primary air	21658 Nm^3/hr
Temperature of Primary air	53°C
Flow rate of cooler inlet air	137756 Nm^3/hr
Excess air	10°C
Clinker discharge temperature from cooler	150°C
Flow rate of gas to coal mill	6405 Nm^3/hr
Temperature of coal mill gas	340°C
Flow rate of cooler hot air	98919 Nm^3/hr
Temperature of hot air from cooler	220°C
Temperature of secondary air	860°C
Dust concentration in Preheater exhaust gas	36.28 g/Nm^3
Surface temperature of kiln	305°C
Surface temperature of preheater	82°C
Surface temperature of cooler	85°C

5. RESULTS

5.1 Results from Raw Mill

Table 5: Mass balance in raw mill (117 tons per hour)

S. No.	Input	Temp (^0C)	Mass, m (kg/h)	Output	Temp (^0C)	Mass, m (kg/h)
1	Infiltrated air (m_{ia})	30	24114	Infiltrated air (m_{ia})	88	24114
2	Gas (m_g)	360	96458	Gas (mg)	88	96458
3	Limestone (m_l)	30	96426	Steam (mst)	88	2989
4	Sweetener Limestone (m_{sl})	30	11344	Raw meal (mrm)	88	350415
5	Laterite (m_{lt})	30	5672	Moisture (mm)	88	585
6	Returned from saperator (m_{rs})	78	234000			
7	Moisture in Limestone (m_{ml})	30	1929			
8	Moisture in Sweetener Limestone (m_{sm})	30	1361			
9	Moisture in Laterite (m_{lm})	30	284			
10	Dust (m_d)	360	2973			
	Total		**474561**			**474561**

Table 6: Energy balance in raw mill (117 tons per hour)

S. No.	Input	c_p (kj/kg^{0}c)	Temp T(^{0}c)	Mass, m (kg/h)	Heat, Q (kj/h) m x c_p x T	Output	c_p (kj/kg^{0}c)	Temp T(^{0}c)	Mass, m (kg/h)	Heat, Q (kj/h) m x c_p x T
1	Infiltrated air	0.9655	30	24114	698431.2	Infiltrated air	0.9908	88	24114	2102514.46
2	Gas	1.0812	360	96458	37544540.26	Gas	0.9745	88	96458	8271954.85
3	Limestone	0.7664	30	96426	2217026.59	Steam	1.962	88	2989	516068.78
4	Sweetener Limestone	0.7632	30	11344	259732.22	Raw meal	0.8232	88	350415	25383247.68
5	Laterite	0.745	30	5672	126769.2	Moisture	4.195	88	585	215958.6
6	Returned from saperator	0.8142	78	234000	14860778.4	Heat loss				26830070.19
7	Moisture in Limestone	4.178	30	1929	241780.86	Unaccounted heat loss				1905366.81
8	Moisture in Sweetener Limestone	4.178	30	1361	170587.74					
9	Moisture in Laterite	4.178	30	284	35596.56					
10	Dust	0.9971	360	2973	1067138.34					
11	Heat from Electrical Energy				8002800					
					65225181.37					65225181.37

Table 7: Enthalpy balance in raw mill (117 tons per hour)

S. No.	Input	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Enthalpy ΔH (kJ/h)	Output	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Enthalpy ΔH (kJ/h)
1	Infiltrated air	0.9655	303	298	24114	116405.2	Infiltrated air	0.9915	361	298	24114	1506268.95
2	Gas	1.0812	633	298	96458	34937280.52	Gas	0.9758	361	298	96458	5929794.13
3	Limestone	0.7664	303	298	96426	369504.43	Steam	1.962	361	298	2989	369458.33
4	Sweetener Limestone	0.7632	303	298	11344	43288.7	Raw meal	0.8249	361	298	350415	18210612.01
5	Laterite	0.745	303	298	5672	21128.2	Moisture	4.195	361	298	585	154606.73
6	Returned from saperator	0.8142	351	298	234000	10097708.4						
7	Moisture in Limestone	4.178	303	298	1929	40296.81						
8	Moisture in Sweetener Limestone	4.178	303	298	1361	28431.29						
9	Moisture in Laterite	4.178	303	298	284	5932.76						
10	Dust	0.9971	633	298	2973	993031.5						

Table 8: Entropy balance in raw mill (117 tons per hour)

