THERMAL ENERGY AUDIT IN PYRO-PROCESSING SYSTEM OF MESSEBO CEMENT FACTORY (LINE-2)

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February, 2018

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A thesis submitted to the School of Graduate Studies of Jimma University Institute of Technology in Partial fulfillment of the requirements for award of Degree of Masters of Science in Mechanical Engineering (Thermal System Engineering Stream)

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DECLARATION

APPROVED BY BOARD OF EXAMINERS

This research work is my original work and has not been presented for a degree in any other university.

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Name Signature

This research work has been submitted for examination with my approval as university supervisor.

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Chairman Signature

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ACKNOWLEDGEMENT

First of all, I would like to gratefully acknowledge the almighty God to get the chance of this program. My deepest gratitude goes to my advisor Balewgize A. Zeru (Asst. Prof.) and my Co-advisor Mr. Desta G. (M.Sc.) for all their limitless efforts in giving me through my work and for providing me useful reference materials.

I pull-out my gratitude to all Messebo cement Factory workers who have devoted their time to give me all necessary information and valuable data for this thesis (particularly Ato Getachew Sahle Deputy Manager of Plant Operations).

Finally, my deepest appreciation goes to Jimma University, School of Graduate Studies, Jimma Institute of Technology, Faculty of Mechanical Engineering, and Thermal System Engineering Stream chair.

ABSTRACT

Cement factory is energy intensive industry that needs a great attention to optimize its energy usage. Messebo Cement Factory utilizes imported raw coal and domestic electric energy. Therefore, reducing energy dissipation enables the factory as well as the country saving of foreign currency and keeps the environment from damage.

The aim of this thesis work is to identify the major energy loss areas in Messebo Cement Factory for the second cement line and to present suitable modification to enhance energy utilization performance of the factory.

This thesis first systematically identifies the energy losses areas. This is achieved by conducting thermal energy bill analysis and determining thermal energy consumption of corresponding units. In the second stage, quantified thermal energy loss of the units is undertaken and finally to look for the energy conservation opportunities.

The result of assessment shows that the Factory has an enormous opportunity for improvement without jeopardizing its product quality and reputation. Thermal energy losses take the lion share for poor energy performance of the factory. The preheater, pre-calciner, kiln and grate cooler are among extremely inefficient devices that needs immediate modification.

A thorough investigation of MCF's energy audit reveals that there is an opportunity of saving of around 67 million birr per annum by replacement of the raw coal by sesame husk partially, adapting heat recovery mechanism and process control and optimization.

Key words: Audit, Kiln, Messebo, Pyro-processing, Thermal Energy, Raw Coal

LIST OF ACRONYMS AND ABBREVIATIONS

CCR	-	Central control room
CDM	-	Clean development mechanism
CV	-	Calorific value
ESPs	-	Electro static precipitator
HCRDI	-	Hefei cement research and design institute
LCR	-	Local control room
LH-HS RC	-	Low heat high Sulphate resistance cement
MCF	-	Messebo cement factory
PC	-	Pre-calciner
PH	-	Pre- heater
PL	-	Production line
PLC	-	Portland limestone cement
PPC	-	Pozzaolana Portland cement
OPC	-	Ordinary Portland cement

SYMBOLS

A	Area
C_c	Average monthly cost
C_f	Clinker factor
CV	Calorific value
D	Diameter
g	Acceleration due to gravity
β	Coefficient of volume expansion
ρ	Density
ε	Emissivity factor
η	Efficiency
δ	Stephen Boltzmann's constant
h	Enthalpy
h_{con}	convection heat transfer coefficient
k	Thermal conductivity
R	Gas constant
Q	Heat
Nu	Nusselt Numbers
$\dot{m}$	Mass flow rate
P	Pressure
Pr	Prdental number
v	Velocity
υ	Kinematic viscosity
T_∞	Ambient temperature
t	Time
$\dot{Q}$	Volume flow rate
γ	Excess air number

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CHAPTER ONE

1. INTRODUCTION

1.1. Background of the study

The cement industry is one of the major energy consuming industries having a high priority in energy conservation. In many countries, energy costs represent the largest component of direct production cost for cement. Energy cost represents as much as 40% to 60% of cement direct production cost[1].

Manufacturing of cement is basically an energy intensive process in that the chemical and physical process reaction takes place at high temperature, besides a considerable amount electrical and thermal energy being needed for grinding and clinker formation. The primary source of energy in cement manufacturing technology are oil, coal, gas and electricity, and secondary sources are utilizing of waste heat of one phase production to other phase of production. The main uses of energy are grinding of raw materials and pyro-processing in the rotary kiln. Grinding consumes mainly electricity, whereas pyro-processing consumes thermal energy in the form of coal, oil, or gas. The heat content of the waste gas from the kiln is used in pre-drying and pre-heating of material in the raw mill the kiln pre-heater respectively[2].

Energy cost is incurred due to the need for large quantities of thermal heat for the kiln, calcinations and drying processes and electrical energy for operation of motors for grinding mills, fans, conveyers and other motor driven process equipment. Theoretically, producing one ton of clinker requires a minimum on 1.6 GJ heats[1]. The specific thermal energy consumption in cement industries in India varies from 2.95 GJ to 4 GJ/ton of clinker[3]. The higher specific energy consumption is due to the harder raw material and poor quality of fuel. A significant quantum of studies can be witnessed in this field. Among them, there are many attempt aiming, not only energy approach to the cement industry, but also the potential means of improvement in energy consumption of cement industry.

Engin and Ari (2005) performed an energy audit analysis of a dry type rotary kiln system with a capacity of 600 ton clinker per day working in a cement plant in Turkey. They found that about 40% of the total input energy was being lost through hot flue gas (19.15%), cooler stack (5.61%) and kiln shell (15.11% convection plus radiation)[4].

The greatest opportunities in reducing energy consumption associated with cement production will be obtained with improvements in cement pyro-processing system. On average, pyro-processing systems in the United States operate at about 40% thermal efficiency[5].

These process improvements will come from better energy management, upgrading existing equipment, adopting new pyro-processing technologies.

Cement industry in Ethiopia uses imported primary energy (fossil fuel) and electricity derived from hydroelectric power station. Even though, the country has a huge amount of deposited fossil fuel but spends millions of dollars annually to meet its primary energy requirement. The increasing cost of energy has caused the industrial sectors.

As stated earlier, the cement sector is one of the major energy intensive industries while playing an important role in the economy of a country. The major part of consumed energy in cement industry is thermal energy which is consumed mainly in the kiln plant for clinker manufacture. Due to this reason, it needs a detailed assessment and audit on how energy is being utilized.

The study is mainly undertaking energy audits of the industries to best suit the available energy management. This can help the country to reduce its fossil fuel consumption, thus improving energy security and improving the country’s balance of payments.

The energy audit has emerged as one of the most effective procedures for a successful energy management program for cement industry. The main aim of energy audits 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 of cement industry.

1.2. Plant Descriptions

1.2.1. Introduction

Messebo Cement Factory Private Limited Company (MCF PLC) is one of EFFORT (Endowment Fund for the Rehabilitation of Tigrai) group companies established in accordance with the commercial code of Ethiopia in 1997. The paid up capital of the company is ETB 240 million.

Messebo cement factory towering down its raw materials descending down from the depth as high as 2km to the bottom of Messebo hill and the some of the raw materials are brought from different areas of Tigrai Region. The hill is Called Messebo from which is derive the plant name 'Messebo Cement Factory'.

The factory has two different production lines with different capacity and operational technology. The first cement line of the factory was constructed in 2001 and erected by ENKA a company based in Turkey. The machineries of the plant are designed and supplied by world renowned cement technology supplier FL Smidth of Denmark. The investment capital of the first line is around ETB 1.2 billion and has clinker capacity of 4000 TPD. The most and modern technology usage is that of the new that expanded in 2011 by HCRDI (Hefei cement research and design institute) with the investment capital ETB 2 billion, and it has clinker capacity of 3000 TPD, the one which is taken as a basis in the research work.

The company is producing four type of cement and the products of the factory meet national and international standard requirement of cement. These are:

Table 1.1 Type of produced cement in MCF PL-2 **[**Source: CMP of MCF**]**

Type produced cement		% Clinker	% Gypsum	% Pozzaolana	% Additives/ High grade limestone
1	Ordinary Portland Cement (OPC)	90-95	5	0	0-5
2	Pozzaolana Portland Cement (PPC)	70-75	5	20-25	0
3	Portland Limestone Cement (PLC)	70-75	5	0-5	20-25
4	Low Heat High Sulphate Resistance Cement (LH-HS)	95	5	0	0

The main process routes for the manufacturing of cement vary with respect to equipment design, method of operation and fuel consumption. Cement manufacturing process basically includes quarry, raw meal preparation, preheating of raw meal, kiln, clinker cooling, grinding, storage and dispatch. Figure 1.1: shows a basic process flow of cement manufacturing. The basic chemistry of the cement manufacturing process begins with the decomposition of calcium carbonate ($CaCO_3$) at about 900°C to leave calcium oxide (CaO, lime) and liberate CO_2; this process is known as calcination. This is followed by the clinkering process in which the calcium oxide reacts at high temperature (typically 1,400°–1,500° C) with silica, alumina and ferrous oxide to form the silicates, aluminates and ferrites respectively which forms the clinker. This clinker is then ground together with gypsum and other additives to produce cement. Fuels are required to generate thermal energy during the process of calcination in preheater tower and during the clinkerization process in Pyro-processing system[6].

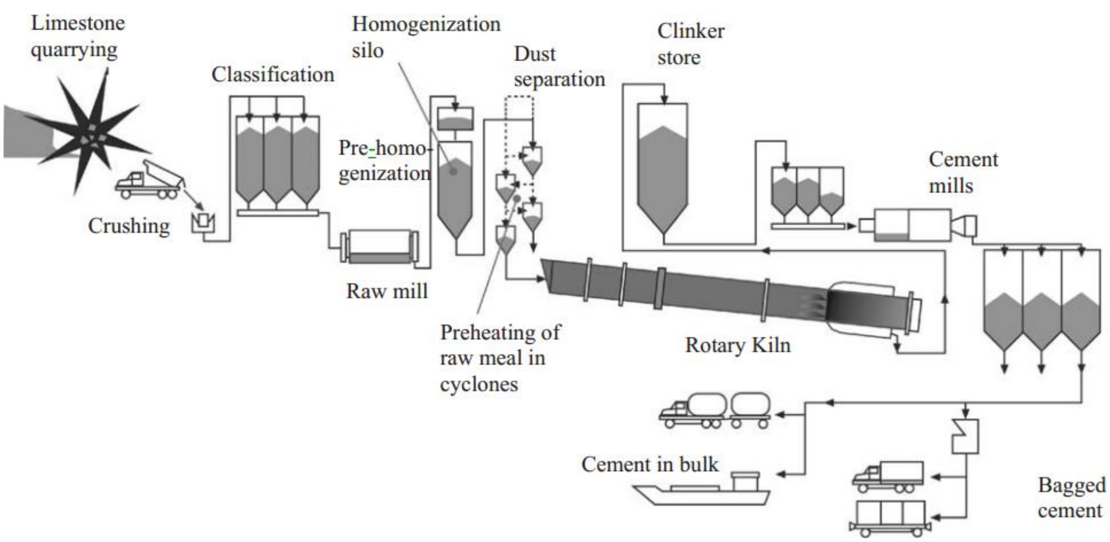

Figure 1.1: Basic Process Flow Cement manufacturing process [6]

The new line (Line-2) has dry type rotary kiln system, latest pre-calciner technology and 6-stage cyclone preheater system used for clinker production. Also it has bag filters rather than ESPs for dust collection and gas treatment.

