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ENERGY AND EXERGY ANALYSIS OF A WHITE CEMENT KILN PLANT

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ABSTRACT

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. This paper reviewed energy and exergy analysis, energy and exergy balance for the white cement industry. The implementation of exergy analysis on the cement production line will be very effective for improving the performance of the system and also reduces the production cost.

This paper deals with the energy and exergy analysis of a wet type rotary kiln system working in a white cement plant in South India. The kiln has a capacity of 120 tonnes of clinker per day. The slurry used for this process contains 40% of water. The rotary kiln includes thermal and chemical processes. Energetic and exergetic efficiency of clinker production is 12.2% and 8% respectively. For the evaporation of water in the slurry requires 21.5% energy. The irreversibility loss of the process is 7337.356kJ/kg of clinker which represents about 73% of total exergy input. The heat loss by convection and radiation together from the kiln surface is about 16.83%.The present technique is proposed as a useful tool in the analysis of energy and exergy utilization, developing energy policies and providing energy conservation measures.

KEYWORDS: Exergy, Energy, Rotary Kiln, Wet Process, White Cement

INTRODUCTION

Known energy sources have been exhausted rapidly nowadays and so, efficient and effective utilization of energy has started to gain a vital importance. For this reason, the collection and valuation of periodical data concerning industry and other final energy consuming sectors are primary conditions in the determination of targets for the studies on energy saving. 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

Cement production is an energy intensive process, consuming about 4 GJ per ton of cement product, with energy typically accounting about 30–40% of the costs of production (Karimi G and Abedi N, 2008). This energy share of the cement industry in the industrial field is found to be ranging between 12% and 15%. For considering all kinds of industries, this share changes between 2% and 6% in terms of total consumption of energy. The typical electrical energy consumption of a modern cement plant is about 110–120kWh per tonne of cement (Mejeoumov GG, 2007). The main thermal energy is used during the burning process, while electrical energy is used for cement grinding (Junior LM, 2003). Specific energy consumption in cement production varies from technology to technology. The dry process uses more electrical but much less thermal energy than the wet process. In industrialized countries, primary energy consumption in a typical cement plant is up to 75% fossil fuel and up to 25% electrical energy using a dry process. Pyro-processing requires the major share of the total thermal energy use. This accounts for about 93–99% of total fuel consumption (Junior LM, 2003, Chinaeci, 2010, Khurana et al 2002). However, electric energy is mainly used to operate both raw materials (33%) and clinker crushing and grinding (38%) equipment. Electrical energy is required to run the auxiliary equipment such as kiln motors, combustion air blowers and fuel supplyetc (22%) to sustain the pyro-process. About 94% of the thermal energy requirement is met by coal in the Indian cement manufacturing and the remaining part ismetby fuel oil and high speed diesel oil. Natural gas is not sufficiently available for the cement industry in India (Lasserre P, 2007).

The energy and exergy analysis is one of the most effective procedures for a successful energy management program. The main aim of energy and exergy analysis is to provide an accurate account of energy consumption and energy use analysis of different components and to reveal the detailed information needed for determining the possible opportunities for energy conservation and amount energy can be effectively recovered.

The exergy analysis can helps to reduce the use of natural resources and this leads to reduction of environment pollution. The main purpose of exergy analysis is todetect and evaluate quantitatively the causes of the thermodynamic imperfections of thermal and chemical processes. The exergy method of thermodynamic analysis is based upon the first and second laws of thermodynamics together, whereas the energy analysis is based upon the first law only, which is a conservation principle. It is a feature of the exergy concept to permit quantitative evaluation of energy degradation.

The data taken from white cement plant located in South India for the investigation. Firstly the mass balance of the rotary kiln system is analysed. 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.