S. No.	Input	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Entropy ΔS (kJ/hk)	Output	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Entropy ΔS (kJ/hk)
1	Infiltrated air	0.9655	303	298	24114	387.38	Infiltrated air	0.9915	361	298	24114	4585.38
2	Gas	1.0812	633	298	96458	78569.97	Gas	0.9758	361	298	96458	18051.47
3	Limestone	0.7664	303	298	96426	1229.66	Steam	1.962	361	298	2989	1124.7
4	Sweetener Limestone	0.7632	303	298	11344	144.06	Raw meal	0.8249	361	298	350415	55436.71
5	Laterite	0.745	303	298	5672	70.31	Moisture	4.195	361	298	585	470.65
6	Returned from saperator	0.8142	351	298	234000	31187.2						
7	Moisture in Limestone	4.178	303	298	1929	134.1						
8	Moisture in Sweetener Limestone	4.178	303	298	1361	94.62						
9	Moisture in Laterite	4.178	303	298	284	19.74						
10	Dust	0.9971	633	298	2973	2233.22						

Table 9: Exergy balance in raw mill (117 tons per hour)

S. No.	Input	Enthalpy ΔH (kJ/h)	T(k)	T0(k)	Entropy ΔS (kJ/hk)	Exergy (kJ/h)	Output	Enthalpy ΔH (kJ/h)	T(k)	T0(k)	Entropy ΔS (kJ/hk)	Exergy (kJ/h)
1	Infiltrated air	116405.2	303	298	387.38	965.77	Infiltrated air	1506268.95	361	298	4585.38	139825.45
2	Gas	34937280.52	633	298	78569.97	11523428.22	Gas	5929794.13	361	298	18051.47	550456.9
3	Limestone	369504.43	303	298	1229.66	3065.63	Steam	369458.33	361	298	1124.7	34296.45
4	Sweetener Limestone	43288.7	303	298	144.06	359.15	Raw meal	18210612.01	361	298	55436.71	1690473.02
5	Laterite	21128.2	303	298	70.31	175.29	Moisture	154606.73	361	298	470.65	14351.99
6	Returned from saperator	10097708.4	351	298	31187.2	803923.22	Exergy Loss					18233466.33
7	Moisture in Limestone	40296.81	303	298	134.1	334.33						
8	Moisture in Sweetener Limestone	28431.29	303	298	94.62	235.88						
9	Moisture in Laterite	5932.76	303	298	19.74	49.22						
10	Dust	993031.5	633	298	2233.22	327533.43						
11	Exergy due to Electrical Work					8002800						
						20662870.14						20662870.14

Table 10 : Mass balance in raw mill (121 tons per hour)

S. No.	Input	Temp T(^{0}c)	Mass, m (kg/h)	Output	Temp T(^{0}c)	Mass, m (kg/h)
1	Infiltrated air (m_{ia})	30	24679	Infiltrated air (m_{ia})	88	24679
2	Gas (m_g)	362	98714	Gas (m_g)	88	98714
3	Limestone (m_l)	30	99749	Steam (m_{st})	88	3091
4	Sweetener Limestone (m_{sl})	30	11735	Raw meal (m_{rm})	88	362395
5	Laterite (m_{lt})	30	5868	Moisture (m_m)	88	605
6	Returned from saperator (m_{rs})	78	242000			
7	Moisture in Limestone (m_{ml})	30	1995			
8	Moisture in Sweetener Limestone (m_{sm})	30	1408			
9	Moisture in Laterite (m_{lm})	30	293			
10	Dust (m_d)	362	3043			
			489484			489484

Table 11: Energy balance in raw mill (121 tons per hour)

S. No.	Input	c_p (kj/kg^{0}c)	Temp T(^{0}c)	Mass, m (kg/h)	Heat, Q (kJ/h) m x c_p x T	Output	c_p (kJ/kg^{0}c)	Temp T(^{0}c)	Mass, m (kg/h)	Heat, Q (kj/h) m x c_p x T
1	Infiltrated air	0.9655	30	24679	714827.235	Infiltrated air	0.9908	88	24679	2151771.882
2	Gas	1.0818	362	98714	38657547.48	Gas	0.9745	88	98714	8465317.784
3	Limestone	0.7664	30	99749	2293429.008	Steam	1.962	88	3091	533679.696
4	Sweetener Limestone	0.7632	30	11735	268684.56	Raw meal	0.8232	88	362395	26252473.63
5	Laterite	0.745	30	5868	131149.8	Moisture	4.195	88	605	223341.8
6	Returned from saperator	0.8142	78	242000	15368839.2	Heat loss				26831431.96
7	Moisture in Limestone	4.178	30	1995	250053.3	Unaccounted heat loss				2815873.98
8	Moisture in Sweetener Limestone	4.178	30	1408	176478.72					
9	Moisture in Laterite	4.178	30	293	36724.62					
10	Dust	0.9981	362	3043	1099473.025					
11	Heat from Electrical Energy				8276400					
					67273606.95					67273890.73