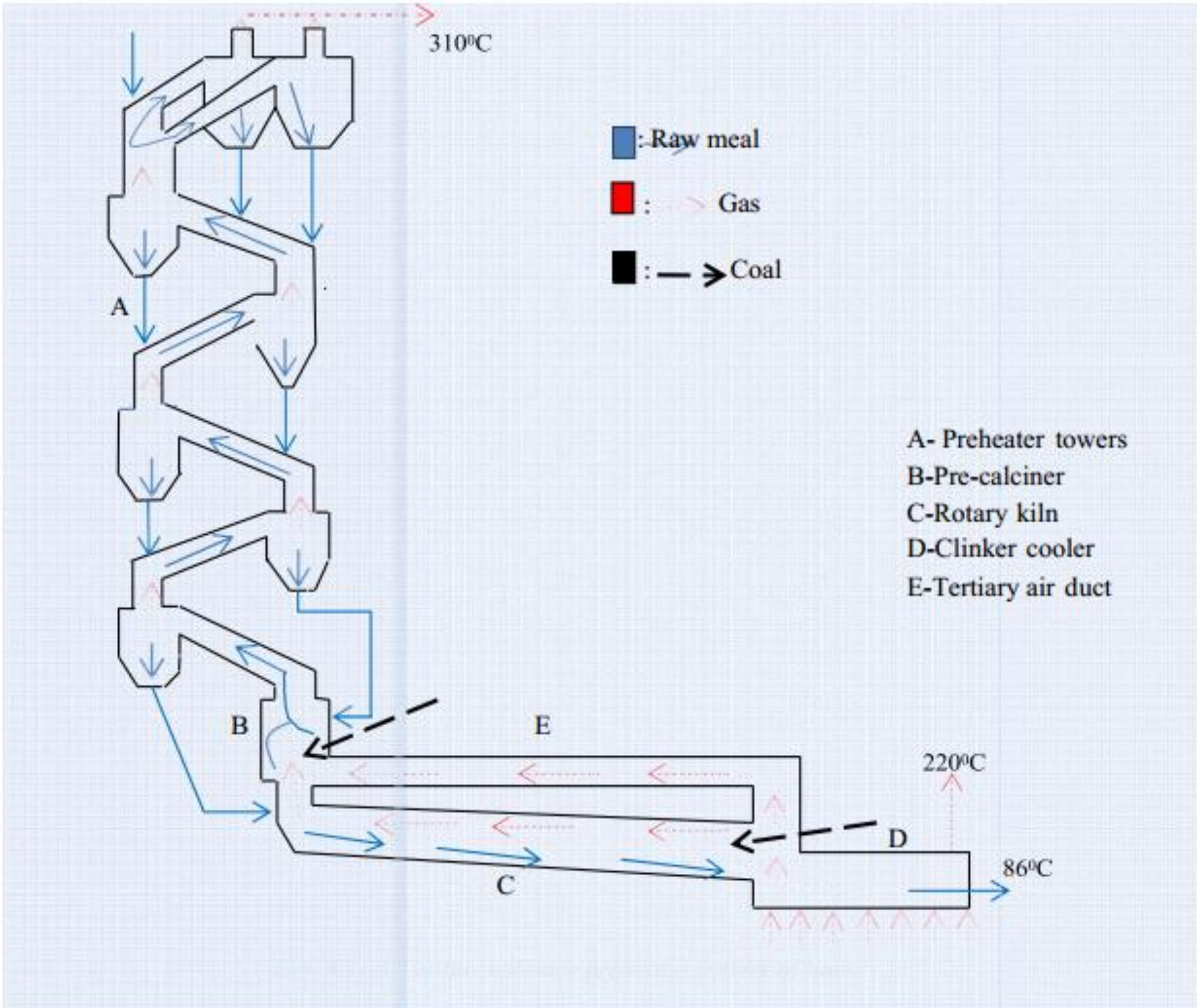

Figure 1.2: An in-line calciner preheater system of line-2

1.2.2. Utilities

The utility systems which the factory uses are:

1. Coal milling utility systems [Thermal Energy utility]: Thermal energy accounts for almost half of the energy costs incurred by the cement factory. A coal is used in the Messebo cement factory. The major use of thermal energy is in the kiln and pre calciner. In plants using coal, an external coal or oil fired furnace is used for generation of hot air required for coal mills. To produce Thermal energy by using firing coal and to distribute it for the end use devices, these utilities are essential.
2. Electricity utility systems: The factory uses electricity to operate electrical appliances (mill drives, fans and conveying systems) and for lighting etc… in the factory.

1.2.3. Major Energy Consuming Equipment's

Pyro-processing requires the major share of the total thermal energy use. This accounts for about 93–99% of total fuel consumption. However, electric energy is mainly used to operate both raw materials (33%) and clinker crushing and grinding (38%) equipment[3].

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[7].

Studies show in Messebo cement factory in the 2016/2017 fiscal year, the electrical energy requirement was (10%) whereas, the thermal energy requirement was 90% [report of COK dep. of MCF].

From the main thermal energy consuming equipment's, the following are mentioned.

- Pyro-processing system
  - Pre heater unit process
  - Pre-calciner unit process
  - Kiln unit process and
  - Grate Cooler unit process

1.3. Problem statement of the study

Energy is now costly and scarce commodity in any cement manufacturing industry, and hence it is essential for each cement industry to develop an energy auditing to find the energy conservation opportunities and methods to reduce energy consumption. The strategy of adjusting and optimizing energy in cement industry, using the energy auditing systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems is needed.

In Messebo, it has been 90% of the energy consumption is thermal energy. This is to huge as compare to other companies' thermal energy requirement which is 75%.

Messebo cement factory have the problem of proper utilization of energy. They did not know their energy consumption patterns in well-defined manner by performing energy audit. This is due to:

- Lack of awareness for the factory owners about energy management, which is expressed:
    - ✓ Lack of skilled human resource in energy management.
    - ✓ The absence of measuring instruments for audit.
    - ✓ Absence of energy audit team in the factories.
- Lack of emission reduction enforcements.

As a result of these facts, *has* will be select to conduct energy audit in Messebo cement factory production line-2. Hence, this thesis targets to examines the energy consumption patterns of the factory and efficiencies of the major energy consuming systems thereby identifying energy conservation opportunities to save energy for the factory to make it more competitive in the market.

The main focus is on the pyro-processing (clinker production stage) system which contains the cyclone preheater, calciner, rotary kiln and grate coolers are the major unit processes that uses huge amount of energy. The coal is injected both to kiln and calciner at different ratio. Due to the high temperature required for the reactions to take place the losses are quite high. This research will look for the best Energy Conservation Opportunities (ECOs).

1.4. Objective of the Study

1.4.1. General Objective

The general objective of the study was auditing thermal energy in pyro-processing system of Messebo cement factory (line -2) and finally to look for the energy conservation opportunities.

1.4.2. Specific Objectives

1. To find out the area of heat/thermal energy loss.
2. To quantify the losses and utilized heats/thermal energy.
3. To identifying thermal energy conservation opportunities.

1.5. Scope of the Study

This study mainly concerned on thermal energy audit of Messebo Cement factory. Having the Cement factory mainly two production lines for cement production process and it is vast to cover the whole production line and having similar process this study will be only on production line-2. In all production process lines basically the cement factory has three stages to produce cement. This are:

Stage 1: raw material preparation

Stage 2: pyro-processing (clinker production) system

Stage 3: finish grinding

Asper the energy bill report of the factory, the pyro-processing system is taking more than 90%, of the total energy.

Hence, the study will focus on looking opportunities to minimize the thermal energy consumption.

1.6. Significances of the study

The outcome of the study will have significant importance. The first and the most merit of the study is its economical consequence since energy is the hot issue of the world in this century. On the other hand, cement factory is energy dissipative. This study stresses on the detection of energy loss units and finding mechanisms to reduce it.

Secondly, cement factory is also known by its enormous greenhouse gas, carbon dioxide disposal. Production of one tone of clinker releases one tone of carbon dioxide. The half of the carbon dioxides is drawn from combustion of fuel. This study will minimize the energy loss which leads the reduction of the production of exhaust gas including CO using the alternative fuels (like Biomass).

1.7. Delimitation

One major challenge encountered during the work of this study was to taking reliable data not in their time and in schedule. Due to the lack of relevant data, some parameters are taken from literature for calculations. The absence of orsat gas analyzer and simulation software is paying the researchers to use some correlation. For the future work, measuring the data at the proper time by considering the parallel parameters will become slightly similar to the plant. And also developing simulation and control program, will lead to the exact auditing system.

1.8. Organization of the Study

This thesis research is organized in 5 chapters which all are necessary in energy audit report arrangements.

Chapter one discusses the need of conducting energy audit, brief introduction of Messebo Cement Factory, problem statement of the study, the general and specific objectives of the research, Scope, significances and Organization of the study.

Chapter two presents meaning of energy audit, types of energy audit and cement production process and the necessary energy inputs of the process are discussed. This chapter reviews recent similar works to be with the stole of the art. From the reviewed articles gap will be identified for further work.

In chapter three, present methodology and material.

Chapter four, deals on thermal energy bill analyses and detailed energy audit of the pyro-processing system is discussed to discover its energy conservation opportunities and to take the feasible energy conservation measures.

In chapter five, conclusions and recommendations of the research are presented. In addition, the thesis contains references and appendixes.

CHAPTER TWO

2. LITERATURE REVIEW

A sizeable amount of energy is used in manufacturing cement. Therefore, focus should be given on the reduction of energy and energy related environmental emissions locally and globally.

Being an energy intensive industry, this accounts for 40–60% of the total production costs. Thermal energy accounts for about 35–50% of the cement production cost. The typical electrical energy consumption of a modern cement plant is about 110–120kW per tons of cement[8].

Many researches and modification have been made to reduce the specific thermal energy consumption. Specific thermal 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. However, electric energy is mainly used to operate both raw materials (33%) and clinker crushing and grinding (38%) equipment[9].

Electrical energy is required to run the auxiliary equipment such as kiln motors, combustion air blowers and fuel supply, etc. (22%) to sustain the pyro-process.

In the last few decades' energy intensive areas have been identified and numerous significant modifications (processes and equipment's) have been made. The main modification in the thermal energy reduction is to achieve a good heat transfer and good heat recovery. To achieve these, raw mix chemistry and fineness, preheater, kiln and cooler was the main concern areas. Mills, Fans, pumps compressors, heat exchangers, and kiln and dryer driving units are the electrical energy consumers. To decrease the fan loads, preheater & cooler technology is hastily changing. Mill technology has become research area for many suppliers and has great advance. Today, many old cement factories are replacing the rotary and planetary cooler by ETA cooler for its energy efficiency. Pneumatic transportation has become obsolete[10].

Cement factories have become research areas to cope with the increasing energy cost and environmental regulation. Researches which have been done so far include new technology development and also modification on the existing technology.

For existing technology, one of trends in energy optimization is modeling. A mathematical model of cement kiln plant without pre-calciner has been established by Elkjore. The effect of different parameters on the specific heat consumption and preheater exit gas temperature are investigated by the author with the aid of that model. The investigated parameters were the amount of the excess air, primary air, false air at the cement kiln, false air in the pre-heater, wall heat losses and kiln gas bypass ratio. Some operation conditions of the process have been kept at a certain value such as the degree of calcinations in the bottom stage cyclone pre-heater, hot meal temperature at the kiln inlet, kiln gas temperature, dust load in the kiln exit gas.

Results of the calculation showed that the specific fuel energy consumption increases with the increases of excess air, primary air, and false air at the kiln inlet, cooler energy loss, false air in the pre-heater and the kiln gas by pass ratio. On the other hand, the pre-heater exits gas temperature increases with the increase of the excess air, false air at the kiln inlet. It decreases with the increase of the false air in the pre-heater and with the kiln gas by pass ratio[11].

A balance model of cement kiln plant with pre-calciner with tertiary air has been established by Ghazi. The effect of various factors such as secondary fuel energy proportion, number of stages of cyclone pre-heater, kiln gas by pass ratio and the type of the fuel used on the energy consumption and the pre-heater exit gas temperature were investigated.

Some operation conditions of the process have been specified at certain values, such as the combustion excess air factors, clinkering temperature, wall heat loss and cooler efficiency. By applying the model on different kiln plants in Egypt and other kiln plants in Germany, the result of calculations showed that the difference between theoretical calculated and measured values of fuel energy consumption are in the range of 0.10 to 5.8 %. The change in the energy losses from the individual sections of the system effects on the fuel consumption by different degrees.

A balance model of cement kiln plant with pre-calciner with tertiary air has also been established by Gardeil *et al.* The effect of various factors such which were considered by Ghazi were investigated. Some operation conditions of the process have been specified at certain values, such as the combustion excess air factors, clinkering temperature, wall heat loss and cooler efficiency. The model was based on various assumptions namely, the de-carbonation behavior of the feed material in the calciner and the temperature difference between the materials and the exit gas at the kiln inlet[12].

The results indicated that the fuel energy consumption and the pre-heater exit gas temperature increases with the increase of the fuel energy proportion. This is in fact due to the increase of the hot meal temperature in the bottom stage cyclone pre-heater.

Thermal analysis of cyclone pre-heater system based on a model has been established by Peng Fei. The model was used to study the effect of dust loads at kiln inlet, precipitation efficiency of the cyclones and number of the stages of cyclone pre-heater on the fuel consumption.

Some operation conditions of the process have been kept constant at certain values, such as kiln exit gas temperature, heat of reaction, wall heat losses, clinker temperature at the kiln outlet, and efficiency of the cooler. The results showed that with the increase of dust load of kiln exit gas by 0.1 kg dust/kg clinker, the specific thermal energy consumption increases by about 13-17 kJ/kg clinker.

The results indicated that the effect of precipitation efficiency of the lower cyclones on the fuel consumption is stronger than of the higher located cyclones.

From industrial experience in cement pyro-processing system plants with pre-calciner equipped with tertiary air duct, productivity ranging from 1041 to 3427 ton of clinker/day, found that the thermal energy loss from the pre-heater is about 0.75-1.25 MJ/kg clinker, the loss through the walls of the rotary kilns is about 0.2-0.55 MJ/kg of clinker, loss from the cooler is about 0.4-0.65 MJ/kg clinker. The change in the energy losses from the individual sections of the system effects on the fuel consumption by different degrees[12].

Furthermore, on applying the mathematical models, the effect of different factors on the apparent degree of calcinations and secondary fuel energy proportion in the calciner have been estimated. Such factors were enthalpy of the kiln exit gas, potassium chloride cycle between kiln and the pre-calciner and the enthalpy of the tertiary air. The results showed that the secondary fuel energy proportion supplied to the calciner decreases with the increase of the kiln exit gas temperature and with the temperature of the tertiary air. On the other hand, the degree of calcinations in the calciner increases with the increase of the kiln exit gas temperature and with KCl concentration in the hot meal.

Recent studies on the modeling of cement manufacturing reported in the literature are mostly based on computational fluid dynamics (CFD) and they mainly study aerodynamic behavior of a particles in the preheating system, the shape and the temperature of the flame in the combustion zone, coal combustion itself as well as oxygen enrichment in the burning zone and not so much the thermodynamics and clinker chemistry taking place in the pyro-processing system[10].

Radwan *et al,* have been studied the modeling, simulation and control of the cement pyro-processing system. A transient model is derived for cement kiln systems. In this work, two control loops were studied the temperature of the preheater calciner loop and the sintering zone temperature outlet of rotary kiln loop.