System Description

Cement is a fine, granular powder with hydraulic properties. During the production of cement, natural resources are consumed in large amounts. The most important raw materials for the manufacture of white cement are limeshell, clay and sand. They are grinded and mixed with 40% water and produce slurry. The wet process kilns have the advantages of finely-ground raw mix and painstaking blending became apparent. Rotary kilns are refractory lined tubes with a diameter up to 2.74 m. They are generally inclined at an angle of 3^0, and complete rotation with 58seconds.The slurry obtained is finely grounded and mixed with water and subsequently fired in a rotary furnace to cement clinkers. For heating furnace oil is used. Furnace oil is preheated by cyclone preheater. The slurry is dried at 200^0C at drying zone where the water particle get evaporated. The chains are provided for the easy moving and for helps drying. In the calcination zone (700–900^0C), calcinations, as well as an initial combination of alumina, ferric oxide and silica with lime, take place. Between 900 and 1200^0C, the clinker component, $2CaO.SiO_2$, forms. Then, the other component, $3CaO.SiO_2$, forms in a subsequent zone in which the temperature rises to 1200^0C. During the cooling stage, the molten phase, $3CaO.Al_2O_3$, formsalite may dissolve back into the liquid phase and appear as secondary belite. Quenching of molten clinker gives greenish white colour to the clinker.

The plant uses wet process for the production process. The kiln has 2.74m diameter at drying zone (15m length) and 2.45m diameter for calcination zone (55m length) and clinkering zone (20m length). The average daily production capacity is 120 ton of clinker, and the specific energy consumption has been estimated to be 9626 kJ/kg clinker.

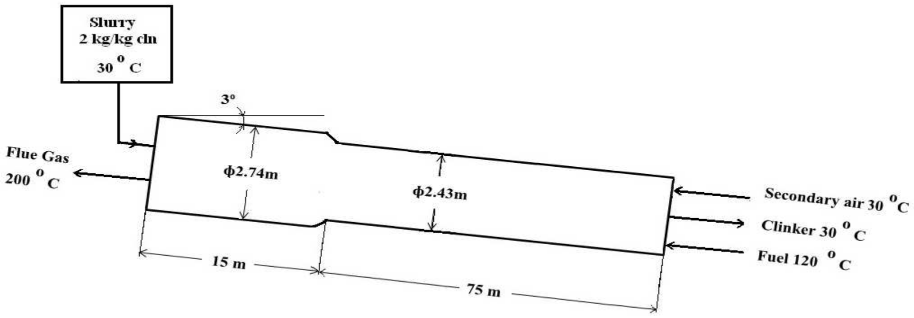

Figure 1: Schematic Diagram of the Kiln System

Average Operational Data

About 240 tonnes of slurry is fed to the kiln in one day. The kiln has three stages to produce the clinker such as drying, calcination, clinkerisation. The kiln is fired with furnace oil. Average operational data of the plant is provided in the Table 1 and the clinker compositions are given in the table 2. For burning fuel used is furnace oil, higher calorific value of the furnace oil is 43263 kJ/kg and lower calorific value is 40870 kJ/kg.

Table 1: Average Operation Data

Productivity	120 Tonnes/Day
Specific fuel consumption	0.225 kg/kg of clinker
Specific heat consumption	10030kJ/kg of clinker
Raw meal / clinker factor	2
Flue Gas Temperature	200 ^{0}C
O_2 % in preheater exit gas	3%

Table 2: Chemical Composition

Components	Clay	Sand	Lime Shell	Raw Mix	Clinker
SiO2	52	92.5	1.2	13.5	23
Al2O3	33	5.6	0.9	6	6
Fe2O3	1.5	1.2	0.2	0.4	0.5
CaO	0	0	53.2	41	68
MgO	2.4	0.4	1.27	3	1.2
LOI	11.1	0.3	43.8	36.1	1.3

Energy Balance

In order to analyse the kiln system thermodynamically, the following assumptions are made:

- Steady state working conditions.
- The change in the ambient temperature is neglected.
- Cold air leakage into the system is negligible.
- Raw material and coal compositions do not change.
- Averaged kiln surface temperatures do not change.

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. For the calculation reference enthalpy is taken as zero at 0^{0}C. The complete energy balance of the kiln is shown in table 2. The total energy used in the process is 10030 kJ/kg-clinkers. The main heat source is furnace oil, producing a total heat of 9626 kJ/kg clinker (96.34%). The majority of the heat energy is consumed for the evaporation of the moisture in the raw material. There is 40% of water in the raw material and the evaporation of water consumes 2148 kJ/kg clinker (21.55%). For the formation of clinker uses only 12.2% of the total energy (1212kJ/kg clinker). Since most of the heat loss sources have been considered, there is only a 1242 kJ/kg-clinker of energy difference from the input heat. This difference is nearly 12.43% of the total input energy and can be attributed to the assumptions and nature of data.