Table 12: Enthalpy balance in raw mill (121 tons per hour)

S. No.	Input	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Enthalpy ΔH (kJ/h)	Output	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Enthalpy ΔH (kJ/h)
1	Infiltrated air	0.9655	303	298	24679	119137.87	Infiltrated air	0.9908	361	298	24679	1540473.05
2	Gas	1.0818	635	298	98714	35987827.35	Gas	0.9745	361	298	98714	6060397.96
3	Limestone	0.7664	303	298	99749	382238.17	Steam	1.962	361	298	3091	382066.15
4	Sweetener Limestone	0.7632	303	298	11735	44780.76	Raw meal	0.823	361	298	362395	18789818.36
5	Laterite	0.745	303	298	5868	21858.30	Moisture	4.195	361	298	605	159892.43
6	Returned from saperator	0.8142	351	298	242000	10442929.20						
7	Moisture in Limestone	4.178	303	298	1995	41675.55						
8	Moisture in Sweetener Limestone	4.178	303	298	1408	29413.12						
9	Moisture in Laterite	4.178	303	298	293	6120.77						
10	Dust	0.9981	635	298	3043	1023542.57						

Table 13: Entropy balance in raw mill (121 tons per hour)

S. No.	Input	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Entropy ΔS (kJ/hk)	Output	c_p (kj/kg^{0}k)	Temp T(^{0}k)	T0 (k)	Mass, m (kg/h)	Entropy ΔS (kJ/hk)
1	Infiltrated air	0.9655	303	298	24679	396.46	Infiltrated air	0.9908	361	298	24679	4689.52
2	Gas	1.0818	635	298	98714	80786.31	Gas	0.9745	361	298	98714	18449.28
3	Limestone	0.7664	303	298	99749	1272.04	Steam	1.962	361	298	3091	1163.08
4	Sweetener Limestone	0.7632	303	298	11735	149.02	Raw meal	0.8232	361	298	362395	57210.73
5	Laterite	0.745	303	298	5868	72.74	Moisture	4.195	361	298	605	486.74
6	Returned from saperator	0.8142	351	298	242000	32254.16						
7	Moisture in Limestone	4.178	303	298	1995	138.69						
8	Moisture in Sweetener Limestone	4.178	303	298	1408	97.88						
9	Moisture in Laterite	4.178	303	298	293	20.37						
10	Dust	0.9981	635	298	3043	2297.73						

Table 14: Exergy balance in raw mill (121 tons per hour)

S. No.	Input	Enthalpy ΔH (kJ/h)	T(k)	T0(k)	Entropy ΔS (kJ/hk)	Exergy (kJ/h)	Output	Enthalpy ΔH (kJ/h)	T(k)	T0(k)	Entropy ΔS (kJ/hk)	Exergy (kJ/h)
1	Infiltrated air	119132.62	303	298	396.46	988.39	Infiltrated air	1540476.83	361	298	4689.52	143000.93
2	Gas	35986585.56	635	298	80786.31	11912265.59	Gas	6060473.13	361	298	18449.28	562587.7
3	Limestone	382238.17	303	298	1272.04	3171.27	Steam	382066.146	361	298	1163.08	35466.82
4	Sweetener Limestone	44780.76	303	298	149.02	371.53	Raw meal	18793366.1	361	298	57210.73	1744569.5
5	Laterite	21858.3	303	298	72.74	181.35	Moisture	159892.425	361	298	486.74	14842.65
6	Returned from saperator	10443165.24	351	298	32254.16	831426.57	Exergy Loss					18795387.11
7	Moisture in Limestone	41675.55	303	298	138.69	345.76						
8	Moisture in Sweetener Limestone	29413.12	303	298	97.88	244.03						
9	Moisture in Laterite	6120.77	303	298	20.37	50.78						
10	Dust	1023532.81	635	298	2297.73	338809.43						
11	Exergy due to Electrical Work					8208000						
						21295854.7						21295854.71