The flow rate of the fuel is manipulated variable for the previous two control loops, but the disturbance variables are combustible properties of the fuel and the reaction energy due to the change the composition of the raw materials. The control system using PID controllers, which is robust with good performance in either set point tracking or disturbance rejection cases[12].

The average thermal energy consumption in Messebo cement factory is significantly higher than the best practice value, indicating that a strong potential for thermal energy efficiency improvements. This paper work is intended to identify the potential energy loss areas and to adapt a mechanism that makes possible energy saving.

To achieve this, energy optimization based on mathematical modeling is the best and the commonly used method. However, it needs depth knowledge of the aerodynamics and the heat transfer phenomena in the kiln. This requires flame temperature measurement, which is the significant factor for heat transfer in the pyro-processing system.

Alternatively, concentration is given on process optimization by performing mass and energy balance on basic units. Mass and energy balance on every unit provides a clear understanding about a loss areas and types. From the information gathered on every unit, the correct modification on process as well as the equipment’s will be made. Today most existing plants follow this approach for modification and optimization. This approach is chosen for its better capacity to identify the loss areas and simplicity to conduct. Moreover, it is less ideal than the other approaches.

2.1. Energy Audit

Energy audit is the key to a systematic approach for decision-making in the area of energy management. It attempts to balance the total energy inputs with its use and serves to identify all the energy streams in a facility. It quantifies energy usage according to its discrete functions. It is the process of assessing the way energy is being used and possibly wasted in industries, factories, energy consuming systems, machines, etc… and if wastage is found, it takes corrective measures to minimize the wastage. Minimization of energy wastage is done by finding better way of meeting the energy demand[13].

As per the Energy Conservation action of 2001, Energy Audit is defined as "the verification, monitoring and analysis of use of energy including submission of technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption"[14].

Energy audit is one of the first tasks to be performed in the accomplishment of an effective energy cost control program. An energy audit consists of a detailed examination of how a facility uses energy, what the facility pays for the energy, and finally a recommended program for changes in operating practices or energy consuming equipment that will cost-effectively save money on energy bills[13].

Saving money on energy bills is attractive to business, industries and individuals alike. Customers, whose energy bills use up a large part of their income and especially those customers whose energy bills represent a substantial fraction of their company's operating costs, have a strong motivation to initiate and continue an ongoing energy cost control program. No-cost or -cost operational changes can often save a customer or an industry on utility bills, capital cost programs with payback times of two years or less can often save an additional. In many cases these energy cost control programs will also result in both reduced energy consumption and reduced emission of environmental pollutants. Energy audit is sometimes called an energy survey or an energy analysis, so that, it is not in a weak position (hampered) with the negative connotation of an audit. The energy audit is a positive experience with significant benefits to the business or individual. An energy audit is a technique for identifying energy losses, quantifying them, estimating conservation potential, evolving technological options for conservation and evaluating techno- economics for the measures suggested[15].

Energy Audit gives a positive orientation to the energy cost reduction, preventive maintenance and quality control programs which are vital for production and utility activities. Such an audit program will help to keep focus on variations which occur in the energy costs, availability and reliability of supply of energy, identify energy conservation technologies, retrofit for energy conservation equipment in industries, factories, households[16].

For the audit to have the maximum value, it should address and express in quantified ways[13]:

- Examination and evaluation of the energy efficiency of all energy consuming systems, processes and equipment (including energy supply and the building envelope)
- Indication of process management inefficiencies with negative impact on energy consumption.

The type of Energy Audit to be performed depends on[13]:

- Function and type of industry
- Depth to which final audit is needed, and
- Potential and magnitude of cost reduction desired

Thus Energy Audit can be classified into the following two types.

I. Preliminary audit
II. Detailed audit

2.1.1. Preliminary audit

Preliminary energy audit is a relatively quick exercise to:

- Establish energy consumption in the organization
- Estimate the scope for saving
- Identify the most likely (and the easiest areas for attention
- Identify immediate (especially no or low-cost) improvements or savings
- Set a ‘reference point’
- Identify areas for more detailed study measurement

Preliminary energy audit uses existing, or easily obtained data. The preliminary audit alternatively called a simple audit, screening audit or walk-through audit which is the simplest and quickest type of audit. It involves minimal interviews with site operating personnel, a brief review of facility utility bills and other operating data, and a walk-through of the facility to become familiar with the building operation and identify glaring areas of energy waste or inefficiency.

Typically, only major problem areas will be uncovered during this type of audit. Corrective measures are briefly described, and quick estimates of implementation cost, potential operating cost savings, and simple payback periods are provided. This level of detail, while not sufficient for reaching a final decision on implementing proposed measures, is adequate to prioritize energy efficiency projects and determine the need for a more detailed audit.

2.1.2. Detailed audit

A wide ranging audit provides a detailed energy project implementation plan for a facility, since it evaluates all major energy using systems. This type of audit offers the most accurate estimate of energy savings and costs. It considers all the equipment’s that use available energy in the factory and performs energy cost saving calculations.

In a comprehensive audit, one of the key elements is the energy balance. This is based on an inventory of energy using systems, assumptions of current operating conditions and calculations of energy use. This estimated use is then compared to utility bill charges. This type of audit will be able to identify all energy conservation measures which are appropriate for the facility given in operating parameters. A detailed financial analysis is performed for each measure based on detailed implementation cost estimates (site-specific operating cost savings, and the customer's investment criteria).

Detailed energy auditing is carried out in three phases: Phase I, II and III.

Phase I - Pre Audit Phase

Phase II – Audit Phase

Phase III - Post Audit Phase

2.1.2.1. Phase I - Pre Audit Phase

In the first phase, data from the energy bills is analyzed in detail to determine what energy is being used and how the use varies with time. The main purposes of conducting pre audit phase in energy auditing include:

- Resource Planning,
- Organize instruments and timeframe,
- Familiarization of process/ plant activities,
- First hand observation and assessment of the present level of operation and practices,
- Orientation, awareness creation,
- Issue questionnaire for the department,
- Informal interview with energy manager or Plant Manager,
- Building up cooperation (conduct of brief meeting or awareness program with all divisional heads and persons concerned),
- Collecting the necessary data, and
- Performing walk through audit.

2.1.2.2. Phase II – Audit Phase

Once all of the basic data have been collected and analyzed, the audit team should tour the entire facility to examine the operational patterns and equipment usage, and should collect detailed data on the facility itself as well as on all energy using equipment.

The facility inspection is an important part of the overall audit process. Data gathered on this tour, together with an extensive analysis of this data will result in an audit report with possible implementation plan.

After the plant survey, the audit team must develop an energy balance to account for the energy use in the facility. Once all energy uses have been identified and quantified, the team can begin analyzing alternatives. Detailed studies to establish and investigate energy and material balances for specific plant departments or items of process equipment are carried out.

The final step of phase two is the audit report which recommends changes in equipment, processes or operations to produce energy cost savings. This phase is the main step of energy auditing activity which includes:

- Conduct of detailed measurements,
- Analysis of energy use/desk top analysis,
- Historic data analysis, baseline data collection (primary data gathering),
- Analyzing the energy and material balance for the areas,
- Energy and material balance & energy loss analysis,
- Design operating data and schedule of operation,
- Cost benefit analysis (annual energy bill and energy consumption pattern),
- Measurements: energy generation and distribution system survey, with portable instruments for collection of more and accurate data. Confirm and compare operating data with design data,
- Identification & consolidation energy conservation measures,
- Conceive, develop and refine ideas,
- Review the previous ideas suggested by energy audit if any,
- Assess technical feasibility, economic viability and prioritization of energy conservation options for implementation,
- Prioritize by low, medium, long term measures and Documentation, report presentation.

2.1.2.3. Phase III Post-Audit Phase

After the energy consumption data has been collected and analyzed, the energy-related systems have been carefully examined, the ideas for improvement have been collected, and management commitment has been obtained, the next steps are to obtain company support for the program, to choose goals, and to initiate for action implementation and following the identified opportunities with their action plan.

Assist and implement energy conservation measures and monitor the performance are the main goal of this phase.

- Action plan, Schedule for implementation
- Follow-up and periodic review

2.2. Cement Production Process

Cement production is a resource-intensive practice involving large amounts of raw materials, energy, labor, and capital. Cement is produced from raw materials such as limestone, chalk, shale, clay, and sand. These raw materials are quarried, crushed, finely ground, and blended to the correct chemical composition. Small quantities of iron ore, alumina, and other minerals may be added to adjust the raw material composition. Typically, the fine raw material is fed into a large rotary kiln1 (cylindrical furnace) where it is heated to about 1,450 degrees Celsius (2,640 degrees Fahrenheit). The high temperature causes the raw materials to react and form a hard nodular material called "clinker." Clinker is cooled and ground with gypsum and other minor additives to produce cement[2].

Beyond the mining of the raw materials, there are three major process steps in cement production (see Figure 2.1 :). These are:

1. Raw material preparation
2. Pyro-processing (clinker production)
3. Finish grinding

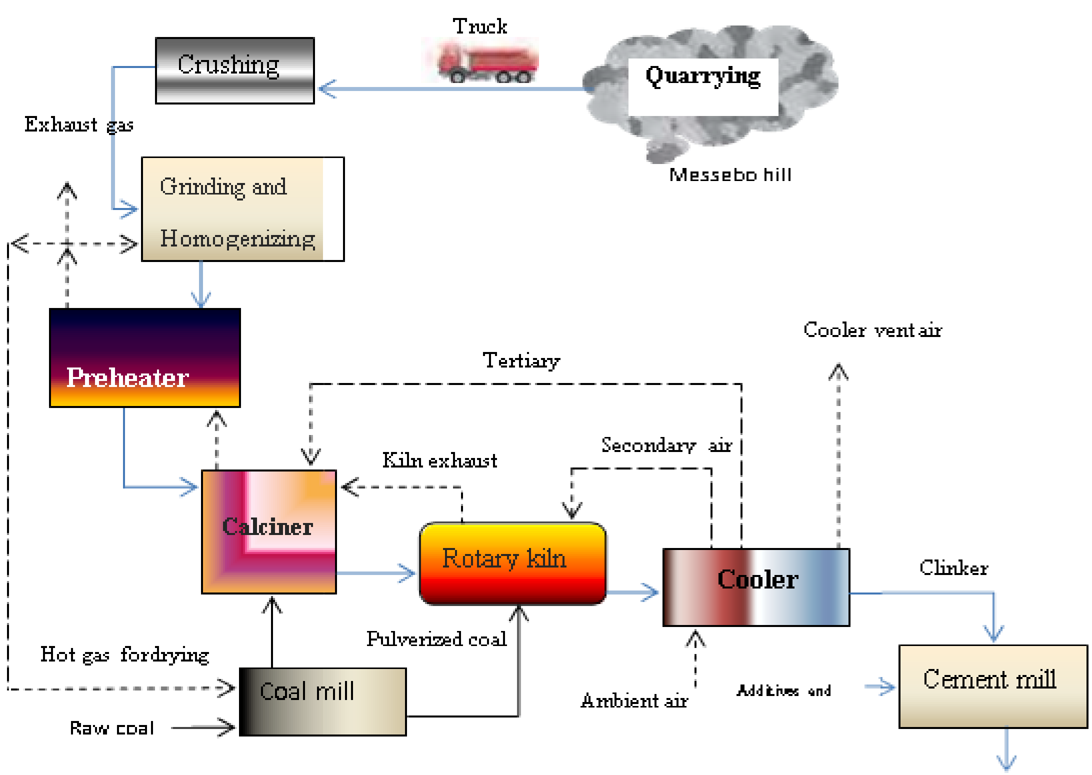

Figure 2.1: Simple schematic of cement production process

Each of these steps has specific energy requirements and consumption patterns, as well as various energy efficiency measures that can be applied to reduce energy use and increase productivity depending on the characteristics of and conditions at each individual cement plant. The remaining energy consumption at cement plants is used for final-product packaging, lighting, and building services. These are typically minor electricity uses compared to the major electricity and fuel consumption in the three major process steps.

2.2.1. Raw Material Preparation

Raw material preparation provides a mixture of raw materials and additives that has the right chemical composition and particle size distribution necessary for clinker production. For plants that receive their raw materials already crushed, this stage usually involves grinding (milling), classification, mixing, and storage. Raw material preparation is an electricity-intensive production step requiring about 25 to 35 kilowatt hours (kWh) per ton of raw material, although it could require as little as 11 kWh per ton[2].

After primary and secondary size reduction, the raw materials are further reduced in size by grinding. The grinding differs with the pyro-processing process (kiln type) used. In dry processing, the materials are ground into a flow able powder in horizontal ball mills or in vertical roller mills. In a ball mill, steel-alloy balls are responsible for decreasing the size of the raw material pieces in a rotating cylinder. Rollers on a round table provide size reduction in a roller mill. Waste heat from the kiln exhaust or the clinker cooler vent, or auxiliary heat from a standalone air heater before pyro-processing, is often used to further dry the raw materials[17].

The moisture content in the raw material feed of a dry kiln is typically around 0.5 percent (0 percent to 0.7 percent)[18].

In short, raw material is derived from the oxides of calcareous, siliceous, argillaceous and ferriferous extracted from the earth by mining and quarrying. These raw materials are crushed by hummer crusher and transported to longitudinal storage hall by belt conveyor. The raw material which ground at the mill into fine powder, blended and stored in silos[4].