Exergy Analysis

A general exergy balance, which can be obtained, is an essentialway to identify the sources of losses in processes of production (Camdali U, et al, 2004). The total exergy of a system can be divided into four components, they are: physical exergy (ex_{ph}), kinetic exergy (ex_{kn}), potential exergy(ex_{po}) and chemical exergy(ex_{ch}), (Rasul et al., 2005; Vedat, 2011). In a cement production process, however, the kinetic exergy and potential exergy are negligible compared to other two.

The specific physical exergy can be expressed as:

$ex_{ph} = (h - h_o) - T_o (s - s_o)$

Assuming ideal gas flow with constant specific heat:

$ex_{ph} = c_p (T - T_o) - T_o (c_p \ln T/T_o - R \ln P/P_o)$

For the solid and liquid streams:

$ex_{ph} = c_p ((T - T_o) - To \ln T/T_o) - v (p - p_o)$

Assuming constant specific volume, v at T_o with neglect of change in pressure.

Chemical exergy is the maximum possible work that can be acquired during a process that brings the system from environmental condition ($T_{o,}$ P_o) to the dead state (T_o, P_o, μ_{oi}) . The chemical exergy of the ideal gas and liquid mixtures is computed from:

ex_{ch} = sum of $x_i (ex\ ch_{oi} + RT_0 \ln(x_i))$

Where x_i is the molar ratio of the species i, and ex_{choi} is the standard chemical exergy.

Three exergy efficiencies of a cement kiln plant are defined as follows:

1- Exergy efficiency, η_{ex} = clinker formation exergy/ exergy input.

It corresponds to the net thermal efficiency (ηg) defined as the fraction of fuel heat that is consumed as latent heats of various clinker forming reactions.

2- Anergy ϕ, defined as the ratio of the exergy loss to the exergy input. It is expressed as follows:

ϕ = ex losses/ ex input

3- The exergy destroyed or the irreversibility of a system, I_{sys}, is given as:

I_{sys} = ex input – ex output = To S_{gen}

Where S_{gen} is the entropy generated

The specific chemical exergies of liquid fuels on a unit mass basis can be determined from Kotas equation (C. Sayin et. al, 2005)

$$e_F^{ch} = [1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\left(1 - 2.0628\frac{h}{c}\right)]|LHV|$$

In the investigated process the actual amount of reacting raw mix = 2 kg to produce 1 kg clinker

Its main compounds in the raw mix is estimated as

Al_2O_3. $2SiO_2$. $2H_2O$ = 0.13 kg

$CaCO_3$ content = 1.12 kg.

$MgCO_3$ content = 0.13 kg

Formation of oxides and decomposition reactions

Kaolinit decomposition:

$Al_2O_3. SiO_2. 2H_2O \rightarrow Al_2O_3 + 2SiO_2 + 2H_2O$

ΔH=964 kJ/kg kaolinite, ΔHr= 125 kJ/kg cli. ex_{ch}= 110 kJ/kg cli

$MgCO_3$ dissociation:

$MgCO_3 \rightarrow MgO + CO_2$

Δ H = 1313 kJ/kg $MgCO_3$, ΔHr = 170 kJ/kg cli. ex_{ch}= 24.4 kJ/kg cli

$CaCO_3$dissociation :

$CaCO_3 \rightarrow CaO + CO_2$

ΔH = 1418 kJ/kg $CaCO_3$, ΔHr = 1558 kJ/kg cli,ex_{ch}=1638.5 kJ/kg cli.

Formation of intermediates:

Formation of CA:

$CaO + Al_2O_3 \rightarrow CA$

ΔH = -115kJ / kg cli, CA= 0.125 kg/ kg cli. ΔHr = -15 kJ/kg cli, ex_{ch} = -36 kJ/kg cli.

Formation of C2F

$2CaO + Fe_2O_3 \rightarrow C_2F$

ΔH = -116 kJ/kg C_2F, C_2F = 0.068 kg/kg cli ΔHr = - 7.8 kJ/kg cli, ex_{ch} = not obtained

Formation ofC_2S:

$2CaO + SiO_2 \rightarrow \beta\text{-}C_2S$

ΔH = -689 kJ/kg C2S, C2S = 0.92 kg/kg cli ΔH_r = -689 kJ/kg cli, ex_{ch}=-706 kJ/kg cli

Clinkering reactions:

Formation of C_4AF:

$CA + C_2F + CaO \rightarrow C_4AF$

$\Delta H = 95$ kJ / kg C4AF, $C_4AF = 0.015$ kg/kg cli $\Delta H_r = 2$kJ/kg cli, $ex_{ch} = 9.03$ kJ/kg cli.