5.2 Results from Kiln System

Total Output Energy = 3886.83 kJ/kg-clinker

Total Input Energy = 4201.21 kJ/kg-clinker

Unaccounted Heat Loss = 314.38 kJ/kg-clinker

Kiln Efficiency = Clinker formation energy / Total input energy

Kiln Efficiency = 1756.24 / 4201.21

Kiln Efficiency = 41.8%

Table 15: Enthalpy balance for kiln system (Production rate of 1400 tons per day)

S. No.	Input	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Enthalpy ΔH_k (kJ/kg clinker)	Output	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Enthalpy ΔH_k (kJ/kg clinker)
1	Raw meal	0.7919	328	298	1.49	35.40	Preheater Exhaust Gas	1.0878	657	298	2.56	999.72
2	Primary air	0.9843	344	298	0.418	18.93	Dust	1.0093	657	298	0.0746	27.03
3	Cooler fan air	0.9681	308	298	3.667	35.50	Clinker	0.8308	368	298	1	58.16
4	Infiltrated air	0.9681	308	298	0.815	7.89	Cooler hot air	1.0226	473	298	2.82	504.65
5							Coal mill gas	1.0482	603	298	0.125	39.96

Table 16: Entropy balance for kiln system (Production rate of 1400 tons per day)

S. No.	Input	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Entropy ΔS_k (kJ/kg clinker)	Output	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Entropy ΔS_k (kJ/kg clinker)
1	Raw meal	0.7919	328	298	1.49	0.1132	Preheater Exhaust Gas	1.0878	657	298	2.56	2.2016
2	Primary air	0.9843	344	298	0.418	0.0591	Dust	1.0093	657	298	0.0746	0.0595
3	Cooler fan air	0.9681	308	298	3.667	0.1172	Clinker	0.8308	368	298	1	0.1753
4	Infiltrated air	0.9681	308	298	0.815	0.0260	Cooler Exhaust Gas	1.0226	473	298	2.828	1.3361
5							Coal mill gas	1.0482	603	298	0.125	0.0924

Table 17 : Exergy balance for kiln system (Production rate of 1400 tons per day)

S. No.	Input	Enthalpy ΔH_k (kJ/kg clinker)	Temp (k)	T_0 (k)	Entropy ΔS_k (kJ/kg clinker)	Exergy $(Ex)_k$ (kJ/kg clinker)	Output	Enthalpy ΔH_k (kJ/kg clinker)	Temp (k)	T_0 (k)	Entropy ΔS_k (kJ/kg clinker)	Exergy $(Ex)_k$ (kJ/kg clinker)
1	Raw meal	35.40	328	298	0.1132	1.67	Preheater Exhaust Gas	999.72	657	298	2.2016	343.6500
2	Primary air	18.93	344	298	0.0591	1.33	Dust	27.03	657	298	0.0595	9.2900
3	Cooler air	35.50	308	298	0.1172	0.58	Clinker	58.16	368	298	0.1753	5.9200
4	Infiltrated air	7.89	308	298	0.0260	0.13	Cooler hot air	504.65	473	298	1.3361	107.6300
5	Coal					4089.92	Coal mill gas	39.96	603	298	0.0924	12.4400
6							Chemical Reaction					1152.53
7							Radiation and Convection					148.06
8							Exergy lost due to irreversibility					2314.1
	Total					4093.63						4093.63

Total Output Energy = 3874.42 kJ/kg-clinker

Total Input Energy = 4146.25 kJ/kg-clinker

Unaccounted Heat Loss = 271.83 kJ/kg-clinker

Table 18 : Enthalpy balance for kiln system (Production rate of 1400 tons per day)

S. No.	Input	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Enthalpy ΔH_k (kJ/kg clinker)	Output	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Enthalpy ΔH_k (kJ/kg clinker)
1	Raw meal	0.7919	328	298	1.49	35.40	Preheater Exhaust Gas	1.0907	668	298	2.53	1021.04
2	Primary air	0.9767	326	298	0.43	11.76	Dust	1.0148	668	298	0.0745	27.97
3	Cooler fan air	0.9655	303	298	2.8	13.52	Clinker	0.8739	423	298	1	109.24
4	Infiltrated air	0.9655	303	298	0.8835	4.27	Cooler hot air	1.0271	493	298	2.056	411.78
5							Coal mill gas	1.0499	613	298	0.133	43.99