2.2.2. Pyro-processing (clinker production)

Clinker production, or pyro-processing, transforms raw materials (primarily limestone) into clinker (lime), the basic component of cement, and releases carbon dioxide during the transformation. Clinker production is the most energy-intensive stage in cement production, accounting for more than 90 percent of the total energy use and virtually all of the fuel use in the industry. Clinker is produced by pyro-processing the raw materials in large kilns[2].

Four important processes occur with the raw material mixture during pyro-processing. First, all moisture is driven off from the materials. Second, the calcium carbonate in limestone dissociates into carbon dioxide and calcium oxide (free lime); this process is called calcination. Third, the lime and other minerals in the raw materials react to form calcium silicates and calcium aluminates, which are the main components of clinker. This third step is known as clinkering or sintering. Fourth, once the clinker is discharged to the clinker cooler from the kiln, it is cooled rapidly to minimize glass phase formation and to ensure maximum yield of alite (tricalcium silicate) formation, an important component for cement-hardening properties[19].

The main kiln type in use throughout the world is the rotary kiln as shown Figure 2.1. In rotary kilns, a tube with a diameter of up to eight meters is installed at a three- to four-degree angle that rotates one to five times per minute. The kiln is normally fired at the lower end, and the ground raw material is fed into the top of the kiln, from where it moves down the tube countercurrent to the flow of gases and toward the flame end of the kiln. As the raw material passes through the kiln, it is dried and calcined, and then finally enters into the sintering zone. In the sintering (or clinkering) zone, the combustion gas reaches a temperature of 1,800 to 2,000 degrees Celsius. Hot clinker is discharged from the lower end of the kiln and is immediately cooled in large air coolers to ensure clinker quality and to lower it to handling temperatures for downstream equipment. Cooled clinker is combined with gypsum and other additives and ground into a fine gray powder called cement. Many cement plants include the final cement grinding and mixing operation at the site. Others ship some or all of their clinker production to standalone cement grinding plants situated close to markets[2].

Rotary kilns are divided into two groups, dry process and wet process, depending on how the raw materials are prepared. In wet process systems, raw materials are fed into the kiln as slurry with a moisture content of 30 to 40 percent. Wet process kilns have much higher fuel requirements due to the amount of water that must be evaporated before calcination can take place. To evaporate the water contained in the slurry, a wet process kiln requires additional length and nearly 100 percent more kiln thermal energy compared to the most-efficient dry kiln (see Table 2.1). Wet process kilns tend to be older operations[2].

Three major variations of dry process systems are used worldwide: long dry kilns without preheaters, suspension preheater kilns, and preheater/pre-calciner kilns. In suspension preheater and preheater/pre-calciner kilns, the early stages of pyro-processing occur in the preheater sections, a series of vertical cyclones, before materials enter the rotary kiln[20].

As the raw material is passed down through these cyclones, it comes into contact with hot exhaust gases moving in the opposite direction, and, as a result, heat is transferred from the gas to the material. Modern preheater/pre-calciner kilns also are equipped with a pre-calciner, or a second combustion chamber, positioned between the kiln and preheaters that partially calcined the material before it enters the kiln so that the necessary chemical reactions occur more quickly and efficiently[21].

Depending on the drying requirements of the raw material, a kiln may have one to six stages of cyclones with increasing heat recovery with each extra stage. As a result, suspension preheater and preheater/ pre-calciner kilns tend to have higher production capacities and greater fuel efficiency compared to other types of systems, as shown in Table 2.1[2].

Table 2.1: Specific Thermal Energy Consumption by Rotary Kiln Type[6]

Kiln Type	Heat Input (MJ/ton of clinker)
Wet	5,860–6,280
Long Dry	4,600
1-Stage Cyclone Suspension Preheater	4,180
2-Stage Cyclone Suspension Preheater	3,770
3-Stage Cyclone Suspension Preheater	3,550
4-Stage Cyclone Suspension Preheater	3,140
5-Stage Cyclone Suspension Preheater plus Calciner plus High-Efficiency Cooler	3,010
6-Stage Cyclone Suspension Preheater plus Calciner plus High-Efficiency Cooler	<2,930

The primary cooling technologies in use today are various configurations of grate coolers and older planetary coolers. In the grate cooler, the clinker is transported over a reciprocating grate through which air flow perpendicular to the clinker flow. In the planetary cooler (a series of tubes surrounding the discharge end of the rotary kiln), the clinker is cooled in a countercurrent air stream. Planetary clinkers are slowly being phased out as new generations of grate coolers enter the market with further operational and efficiency improvements. Modern clinker coolers route the heated air to the pre-calciner to serve as preheated combustion air, or to the preheaters to preheat raw material prior to entering the kiln. The primary energy consumption in a clinker cooler is the electricity required to push cooling air through the cooler[2].

Generally, the raw meal from silo enters to the preheater in which the hot gases from the kiln heat the raw material as they swirl down through the six stage cyclone preheaters to calciner. The preheater is equipped with a pre-calciner, which 60% of pulverized coal is injected, up to 95% of the raw meal calcination performed. Then, the calcined meal which is the semi product of clinker is cascaded down the calciner into rotary kiln to reach the required reactions inside the kiln; clinker which is the semi product of cement is produced. Clinker is rapidly cooled in cooling unit after the rotary kiln[22].

2.2.3. Finish Grinding

Once the clinker has been cooled, it must be crushed and mixed with other materials to produce the final cement product. After cooling, clinker is often stored in domes, silos, or bins. The material-handling equipment used to transport clinker from the clinker coolers to storage and then to the finish mill is similar to equipment used to transport raw materials (for example, belt conveyors, deep bucket conveyors, and bucket elevators)[2].

To produce cement, clinker nodules are ground to the consistency of powder. If the blending material is not already in a powdered state, it also must be crushed and ground prior to blending. Ordinary Portland cement is composed of 95 percent clinker and 5 percent additives. “Blended cement” is the term applied to cement that is made from clinker that has been ground with a larger share of one or more additives. These additives can include such materials as fly ash from power plants, blast furnace slag volcanic ash, and pozzolans. The finish grinding is typically done in ball mills, ball mills combined with roller presses, vertical roller mills, or roller presses. Coarse material is separated in a classifier and returned to the mill for additional grinding to ensure that the final product has uniform surface area[23].

In short, the cement mill is that of closed circuit ball mill. The clinker is transported to the finish mill by a conveyor belt to be ground with small amount of gypsum, to control the set properties of the produced cement, and small additives are added. Different clinker types and different types of additives are used, depending on what type of cement that is to be produced.
Finally, the cement is packed or bagged by a rotary packing machine or manual bag feeding. The machine delivers to truck loading lines and Weight Bridge is installed near the dispatch building for weighing trucks. The bagged cement is either in car loading bench or directly loaded by belt car loader on to trucks. The bulk loading spouts are placed in the side of cement silo[2].

CHAPTER THREE

3. METHODOLOGY AND MATERIAL

3.1. Methodology of the Study

This chapter is describing the methodology of this study; It is concerned a number of separate sections, which were developed individually and combined to come up with the complete study of the thermal energy audit on Messebo Cement factory. Each part required research and understanding to enable the study to be carried out in desired manner. Generally, can follow as shown below on the flow chart.

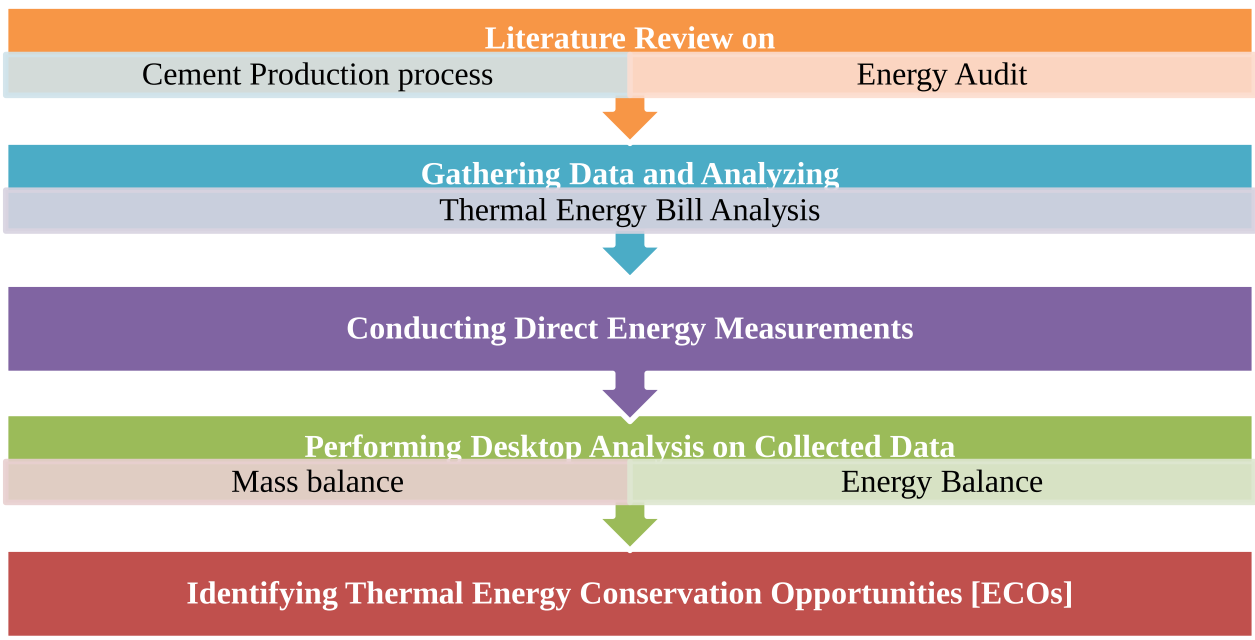

Figure 3.1: Flow chart of the study [Methodology]

A review of literature was conducted on the area of industrial energy use and efficiency in relation to cement factory. Available books, case studies, previous project work and guidelines are surveyed in order to have a clear understanding of the subject matter.

The first step on the way to energy conservation is finding out where and how energy is spent in the plant. A detailed investigation and measurement of existing plant operation parameters, helps to identify the areas with the greatest potential for improvement and the most appropriate measures for achieving this improvement.

In this study the researcher's works with all temperature source, and do the study in order to account the energy from these temperatures to reduce fuel consumption and thus, to improve thermal efficiency. As stated in the above, to perform this research work, the production process of cement and detailed flow chart of the process specially the pyro-processing system were studied by the researcher's in order to get all input and output parameters. This deals mainly with the pyro-processing system because it is the most energy intensive process from any other unit processes.

The primary approach to this study involved walk-through survey of the whole plant, internet resource and in depth interviews and sudden questioning with the production manager, division head, shift engineers and laboratory technician to collect the necessary data. Some particular data are also collected from Central Control Room (CCR) and Local Control Room (LCR).

As pointed above, out of the source, the surface temperature of the main unit process (grate cooler, kiln shell, calciner and preheater) have been measured directly.

The surface temperature of grate cooler is taken by rough measuring of six boxes vertically and 19 sections horizontally.

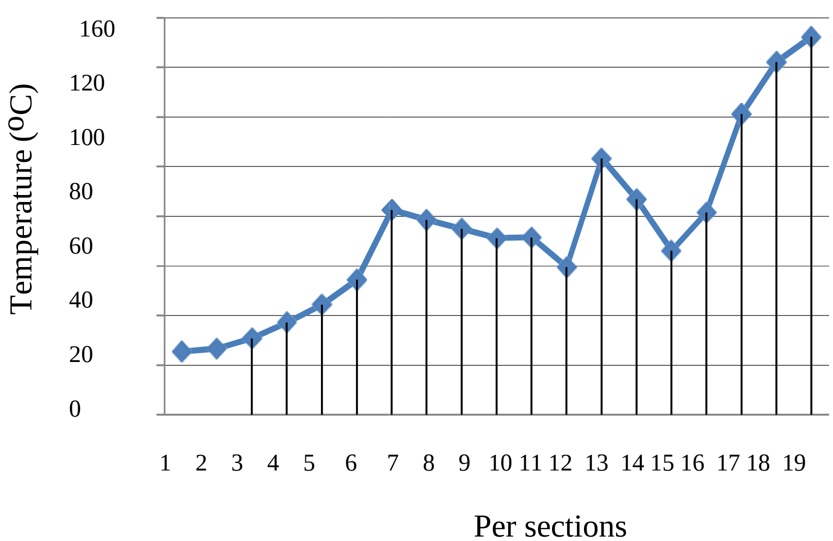

Figure 3.2: Surface temperature of grate cooler versus section

The surface temperature of kiln is lowered in such part of the shell due to the coolant in the rotating type.