Formation of C_3A:

$CA + 2CaO \rightarrow C_3A$

$\Delta H = 35$kJ/kg C_3A, $C_3A=0.15$ kg /kg cli. $\Delta H_r = 2.6 ex_{ch} = 16$ kJ/kg cli.

Formation of C_3S:

$\beta\text{-}C_2S + CaO \rightarrow C_3S$

$\Delta H = 63$ kJ/kg C_3S, $C_3S = 0.62$ kg / kg cli. $\Delta H_r = 38$kJ/kg cli, $ex_{ch} = 62$ kJ/kg cli.

Mineral composition of the produced clinker (in wt %) is as follows:

$C_3S = 61$ %, $C_2S = 21$%, $C_3A = 15$%, $C_4AF = 3$%

Sum of consumed heat in all chemical reactions = 1219 kJ/kg cli.

Sum of consumed exergies in all chemical reactions =807 kJ/kg cli.

RESULTS AND DISCUSSIONS

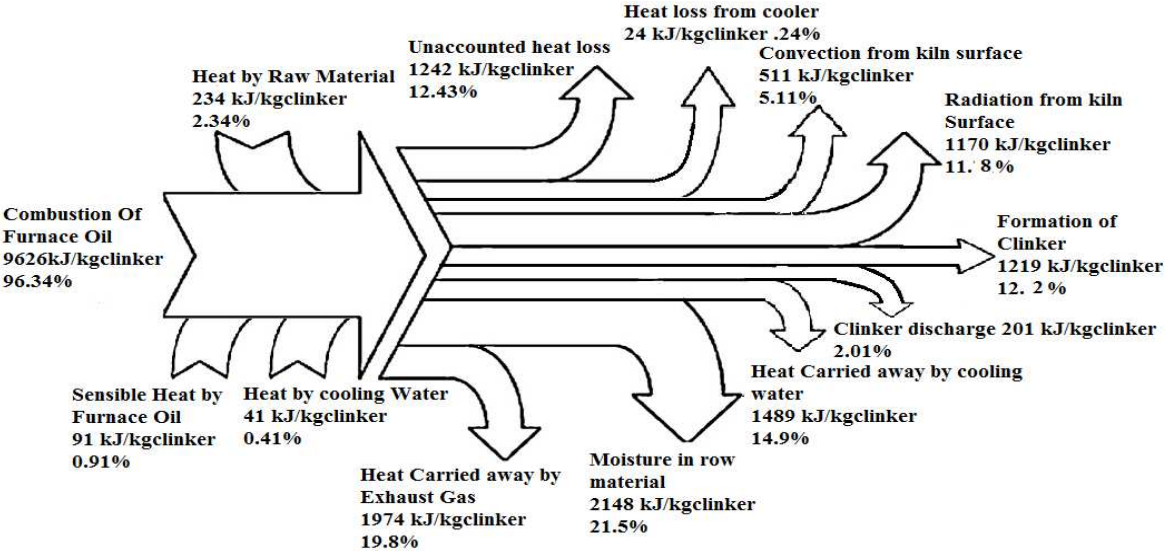

Figure 2: Energy Balance

The energy and exergy analyses in the rotary kiln which contributes to quality of the cement are performed using the First and Second Law of Thermodynamics. Figure 2 shows the Sankey diagram demonstrating magnitudes and percentages of energy flows and losses. It is seen from the obtained results that the unit energy input is 9992 kJ/kg-clinker (96.34%) into the system. The evaporation of water takes 21.5% of the total heat input. In this wet process system the slurry contain 40% of water. During the evaporation process this is needed to be heated from 25^0C to 100^0C and then it requires latent heat of vaporization. Vaporization water requires 2148 kJ/kg-clinker energy. Even though it takes large quantity of heat, this process produces good quality clinker. The formation of clinker consumes 12.15% of the total heat input.