Table 19: Entropy balance for kiln system (Production rate of 1400 tons per day)

S. No.	Input	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Entropy ΔS_k (kJ/kg clinker)	Output	c_p (kJ/kgk)	Temp (k)	T_0 (k)	Mass m_k (kg/kg clinker)	Entropy ΔS_k (kJ/kg clinker)
1	Raw meal	0.7919	328	298	1.49	0.1132	Preheater Exhaust Gas	1.0907	668	298	2.53	2.2275
2	Primary air	0.9767	326	298	0.43	0.0377	Dust	1.0148	668	298	0.0745	0.0610
3	Cooler fan air	0.9655	303	298	2.8	0.0450	Clinker	0.8739	423	298	1	0.3061
4	Infiltrated air	0.9655	303	298	0.8835	0.0142	Cooler hot air	1.0271	493	298	2.056	1.0631
5							Coal mill gas	1.0499	613	298	0.133	0.1007

Table 20: Exergy balance for kiln system (Production rate of 1400 tons per day)

S. No.	Input	Enthalpy ΔH_k (kJ/kg clinker)	Temp (k)	T_0 (k)	Entropy ΔS_k (kJ/kg clinker)	Exergy $(Ex)_k$ (kJ/kg clinker)	Output	Enthalpy ΔH_k (kJ/kg clinker)	Temp (k)	T_0 (k)	Entropy ΔS_k (kJ/kg clinker)	Exergy $(Ex)_k$ (kJ/kg clinker)
1	Raw meal	35.40	328	298	0.1132	1.67	Preheater Exhaust Gas	1021.04	668	298	2.2275	357.24
2	Primary air	11.76	326	298	0.0377	0.52	Dust	27.97	668	298	0.0610	9.79
3	Cooler air	13.52	303	298	0.0450	0.11	Clinker	109.24	423	298	0.3061	18.02
4	Infiltrated air	4.27	303	298	0.0142	0.04	Cooler hot air	411.78	493	298	1.0631	94.99
5	Coal					4089.92	Coal mill gas	43.99	613	298	0.1007	13.97
6							Chemical Reaction					159.37
7							Radiation and Convection					1236.04
8							Exergy lost due to irreversibility					2202.84
	Total					4092.26						4092.26

6. CONCLUSION

- The energy and exergy analysis of the raw mill of the typical cement plant indicates that exergy utilization was even worse than energy utilization. This process represents a big potential for increasing the exergy efficiency. It is clear that a conscious and planned effort is needed to improve exergy utilization in the raw mill.
- The energy analysis of the kiln emphasized the need for identifying the areas of energy saving opportunities. There are areas of serious energy losses, which lead to the drop of thermal performance of the kiln system.
- The conservation technique for improving efficiency was proposed. Waste heat recovery steam generation and secondary shell energy conservation measures were studied. Waste heat recovery steam generation unit can generate up to 7 MW of electricity.
- The secondary shell concept can save up to 6.9% of thermal energy, which is equivalent to percentage margin and energy efficiency of the unit increased by 3 to 4%.
- The above measures increase the available amount of energy or, in other words can decrease the fuel consumption considerably and thus decrease of CO_2 emissions.
- The waste heat recovery and secondary shell concept shows a relatively remarkable improvement over the existing system. It has been suggested that waste heat recovery system must also be incorporated in the design of new industries to minimize energy consumption,

manufacturing cost and improve the product quality.

- The exergy analysis accounts for the operation indicating the location of energy degradation in the process. The main cause of irreversibility in the process was due to conversion of chemical energy of fuel to thermal energy in the kiln system.

It may also be concluded that the energy and exergy analysis reported in this study will provide the investigators with knowledge about how effectively and efficiently a sector uses its energy resources.

5.3 Scope for Future Work

If economic environment is introduced by establishing prices for these losses at various places in the process, the researchers can concentrate on the areas that are important economically as well as thermodynamically in a single step. Cement processes require a high temperature energy source to drive the chemical reactions to form cement clinker. This produces an excess of energy at low temperature and results in significant sensible heat within the flue gases. This excess heat could be balanced with the sensible heat required for regenerating the solvent within a potential carbon capture plant. So researchers are recommended to make a study to forecast CO_2 emissions from the cement industries in India with integrated carbon capture and compare it with the results for the option without carbon capture.

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