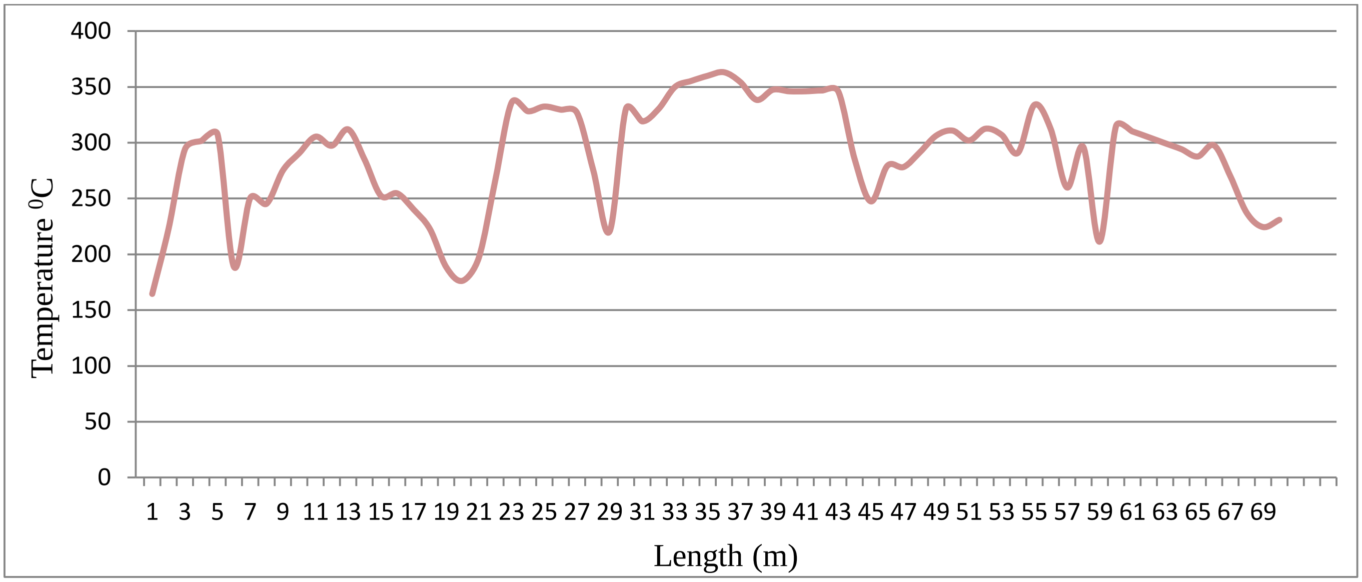

Figure 3.3: Rotary Kiln Surface Temperature versus its length

Once having these parameters, it can be analyzed quantitatively for detailed audit for taking steps to conserve energy lost. For estimation of the most energy available, governs by the following formula:

$$Q = mC_p(T - T_{ref.}) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.1)$$

Where, $m = specific\ mass\ (Kg/Kg.cli)$

$C_p =$ average specific heat $(Kg/Kg.cli)$

$T_{ref.} =$ reference temperature °C

$T =$ temperature of raw material °C

This basic calculation of sensible heat can be adapted for all materials and gases flow like clinker, raw meal, dust, exhaust gas, waste gas, cooling air, false air, etc. Also the value of specific heat capacity can be calculated at given temperature by Kirchhoff law.

$$C_p = A + BT + CT^2 + DT^3 \dots \dots \dots \dots \dots \dots \dots \dots \quad (3.2)$$

A, B, C, D is constant and T is the temperature of material at any instant.

3.2. Material

The requirement for an energy audit such as identification and quantification of energy necessitates measurements; these measurements require the use of instruments. These instruments must be portable, durable, easy to operate and relatively inexpensive[13].

The parameters generally monitored during energy audit may include such as temperature & heat flow, radiation, air and gas flow, liquid flow, revolutions per minute (RPM), air velocity, noise and vibration, dust concentration, Total Dissolved Solids (TDS), pH, moisture content, relative humidity, flue gas analysis – CO_2, SO_x, NO_x, O_2,CO, combustion efficiency[24].

Key instruments used for thermal energy audit are listed below.

Contact thermometer:

These are thermocouples which measures for example flue gas, hot air, hot water temperatures by insertion of probe into the stream. For surface temperature, a leaf type probe is used with the same instrument[13].

Infrared Thermometer:

This is a non-contact type measurement which when directed at a heat source directly gives the temperature read out. This instrument is useful for measuring hot spots in furnaces, surface temperatures[13].

Combustion analyzer:

This instrument has in-built chemical cells which measure various gases such as SO_x, NO_x, O_2 *and* CO.

Pitot tube and manometer:

Air velocity in ducts can be measured using a pitot tube and inclined manometer for further calculation of flows.

CHAPTER FOUR

4. THERMAL ENERGY AUDIT ON THE PYRO-PROCESSING SYSTEM OF MCF PL-2

4.1. Thermal Energy Bill Analysis of MCF PL-2

4.1.1. Introduction

For each of the process steps within the boundary, the major energy use at that step of clinker production (pyro-processing system) the combustion of fuel to generate the heat required. Fuel coal is the main sources of energy in the Messebo cement production[2].

This implies that Thermal energy is used for the production of cement in MCF PL-2 and so, the factory pays cost for this energy sources. The energy bills show that as the factory paid 465,884,546.30 Birr for Raw Coal for the selected audit year (from July 2008 E.C to June 2009 E.C). The bill analysis is necessarily dependent on the paid money to the used energy by the factory.

4.1.2. Thermal Energy Consumption Data

Bills and all thermal energy consumption data of the MCF PL-2 are listed within the factory Daily Material Production and Stock Report for many years. From these only 12-months (from July 1st 2008 E.C to June 30th 2009 E.C) data regarding the factory consumption of Raw Coal and produced clinker are presented in Table 4.1 and used in the analysis.

Table 4.1: Clinker and Cement Production [**Ton**] in the Audit Year [the Fiscal Year] ***July 2008 E.C - June 2009 E.C*** [MCF PL-2]

Month	Ordinal Clinker	Special Clinker	Total Clinker	PPC	OPC	LH-HS RC	PLC	Total Cement
July	93066	0	93066	42377	30482	4913.45	0	77771.79
August	31248	0	31248	39614	33037	4645.74	0	77296.26
September	83835	0	83835	33576	53763	4719.04	0	92058.85
October	110,581.00	0	110581	61563	50129	0	0	111691.72
November	101266	0	101266	42211	40483	0	0	82694
December	104689	0	104689	70254	52954	0	0	123208.55
January	50761	0	50761	53925	29927	0	0	83852.18
February	71246	0	71246	49516	40134	0	0	89650.29
March	105653	0	105653	78659	62193	0	0	140852.15
April	98717	0	98717	62964	44118	0	0	107081.49
May	49606	0	49606	84674	31304	0	0	115978.18
June	96640	0	96640	81057	46755	0	0	127811.77
			997,308.00 ton					**1,229,947.23 ton**

4.1.3. Thermal Energy Consumption of Benchmark Countries

The energy intensities of benchmark factories which produce cement at greater amount and had so far good practices of cement production at efficient use of energy are included. By taking the average values of raw coal energy intensity consumption patterns at national level, the following table provide the data of benchmark countries [*India, Turkey, Brazil, Germany, and USA*][25].

Table 4.2: Specific thermal energy intensity of the benchmark countries

Benchmark Countries	Specific Thermal energy intensities [GJ/ton of clinker]
India	3.275
Turkey	2.951
Brazil	3.162
Germany	3.301
USA	2.901

Source: [26]

4.1.4. Monthly Thermal Energy Cost Analysis of MCF PL-2

The collected raw coal consumption pattern is processed into monthly factory paid fuel energy intensity. The total cost of raw coal is the number of ton consumed times the price per ton of coal. Raw coal has specific gravity of 1.35 ($\rho_{coal} = 1350\ kg/m^3$) [27] and the gross calorific value (GCV) of $27{,}068.18\ kJ/kg$. The average price raw coal in the audit year is$3787.67\ Birr/ton$ [28]. Monthly raw coal cost is given by equation 4.1.

$$\mathrm{MCC} = \mathrm{C_c} \times \mathrm{Monthly\ coal\ used\ in\ ton} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

Where:

$\mathrm{MCC} -$ Monthly coal cost [Birr]

$\mathrm{C_c} -$ Average monthly cost of one ton raw coal Birr/ton

Then calculate with these formulas and tabulated in table 4.1as follows.

Table 4.3 Monthly Raw Coal cost at MCF PL-2

Billing Period (E.C)	Total production of clinker [ton]	Monthly coal used [ton]	Cost of coal [Birr]
July 2008	93,066.00	12,691.00	48,069,319.97
August 2008	31,248.00	4,187.00	15,858,974.29
September 2009	83,835.00	12,509.37	47,381,365.47
October 2009	110,581.00	14,356.12	54,376,245.04
November 2009	101,266.00	12,875.63	48,768,637.48
December 2009	104,689.00	12,963.49	49,101,422.17
January 2009	50,761.00	6,723.04	25,464,656.92
February 2009	71,246.00	3,861.64	14,626,617.98
March 2009	105,653.00	14,343.89	54,329,921.84
April 2009	98,717.00	13,170.04	49,883,765.41
May 2009	49,606.00	1744.69	6,608,309.97
June 2009	96,640.00	13574.39	51,415,309.77
Total	**997,308.00**	**123,000.30**	**465,884,546.30**

Source: COK and CMP Dep't of the plant

4.1.5. Monthly Thermal Energy Intensity Consumption Pattern of MCF PL-2

Monthly energy intensity consumptions of the factory are defined as an average monthly energy needed to produce one ton of cement which are given by the following equations.

$$\mathrm{MCEI} = \frac{\mathrm{GCV} \times \rho_c \times \text{monthly coal energy intensity}}{\text{monthly cement produced}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

Where:

MCEI − Monthly coal energy intensity

GCV − Gross calorific value of coal in kJ/kg of coal $\rho_c - density\ of\ coal$

Substituting data from table 4.2 and 4.3 in equations (4.2) and the value are given in table 4.4.

Table 4.4 Monthly raw coal energy intensity of MCF PL-2

Billing Period (E.C)	Raw coal energy intensities [GJ/ton of clinker]	Total monthly produced of clinker [ton]
July 2008	4.98	93,066.00
August 2008	4.90	31,248.00
September 2009	5.45	83,835.00
October 2009	4.74	110,581.00
November 2009	4.65	101,266.00
December 2009	4.52	104,689.00
January 2009	4.84	50,761.00
February 2009	4.98	71,246.00
March 2009	4.96	105,653.00
April 2009	4.88	98,717.00
May 2009	4.29	49,606.00
June 2009	5.13	96,640.00
Monthly Average	**4.860**	

4.1.6. Thermal Energy Intensity Comparisons of MCF PL-2 with Benchmarks

The comparison is energy intensities of MCF PL-2 and the benchmarks. It can be seen that there is a significant difference between the energy intensities of the MCF PL-2 and the benchmarks. From the twelve months' coal energy intensities analyses of MCF PL-2, the ranges are from 5.45 to 4.29 GJ pre 1 ton of clinker with monthly average of **4.860** GJ/ton cli. The following table shows the difference in energy intensity of MCF PL-2 with the benchmarks[28].

Table 4.5 MCF PL-2's energy intensity comparison with benchmarks

Benchmarking countries	Specific Thermal energy intensities [GJ/ton of clinker]	Average CEI (Difference) $GJ/ton - cli$
India	3.275	1.585
Turkey	2.951	1.909
Brazil	3.162	1.698
Germany	3.301	1.559
USA	2.901	1.959
MCF PL-2	4.860	1.742

From the above table 4.3, the coal intensities of MCF PL-2 have significant difference from benchmarks. This shows that the energy utilization performance of the factory is low. Due to this, unnecessary cost will occur in MCF PL-2. The cost of coal occurred due to energy intensity difference can be estimated using the following relation.

$$AC_C = \frac{DEI_c \times FAPC \times CC}{GCV} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 4.3$$

Where:

AC_C − Difference in annual cost due to lower efficiency of coal energy intensity

DEI_c − Difference of coal energy intensity

FAPC − Factory annual production capacity

$\mathrm{CC} - \text{Average cost of fuel in the audit year [Birr]}$

$\mathrm{GCV}\ - \text{Gross calorific value of firing coal}\ KJ/ton$

The following are necessary data used to calculate annual cost occur on the factory due to lower energy intensity efficiency.

- MCF PL-2 Production in 2008/2009 E.C = 997,308.00 tons of clinker
- Average cost of firing coal in the audit year = 3787.67 Birr/ton
- Specific heat of firing coal = 27068.18 Kj/Kg
- Average value of the difference in coal energy intensity = 1.742 GJ/ton of clinker.

Substituting the above values in equation (4.3) and give the annual total thermal energy cost due to lower efficiency of coal use in the factory as:

$$\mathrm{AC_C} = \frac{1.742\,\frac{\mathrm{GJ}}{\mathrm{ton-cli}} \times 997{,}308.00\ \mathrm{tons-cli/year}\ \times 3787.67\ \mathrm{Birr/ton}}{27068.18\,kJ/Kg}$$

$$\mathrm{AC_C} = 243{,}103{,}119.50\ \ \mathrm{Birr/year}$$

4.1.7. Conclusions on Energy Intensity Comparisons

Based on the above analyses, the factory costs $243{,}103{,}119.50\ \mathrm{Birr/year}$ which occur due to poor thermal energy management. This cost is in comparison with the benchmarks. Though the benchmarks have their own limitation in energy utilization, it is a relative indication of inefficient of the factory in energy utilization. So, the factory can conduct energy audit on its major energy producing unit and end use devices to know the basic energy losses. This helps the factory to find out energy conservation opportunities and take the energy conservation measures.

4.2. Thermal Energy Consuming units of the plant

Cyclone type pre-heaters are widely used to pre-heat the raw material before it enters the kiln intake. In a typical dry rotary kiln system, pre calcination gets started in the pre-heaters, and approximately one third of the raw material would be pre-calcined at the end of pre-heating[2].

Raw material is preheated by the gases of the combustion arising from primary and secondary firing systems (rotary kiln, calciner respectively). Fuel energy is introduced into the feed materials outside the rotary kiln, so that calcium carbonate in the materials is already de-carbonated to a great extent before entry into the rotary kiln. The preheated feed material enters the calciner where it is wholly or partially calcined. The reactions in the calciner is supplied by the kiln exist gas and by the fuel fired in the calciner. The temperature of the pre-heated material would be of the order of 850 ^{0}C. The solid material (hot-meal) and the gas leaving the calciner are separated from each other in the bottom cyclone[20].