Figure 2. shows the Sankey diagram demonstrating magnitudes and percentages of energy flows and losses. The results shows that fuel combustion generate heat of 9626 kJ/kg-clinker (96.34%). The total sensible heats of raw meal, coal and air at the input are found to be 91.3 kJ/kg-clinker (0.91%). The first law efficiency of the system is found to be 12.19%. The major energy losses such as evaporation of water in the slurry, kiln exhaust gas, clinker cooler hot water and radiation and convection of kin system were estimated to be 2148 kJ/kg-clinker (21.5%)1973 kJ/kg-clinker (19.76%), 1489 kJ/kg-clinker (14.9%) and 1680 kJ/kg-clinker (16.81%) respectively. The other heat losses are clinker discharge 201kJ/kg-clinker (2.01%) and dust 14.3 kJ/kg-clinker (0.14%). The unaccounted heat loss was found to be 1242 kJ/kg-clinker (12.43%).

The exergy analysis results can be used to guide system performance improvement. Total exergy input to the rotary kiln system is 9736 kJ/kg-clinker. Exergy efficiency of the clinker production is 8.3%. Total anergy of kiln is 2526 kJ/kg-clinker (26%). The irreversibility of the system is 7111kJ/kg-clinker, which is about 73% of total Exergy input.

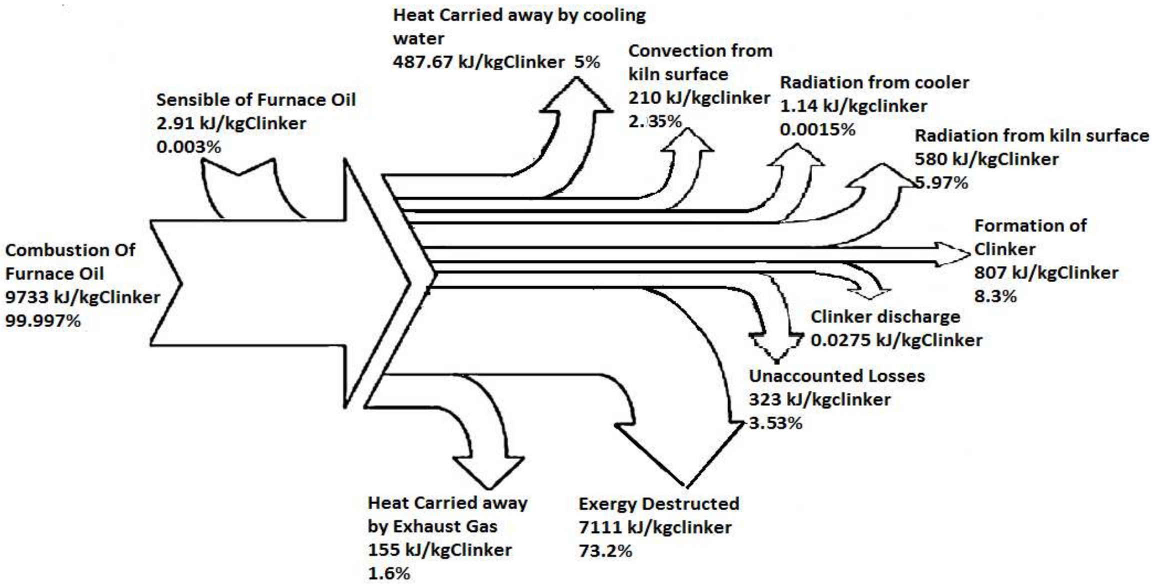

Figure 3: Exergy Balance Sheet

CONCLUSIONS

Efficiency of wet process is very low is due to large amount of water content. The slurry containing 40% water by mass at 20°C contains 64.33% water by volume. The evaporation of water particle requires 21.5% of heat input; this is higher than the energy required for the production of clinker (12%). Heat losses by conduction, convection and radiation from the kiln are found to be about 16.83%.

Exergetic efficiency of clinker production is 8.2 % of total exergy input. The irreversibility of the system is 73.11% (7111 kJ/kg-clinker). In the kiln, exergy losses have been calculated about 73% and the exergy losses are exhausted due to the irreversibility.

The analysis indicates that exergy utilization at the kiln was even worse than energy utilization. That is, this process represents a big potential for increasing the exergy efficiency. It is clear that a conscious and planned effort need to improve exergy utilization in rotary kiln. Considering the existence of energy efficient technologies in the similar sectors, the major problem is delivering these technologies to consumers or using effective energy-efficiency delivery mechanisms.

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