The solid material is fed to the rotary kiln and passes towards the flame and the gases passes to the upper stage of the pre-heater. In the rotary kiln, solid materials is almost completely calcined in counter current flow with combustion of the gases from the primary firing burner (rotary kiln) and is heated to the clinkering temperature causing partial fusion which promotes the formation of the clinker phase. During the cooling stage, the molten phase, C_3S, forms. Fast cooling of the product (clinker) enables heat recovery from the clinker and improves the product quality[20].

Generally, the major parts of pyro-processing system are mostly concerned with chemical reaction or combination of clinker components of calcium silicates, aluminates and aluminous and ferrites. These parts are the kiln, cooler, calciner and preheater performs different process[29].

Table 4.6: Thermal energy optimization in pyro processing

Unit operations	Functions	Process performance
Preheater	Drying & preheating	- Vaporization of physically absorbed water - Vaporization of chemically bonded water - Preheating the raw meal before feed to kiln
Calciner	Calcining	- Decomposition of $MgCO_3$ and $CaCO_3$ - Partial formation of C_2S
Rotary Kiln	Sintering	- Complete decomposition of $CaCO_3$ - Formation of C_2S, C_3A, C_4AF and C_3S
Cooler	Cooling	- Cooling clinker to lowest possible temperature - Recovery of heat as secondary and tertiary air

Preheater

The type and operation of the pre-heater may also an important influence on the fuel energy consumption of cement kiln plant. The thermal efficiency of the pre-heater depends on the number of the stages. Preheaters (PH) enable the raw material to be preheated before entering the kiln. The raw meal is introduced at the inlet duct in the top-most stage of PH[30]. It is subsequently pre-heated by hot counter current gas flow as it is continuously collected and passed down different cyclones from preheater's to calciner.

Pre-calciner

In pre-calciner, raw meal flows from the bottom stage of preheater and heat for calcination is supplied by firing fuel in it [30]. The fuel is burned in the calciner to achieve 92-95% of the total material calcination before it is collected in the bottom cyclone and made to enter the kiln [22]. The combusted air to the calciner is taken from the kiln via riser duct and from a separate tertiary air duct flowing from the clinker cooler. The degree of calcination achieved at the pre-calciner directly related to the amount of fuel fired in the calciner. When 60% of the total fuel fired is routed to the pre-calciner, the degree of calcination achieved is 92-95 %. Temperature of the mix begins to rise when calcination is complete changing the flow characteristics as the material flow through the rotary kiln.

Rotary kiln

The pyro-processing takes place in the rotary kiln. The calcined raw mix along with unconverted raw meal from pre-calciner is supplied to the kiln system in powder form. Rotary cement kilns are used for converting raw meal into cement clinker. The kiln is designed to maximize the efficiency of heat transfer from fuel to the raw material and also to ensure uniform mixing. In a dry rotary kiln, feed material with much lower moisture content (0.5%) is used, thereby reducing the need for evaporation and reducing kiln length. Recent developments have added multi-stage suspension preheaters (i.e. a cyclone) or shaft preheater. Pre-heater technology was more recently developed in which a second combustion chamber was added between the kiln and a conventional pre-heater that allows for further reduction of specific fuel consumption.

The kiln contains four sections namely preheating zone, calcination zone, burning zone and cooling zone. In the preheater tower, the raw materials are heated rapidly to a temperature of about 900°C, where the limestone forms burnt lime. In the rotating kiln, the temperature reaches about 1450°C. At this temperature, minerals fuse together to predominantly form calcium silicate crystals – cement clinker.

Grate cooler

The main function of cooler is to cool the clinker and transfer the energy to air. The clinkers are losing heat by conduction, convection and radiation to the cooling air coming from fan below the clinker bed. The grate cooler has **14** fans whose air flow can be controlled individually. This air is then use as a secondary or tertiary in kiln and calciner respectively. The cooler is in continuous mode and it is assuming to be steady[30]. So there will be no accumulation of energy in any stage. Grate cooler is divided into two zones warm and cold. Clinker bed in grate cooler assumes which is rectangular. The whole clinker bed is divided into number of stages and number of stage depends upon the height, length, mass, density, width, and residence time of clinker.

Gas Distribution in pyro-processing system

Cooling air

The cooling air is generally divided into three: One part, the **secondary air**, is used as combustion air in the primary burning zone, in the rotary kiln. Another part, called the **tertiary air**, is drawn from the cooler to the pre-calciner through a separate duct, the tertiary air duct, and used as combustion air in the secondary burning zone, in the pre-calciner. The last part of the cooling air, which may be called **excess cooling air**, is drawn out of the cooler and released to the surroundings. The temperature of the excess cooling air discharged from the cooler is 260 ^{0}C.

Table 4.7: Combustion air distribution [2]

Components of cooling air	Distribution (%)
Secondary air	15 % to rotary kiln
Tertiary air	25 % to pre-calciner
Vent (excess) air	60 % to atmosphere

The air supplied through the main burner is called primary air. With indirect firing, it contributes about 10 % to the total combustion air required in the primary burning zone. The secondary air, which is preheated in the cooler to about 900 ^{0}C, constitutes the major part of the combustion air in rotary kiln[31].

False air

False air is not desired air, which enters the kiln system in an uncontrolled manner through leaks and openings. In the preheater and in the kiln inlet/outlet seal, air will infiltrate the kiln system. Some false air is also believed to leak into the cooler, mainly through the clinker exit channel. The false air flows are taken into consideration through false air parameters, which express the amount of false air as a function of the clinker production. False air in the pre-calciner and cooler is almost neglected.

Exhaust Gases

The ID fan which is found at the bottom base of the preheater group sucks an exhaust gas from the kiln system for different purpose, such as to preheat the raw meal before entering it to kiln, preheat raw material in the raw mill and to treat the gas in the gas treatment before leaving to the atmosphere.

Circulation of Dust

Dust will be entrained by the kiln gas and transferred to the meal in the re burning chamber of the pre-calciner. Likewise, dust is entrained by the secondary air and transferred to the solids in the rotary kiln. These dust cycles imply a transfer of energy from the kiln to the pre-calciner and the cooler, respectively. The dust flows are described by clinker specific parameters.

4.3. Mass and Energy Balance

4.3.1. Mass Balance

Mass balances is prerequisite to all other calculations in the solution of process engineering problems.

Total mass of input = Total mass of output……………… (4.4)

They are used in industry to calculate mass flow rates of different streams entering or leaving chemical or physical processes[32].

The General Balance Equation

Suppose clinker is a component of both the input and output streams of a continuous process unit shown below, these flow rates of the input and output are measured and found to be different.

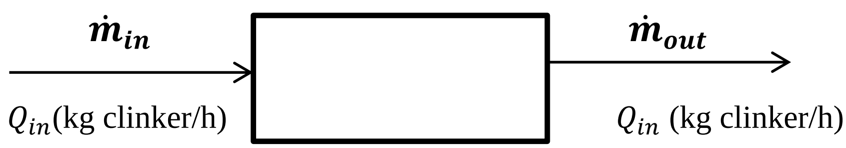

Figure 4.1: Bock diagram of material balance

If there are no leaks and the measurements are correct, then the other possibilities that can account for this difference are that clinker is either being generated, consumed, or accumulated within the unit.

A balance (or inventory) on a material in a system (a single process unit, a collection of units, or an entire process) may be written as given in Equation (4.5):

$$\dot{m}_{input} + \dot{m}_{\text{generation}} - \dot{m}_{output} - \dot{m}_{\text{consumption}} = \dot{m}_{\text{accumulation}} \quad (4.5)$$

(enters through system boundaries)	(produced within system boundaries)	(leaves through system boundaries)	(consumed within system)	(buildup within system)

This general balance equation may be written for any material that enters or leaves any process system; it can be applied to the total mass of this material or to any molecular or atomic species involved in the process[32].

The general balance equation may be simplified according to the process at hand. For example, by definition, the accumulation term in continuous process is zero. Thus, equation becomes (4.5):

Input + generation = output + consumption…………………………………………………… (4.6)

For physical process, since there is no chemical reaction, the generation and consumption terms will become zero, and the balance equation for steady-state physical process will be simply reduced to:

Input = Output ……………………………………………………………….......................... (4.7)

It is usually more convenient to define mass/energy data per kg clinker produced per unit time. Quantification of the input and output streams will lead to the numerical specification for the energy analysis.

Table 4.8: Pyro-processing system raw meal and coal meal flow rate [Source: log sheet, central control room]

Kiln raw meal feed rate (t/h)	210
Kiln raw coal feed rate (t/h)	9
Pre-calciner raw coal feed rate (t/h)	13.5
Clinker factor	1.6
Clinker production rate	131.25

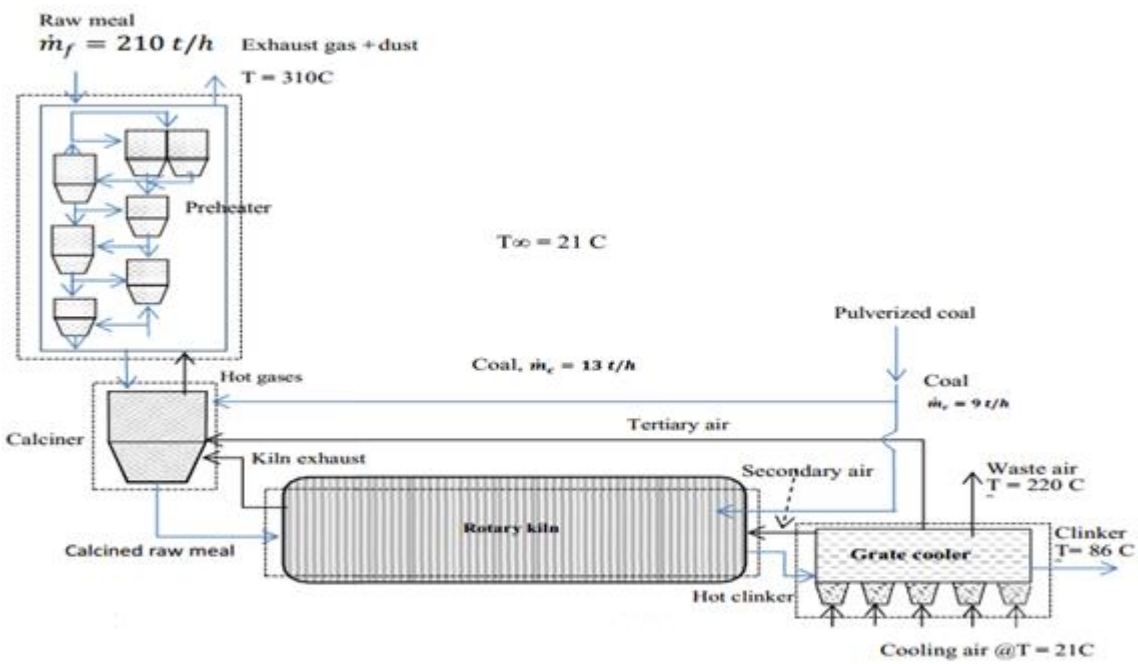

Figure 4.2: Material and energy flow in kiln systems

Table 4.9: Pressure drops [negative pressure] at different location of pyro-processing

Location	Pressure [mbar]
1st stage cyclone	58
6th stage cyclone	11.7
Kiln hood	67
Kiln inlet seal	2.957

Source: log sheet, central control room

Calculation of Primary Air

The calciner primary air and kiln primary air which enters to the fuel pipe is determined by the pressure. The primary air is entered through a pilot tube to both two burners with a diameter of 0.23m. Taking the ambient air at 21°C temperature having a density to be $\rho = 1.2\ kg/m^2$. Therefore, the above parameters can be calculated by the following mode of air velocity formula and velocity pressure is 110 mbar[12]:

$$v = K_p \times \sqrt{\frac{v_p \times 2 \times g}{\rho}} \quad \ldots\ldots (4.8)$$

$K_P = constant = 0.98$

$v_p = velocity\ pressure = 110\ mbar$

$g = gravity, 9.81\ m/s^2$

$\rho = density\ of\ air = 1.2\ Kg/m^2$

$$v = 0.98 \times \sqrt{\frac{110 \times 2 \times 9.81}{1,2}} = 41.56\ m/s$$

$$\text{Area of the pipe, A} = \pi \times \frac{D^2}{4} = \pi \times \frac{0.23^2}{4} = 0.042\ m^2$$

The amount of air entered through the pipe (volume flow rate) and the mass flow rate can be calculated using eq. 4.9 and 4.10

$$V = A \times v = 0.042\ m^2 \times 41.56\ m/s = 1.75\ m^3/s \ldots\ldots (4.9)$$

$$m = \rho \times V = 1.2\ kg/m^2 \times 1.75\ m^3/s = 2.10\ kg/s \ldots\ldots (4.10)$$

This value is assumed to be the same to both the kiln primary air and calciner primary air.

$$\dot{m}_{primary\ air} = \frac{2.10\ kg/s}{36.46} = 0.058\ kg/kg\ of\ cli$$

Calculation of False Air

The false air which enters to the meal pipe or manhole of the preheater and kiln inlet or outlet seal is determined by the negative pressure of the ID fan be calculated by the following mode of air velocity formula [12].

$$v = 4.43 \times \sqrt{\left(\frac{\Delta P}{\gamma g/cm^3}\right)}$$

a. False air in Top Preheater Cyclone

Negative pressure in the 1st stage cyclone, $\Delta P = 58mbar\ (5{,}800\ N/m^2)$

The excess air number at bottom cyclone is calculated based on the Orsat gas analyzer Composition of gases in the bottom cyclone is measured to be $(CO_2 = 26.1\%\ and\ O_2 = 2.1\%)$ by the FLSmdith [33].

Excess air number, $\gamma = \frac{1}{1-\frac{79}{21}+\frac{O_2}{100-O_2-CO_2}} = 1.39\ g/cm^3$

Since, the diameter of the opening is $D = 0.1m$

$$A = \pi * \frac{D^2}{4} = \pi * \frac{0.1^2}{4} = 0.0079\ m^2$$

Air velocity, $v = 4.43 \times \sqrt{\left(\frac{5{,}800\ N/m^2}{1390 Kg/m^3}\right)} = 9.05\ m/s$

The amount of false air entering through the pipe is:

$$V = v * A = 9.05\ m/s * 0.0079\ m^2 * 3600\ \ s/h = 257.38\ m^3/h$$

$$\dot{m}_{false\ air} = \frac{257.38\ m^3/h * 1.2\ \ kg/m^3}{131.25\ \ t/h} = 0.0024\ \ kg\ of\ false\ air/kg\ of\ cli$$

b. False air in Bottom Cyclone

Negative pressure in the 6th stage cyclone, $\Delta P = 11.7mbar\ (1{,}170\ N/m^2)$

The excess air number at bottom cyclone is calculated based on the Orsat gas analyzer Composition of gases in the bottom cyclone is measured to be $(CO_2 = 24.1\%\ and\ O_2 = 3.4\%)$ by the FLSmdith [33].

Excess air number, $\gamma = \frac{1}{1-\frac{79}{21}+\frac{O_2}{100-O_2-CO_2}} = 1.2\ g/cm^3$

Air Velocity, $v = 4.43 \times \sqrt{\left(\frac{1{,}170\ N/m^2}{1200 Kg/m^3}\right)} = 4.37\ m/s$

Since, the diameter of the opening is $D = 0.1$ m

$$A = \pi \times \frac{D^2}{4} = \pi * \frac{0.1^2}{4} = 0.0079\ m^2$$

The amount of false air entering through the pipe is:

$$V = v \times A = 4.37\ m/s \times 0.0079\ m^2 \times 3600\ \ s/h\ = 124.28\ m^3/h$$

$$\dot{m}_{\text{false air}} = \frac{124.28\ m^3/h \times 1.2\ \ Kg/m^3}{131.25\ \ t/h} = 0.0011\ \ \text{kg of false air/kg} - \text{cli}$$

c. False air at kiln hood

The excess air number at kiln hood is calculated based on the Orsat gas analyzer Composition of gases in the kiln hood is measured to be ($CO_2 = 28.2\%$ *and* $O_2 = 2.2\%$) by the FLSmdith [33].

Negative pressure in the kiln hood, $\Delta P = 67 mbar$ $(6{,}700\ \ N/m^2)$

Excess air number, $\gamma = \frac{1}{1-\frac{79}{21}+\frac{O_2}{100-O_2-CO_2}} = 1.135\ g/cm^3$

Air Velocity, $v = 4.43 \times \sqrt{\left(\frac{6{,}700\ N/m^2}{1135 Kg/m^3}\right)} = 10.76\ m/s$

Since, the diameter of the kiln hood opening is $D = 0.46$ m

$$A = \pi \times \frac{D^2}{4} = \pi \times \frac{0.1^2}{4} = 0.166\ m^2$$

The amount of false air entering through the pipe is:

$$V = v \times A = 10.76\ m/s \times 0.166\ m^2 \times 3600\ \ s/h\ = 6437.54\ m^3/h$$

$$\dot{m}_{\text{false air}} = \frac{6437.54\ m^3/h \times 1.2\ \ Kg/m^3}{131.25\ \ t/h} = 0.059\ \ \text{kg of false air/kg of cli}$$

d. False air at kiln inlet seal

The amount of false air is calculated based on the Orsat measurements. By the FLSmdith [33], the fraction of gases is ($CO_2 = 26.6\%\ and\ O_2 = 1.7\%$)

Excess air number, $\gamma = \frac{1}{1-\frac{79}{21}+\frac{O_2}{100-O_2-CO_2}} = 1.1\ g/cm^3$

The negative pressure at the kiln inlet is taken from the plant $\Delta P = 295.7\ Pa\ (295.7\ N/m^2)$
Therefore, the air velocity is:

Air Velocity, $v = 4.43 \times \sqrt{\left(\frac{295.7\ N/m^2}{1100 Kg/m^3}\right)} = 2.3\ m/s$

The minimum combustion air,

$L_{min} = \text{spe. thermal cons} \times \text{total combustion air}/1000\ Kcal/kg$

Since the specific thermal cons $= 762.63\ Kcal/Kg$

Total combustion air $=$ sec. air $+$ pri. air $= 0.64\ Kg/Kg - cli + 0.058\ Kg/Kg - cli = 0.037\ Kg/Kg - cli$

$L_{min} = \frac{0.037 Kg\ of\ air/Kg-cli \times 762.63\ Kcal/Kg}{1000 Kcal/kg} = 0.028\ Kg\ of\ air/Kg - cli$

Therefore, the amount of false air

$$\dot{m}_{false\ air} = (\gamma \times L_{min}) \times 11.72\% = (1.1\ g/cm \times 0.028\ kg\ of\ air/kg - cli) * 11.$$
$$= 0.0036\ kg\ of\ air/kg - cli$$

4.3.1.1.*Mass Balance in Cooler*

The mass balance equation is given by eq. 4.7

For simplicity the dust content of the tertiary air duct is neglected [2]. The mass flow rate of clinker input and output is the same because mass flow rate in grate cooler remain constant.

Table 4.10: Cooling fan capacity

Cooling fan	Air			Cooling fan	Air		
	m^3/h	Kg/h	$Kg/Kg-cli$		m^3/h	Kg/h	$Kg/Kg-cli$
1	45,100	55,022	0.42	8	27,300	33,306	0.25
2	24,600	30,012	0.23	9	27,300	33,306	0.25
3	33,800	41,236	0.31	10	27,000	32,940	0.23
4	37,900	46,238	0.35	11	29,300	35,740	0.27
5	36,600	44,652	0.34	12	22,500	27,450	0.21
6	49,600	60,512	0.46	13	19,600	23,912	0.18
7	58,800	71,736	0.55	14	18,800	22,936	0.17
Sub total	=2.66				=1.58		
Overall total = 4.24 $Kg/Kg-cli$							

Source: Grate cooler log sheet, October 2017

Capacity of cooling air= $4.24\ kg/kg-cli$,   and $\dot{m}_{cli\ discharge} = 1\ kg/kg-cli$

From table 4.8: can calculate the following items as follow:

$$Secondary\ air = 15\% \times 4.24\ kg/kg-cli$$

$$Tertiary\ air = 25\% \times 4.24 = 1.06\ kg/kg-cli$$

$$Vent\ air = 60\% \times 4.24\ kg/kg-cli = 2.54\ kg/kg-cli$$

$$\dot{m}_{coolingair} + \dot{m}_{cli} = \dot{m}_{sec\ air} + \dot{m}_{ter\ air} + \dot{m}_{vent\ air} + \dot{m}_{cli\ discharge}$$

$$\dot{m}_{cli} = 0.64 + 1.06 + 2.54 + 1 - 4.24 = 1\ kg/kg-cli$$

4.3.1.2.Mass Balance in Rotary Kiln

Primary air, $\dot{m}_{Pri\ air} = 0.058\ kg/kg - cli\ [calculated]$

$$\dot{m}_{kcoal} = 9\,t/h = 0.072\ kg/kg - cli$$

$$\dot{m}_{pcal} = 90\% \times 210\,t/h = 1.51\ kg/kg - cli$$

$$\dot{m}_{kcoal} + \dot{m}_{\mathrm{sec}\,air} + \dot{m}_{\mathrm{P}\,cal} + \dot{m}_{pri\ air} = \dot{m}_{kiln\ flue\ air} + \dot{m}_{cli}$$

$$\dot{m}_{kiln\ flue\ air} = 0.072 + 0.64 + 1.51 + 0.058 - 1 = 1.28\ kg/kg - cli$$

4.3.1.3.Mass Balance in Calciner

$$\dot{\mathrm{m}}_{\mathrm{coal}} = 13.5\ \mathrm{t/h} = 0.11\ \mathrm{kg/kg - cli}$$

$$\dot{\mathrm{m}}_{\mathrm{pri\ air}} = 0.058\ \mathrm{kg\ of\ primary\ air/kg - cli}\ \ \text{(calculated in the above)}$$

$$\text{Mass of hot meal} = 90\% \times \text{Kiln feed} = 0.9 \times 210\ \mathrm{t/h} = 189\ \mathrm{kg/kg - cli}$$
$$= 1.51\ kg/kg - cli$$

$$\dot{m}_{calcined} = 1.51\ Kg/Kg - cli$$

$$\dot{m}_{coal} + \dot{m}_{pri\ air} + \dot{m}_{flue\ gas} + \dot{m}_{hot\ meal} + \dot{m}_{ter\ air} = \dot{m}_{cal\ flue\ gas} + \dot{m}_{calcined}$$

$$\dot{m}_{cal\ flue\ gas} = 0.11 + 0.058 + 1.51 + 1.28 + 1.06 - 1.51 = 2.54\ Kg/Kg - cli$$

4.3.1.4.Mass Balance on Pre-heater

The mass loss from the raw meal in the preheater is relatively small; thus it is taken as one-unit process inside a boundary system. The mass flow rates of the dust and exhaust gas are separately calculated. The efficiency of top cyclone is 90%, therefore the dust concentration will be:

$$\text{Dust concentration} = 0.1 \times 210\ \mathrm{t/h}$$

$= 0.16\ \mathrm{kg/kg - cli}$ The capacity of the ID fan is $750{,}000\ \mathrm{m^3/h}$ of gases sucks by the negative pressure.

$$\mathrm{V} = 750{,}000\,\mathrm{m^3/h}$$

$$\text{The specific capacity of ID fan} = \frac{750{,}000\mathrm{m^3/h}}{131.25\mathrm{t/h}} = 5.71\ \mathrm{m^3/kg - cli}$$

With density capacity of ID fan $= 0.512\ \mathrm{kg/m^3}$ [15];

$$\text{Specific capacity of ID fan} = 5.71\ \mathrm{m^3/kg - cli} \times 0.512\ \mathrm{kg/m^3} = 2.92\ \mathrm{kg/kg - cli}$$

4.3.1.5.Calculation on Clinker CO_2 Emission

The production process is diagrammatically shown in Fig. 4.3 (Association of Cements Material Producers, 2010) and the key stages are described Share of total CO_2 emissions across the Portland cement production process[34].

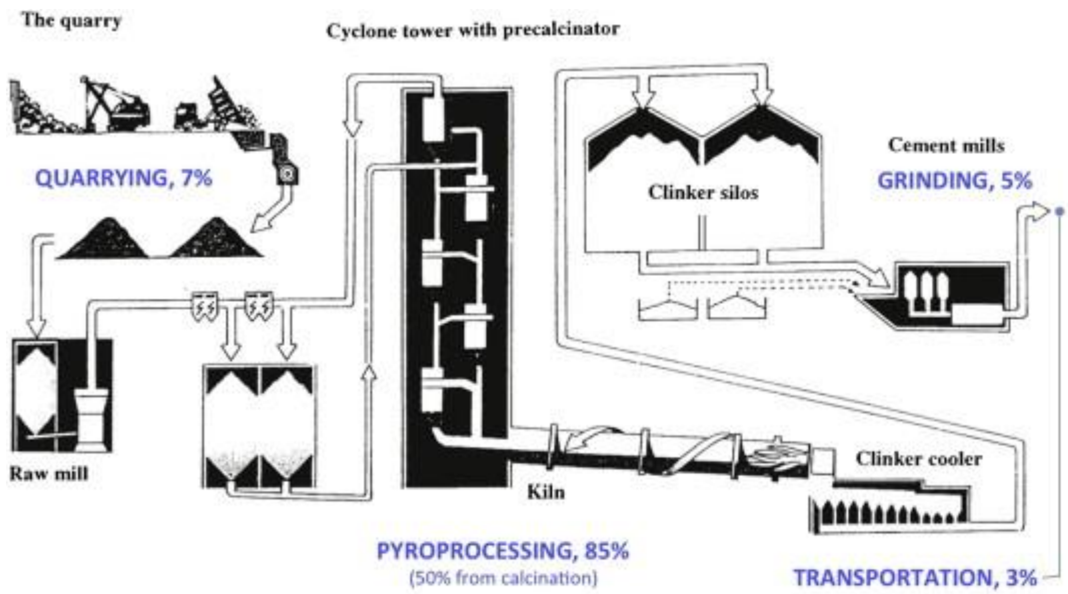

Figure 4.3: Share of total CO_2 emissions across the Portland cement production process

Table 4.11: Raw meal feed composition [Source: raw meal chemical analysis report]

Oxides	Kiln feed composition (%)
CaO	43.5-43.9
MgO	0.7
Al_2O_3	2.9-3.1
Fe_2O_3	2-2.2
SiO_2	12.5-13

Assume the decomposition of the $MgCO_2$ is 100% and decomposition of $CaCO_2$ calcined. Therefore, the amount of $CaCO_2$ or un-calcined entering to kiln inlet will be calculated as:

$$\overbrace{\underbrace{CaCO_3}_{100}}^{x} \xrightarrow{yields} CaO + \overbrace{\underbrace{CO_2}_{56}}^{43.8} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$x = \%\ of\ CaCO_3 = \frac{43.8 \times 100}{56} = 78.21\%$$

The amount of $CaCO_3\ from\ top\ cyclone\ feed = 189 \times 0.7821 = 147.82\ \ t/h$

Therefore, the amount of calcined $CaCO_3$ in the calciner which is 93% calcined:

$Amount\ of\ calcined\ CaCO_3 = 147.82 \times 0.93 = 137.47\ \ t/h$

$Amount\ of\ uncalcined\ CaCO_3 = 147.82 \times 0.07 = 10.35\ \ t/h$

$$\underbrace{\overbrace{CaCO_3}^{137.43}}_{100} \xrightarrow{yields} CaO + \underbrace{\overbrace{CO_2}^{x}}_{44} \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

$$x = \frac{137.43 \times 44}{100} = 60.49\ \ t/h$$

$Amount\ of\ CO_2\ removed\ from\ the\ uncalciend\ CaCO_3\ at\ kiln\ calcination\ zone$

$$x = \frac{10.35 \times 44}{100} = 4.55\ \ t/h$$

$Amount\ of\ CO_2\ removed\ from\ the\ \ MgCO_3\ decomposition;$

$$\underbrace{\overbrace{MgCO_3}^{0.7}}_{40} \xrightarrow{yields} MgO + \underbrace{\overbrace{CO_2}^{x}}_{44} \ldots \ldots \ldots \ldots \ldots \ldots \text{(3)}$$

$$x = \frac{0.7 \times 44}{40} = 0.77\%$$

$Therefore, the\ amount\ of\ CO_2\ removed\ from\ the\ \ MgCO_3\ decomposition\ will\ be;$

$x = 0.77\% \times 189\ \ t/h = 1.45\ \ t/h$

Table 4.12: Characteristics and Summery of material Balance

Parameter	Value
Kiln diameter	4.6 m
Kiln length	70 m
Clinker factor	1.6
Raw meal	1.6 $kg/kg\ of\ cli$
Exhaust gas	2.92 $kg/kg\ of\ cli$
Dust preheater	0.16 $kg/kg\ of\ cli$
False air	0.066 $kg/kg\ of\ cli$
Primary air	0.058 $kg/kg\ of\ cli$
Secondary air	0.64 $kg/kg\ of\ cli$
Tertiary air	1.06 $kg/kg\ of\ cli$
Cooling air	4.24 $kg/kg\ of\ cli$
Clinker	1 $kg/kg\ of\ cli$
Vent air	2.54 $kg/kg\ of\ cli$
Coal feed to primary burner	0.069 $kg/kg\ of\ cli$
Coal feed to secondary burner	0.103 $kg/kg\ of\ cli$

As shown from the table 4.12: 1.6 $kg/kg\ of\ cli$ raw meal is feed to the pyro processing system, than the pyro-processing system discharge 1 $kg/kg\ of\ cli$, since the capacity factor of the plant is 1.6, and the cooling air capacity is 4.24 $kg/kg\ of\ cli$ which is distributed 0.64 $kg/kg\ of\ cli$ to kiln system as the secondary air,1.06 $kg/kg\ of\ cli$ to the pre-calciner as tertiary air and the others 2.54 $kg/kg\ of\ cli$ to the atmosphere as vent air.

The raw coal is feed to the kiln burner and pre-calciner 40% and 60% respectively. Which is 9 ton/hour (0.069 $kg/kg\ of\ cli$) to the primary burner (kiln) and 13.5 ton/hour (0.103 $kg/kg\ of\ cli$) to the secondary burner (pre-calciner).

4.3.2. Energy Balance

The heat balance is done based on coal firing quantity, measured air flow rates and temperature. In order to analyze the kiln system thermodynamically, the following assumptions are made:

1. Steady state working conditions.
2. The change in the ambient temperature is neglected.
3. Cold air leakage into the system is negligible.
4. Raw material and coal compositions do not change.
5. Feed rate of raw material and coal are considered as constant.
6. Coal is fully combusted in calciner and kiln.
7. Feed rate of raw material and coal are considered as constant.
8. The reference enthalpy is considered to be zero at 0^0C for the calculations.

The specific enthalpy of various components is obtained from perry [35]. The input energy with various streams is calculated per Kg clinker produced.

4.3.2.1.Heat input from Combustion of Coal

Messebo Cement factory uses South Africa imported coal as basic raw coal of the pyro-processing (clinker production) system to both kiln and calciner burners. As pointed in the above, the production line uses the new pre-calciner technology (secondary burner) with a coal consumption of 13.5 t/h and the primary burner which injected to kiln end feeds 9 t/h of coal.

Table 4.13: proximate analysis of coal composition [Source: Raw coal chemical analysis report [Bomb calorimeter] [36]]

Proximate analysis	South African Coal (%)
Moisture	0.5-1
Volatile matter	25-26
Ash	15-16
Calorific value	27,068.18 $Kj/Kg - coal$

Table 4.14: Coal ash composition [Source: Coal ash proximate analysis report [36]]

Components	**South African Coal (%)**
SiO_2	47-49
Al_2O_3	25-30
Fe_2O_3	5
CaO	8-10
MgO	2-3

Moisture content analysis of coal calculation, $X = \frac{w_i - w_o}{w_i}$ … … … … … … … … … … … … … … (4.11)

Where $w_i = input\ mass\ flo\ rate\ of\ the\ coal$

$w_i = output\ mass\ flo\ rate\ of\ the\ coal$

South African coal is feed 22.5t/h of coal consumption of the two burners at 0.0075 moisture content.

$$0.0075 = \frac{22.5\ t/h - w_o}{22.5\ t/h}, then\ w_o = 22.33\ t/h = 0.115\, Kg/Kg - cli\ (dry\ basis)$$

The mass of moisture is:

$$\dot{m}_{moisture} = 22.5\ t/h - 22.33\ t/h = 0.17\ t/h = 1.25 \times 10^{-3}\ Kg/Kg - cli$$

The total moisture amount in the coal is $1.25 \times 10^{-3}\ Kg/Kg - cli$

$Q_1 = m \times CV$ Where CV= calorific value of coal ($kJ/kg - coal$)

- Coal is introduced at two parts:
  1. **Kiln firing** (primary/main burner 40% from the total feed)

$$Q_{kiln} = (m \times CV) * 0.4 = [(0.115\, kg/kg - cli \times 27{,}068.18\, kJ/kg\ ) \times 0.4]$$
$$= 1245.136\, kJ/kg - cli = 298.83\ kCal/kg - cli$$

2. **Calciner firing** (secondary burner 60% from the total feed)

$$Q_{cal} = (m \times CV) \times 0.6 = [(0.115\, kg/kg - cli \times 27{,}068.18\, kJ/kg\ ) \times 0.6]$$
$$= 1867.7\, kJ/kg - cli = 448.248\, kCal/kg - cli$$

Therefore,

$$\mathrm{Q_1 = Q_{kiln} + Q_{cal} = 1245.136\ Kj/Kg - cli + 1867.7\ kJ/kg - cli = 3112.836}\ kJ\mathrm{/kg - cli}$$
$$\mathrm{= 747.08\ kCal/kg - cli}$$

4.3.2.2.Heat input from Sensible heat by coal

$$\mathrm{Q_2 = m_{coal} \times C_p \times \Delta T = m_{coal} \times C_p \times (T - T_\infty)}$$

Where, $\mathrm{m_{coal} = 0.17\ kg/kg - cli}$

$\mathrm{C_P = 1.13\ kJ/kg - cli}$

$\mathrm{T = 43\ °C}$ and $\mathrm{T_\infty = 21°C}$

$$\mathrm{Q_2 = 0.17\ Kg/Kg - cli * 1.13\ Kj/Kg - cli * (43\ °C - 21°C) = 4.23\ Kj/Kg - cli}$$
$$\mathrm{= 1.01\ Kcal/Kg - cli}$$

4.3.2.3.Heat input from raw material feed

$$\mathrm{Q_3 =\ m_{raw\ m.} \times C_P \times (T_f - T_\infty)}$$

Where, $\mathrm{m_{raw\ m.} = 1.6\, kg/kg - cli,\ C_P = 0.85\ kJ/kg\ °C\ and\ T_f = 50\ °C}$

$$\mathrm{Q_3 =\ 1.6\, kg/kg - clI\ \ \times 0.85\ }kJ\mathrm{/kg\ °C * (50\ °C - 21\ °C)}$$
$$\mathrm{= 39.44\ kJ/Kg - cli = 9.44\ kCal/kg - cli}$$

4.3.2.4.Heat input from Organic Substance in Kiln Feed

$$\mathrm{Q_4 = F \times C_f \times H_{carbon}}$$

$\mathrm{Q_4}$ = Heat input from organic substance (exclusively carbon content)

F = carbone content in % = 0.35%

$\mathrm{C_f} = clinker\ factor(1.6\ \ kg/kg - cli)$

$\mathrm{H_{carbon}}$ = heat capacity of carbone (≈ 33,000 kJ/kg)

$$\mathrm{Q_4} = 0.0035 \times 1.6 \ \mathrm{kg/kg-cli} \times 33{,}000 \ kJ/\mathrm{kg} = 184.80 \ \mathrm{kJ/kg-cli}$$
$$= 44.21 \ \mathrm{kCal/kg-cli}$$

4.3.2.5.Heat input from Cooling Air

The heat balance of Grate cooler is done based on clinker quantity coming in the cooler, measured air flow rates and temperature. Therefore:

$$\mathrm{Q_5} = \mathrm{m_{cooling\ air}} \times \mathrm{h_{cooling\ air}}$$

Where,

$$Q_5 = 4.24 \ Kg/Kg \ of \ cli \times 27.3 \ kJ/kg = 115.75 \ kJ/kg = 27.78 \ kCal/kg \ of \ cli$$

4.3.2.6.Heat input from Infiltration Air

The temperature of the false air in all units is assumed to be equal to the ambient temperature.

$$\mathrm{Q_6} = \mathrm{m_{false\ air}} \times \mathrm{h_{false\ air}}$$

$$m_{false\ air} = mass \ of \ false \ air$$

$$h_{false\ air} = enthalpy \ of \ false \ air \ at \ ambient \ air = 27.3 \ kJ/kg$$

$$Total \ mass \ of \ false \ air$$
$$= (0.0024 + 0.0011 + 0.059 + 0.0036) \ kg \ of \ false \ air/kg \ of \ cli$$
$$= 0.066 \ kg/kg \ of \ cli$$

$$Q_6 = 0.066 \ kg/kg \ of \ cli \times 27.3 \ kJ/kg = 1.8 \ kJ/kg \ of \ cli = 0.43 \ kCal/kg \ of \ cli$$

4.3.2.7.Heat Required for Clinker Formation

Formation energy of the clinker is calculated by using the ZurStrassen equation[12].

$$\mathrm{Q_7} = 4.11[\mathrm{Al_2O_3}] + 6.48[\mathrm{MgO}] + 7.646[\mathrm{CaO}] - 5.116[\mathrm{SiO_2}] - 0.59[\mathrm{Fe_2O_3}] \ldots\ldots\ldots\ldots (4.12)$$

Where,

$\mathrm{Q_7}$ = heat formation of clinker [kCal/kg of cli]

Table 4.15: Clinker Composition

Clinker Component	Composition (%)
SiO_2	23-24
Al_2O_3	4-5
Fe_2O_3	3.7-4.3
CaO	65.5-67
MgO	1.2-1.5

Source: Clinker chemical analysis report [36]

Al_2O_3, MgO, CaO, SiO_2 and Fe_2O_3 = clinker composition

$$Q_7 = 4.11[4.5] + 6.48[1.35] + 7.646[66.25] - 5.116[23.5] - 0.59[4] = 411.2\ \text{kCal/kg of cli}$$
$$= 1713.33\ kJ/kg\ of\ cli$$

4.3.2.8.Heat Loos by the Exhaust Gas

Table 4.16: Exhaust Gas Composition [Source: [31]]

Components	Fraction [%]	$C_P(kJ/kg.K)$	
N_2	72.39	1.040	$C_{P\ ex.g} = 72.39\%\ C_{P\ N_2} + 23.73\%\ C_{P\ CO_2} + 3.57\%\ C_{P\ O_2} + 0.03\%\ C_{P\ CO}$
CO_2	23.73	0.844	$= 0.7530 + 0.2003 + 0.0356 + 0.00033$
O_2	3.57	0.9964	
CO	0.03	1.0891	$C_{P\ ex.g} = 0.9892\ kJ/Kg.K$

$$Q_8 = m_{exhaust\ gas} \times C_{p\ ex.g} \times \Delta T$$

Where, Q_8 = Heat from the exhaust gas (kJ/kg of cli)

$m_{exhaust\ gas}$ = mass of exhaust gas (kg ex. gas/kg of cli) = 2.92 kg/kg of cli

$C_{p\ ex.g}$ = specific heat capacity(kJ/Kg. °C)

T = temperature of the exhaust gas (°C) = 310 °C

T_∞ = ambient temperature (°C) = 21 °C

$Q_8 = 2.92\, kJ/\text{kg of cli} \times 0.9892\ \text{kJ/Kg.°C} \times (310 - 21) = 834.76\ kJ/\text{kg of cli}$

$= 200.34\ \text{kCal/kg of cli}$

4.3.2.9.Heat Loss due to Evaporation

$Q_9 = m_{H_2O} \times \left(h_{fg(50°C)} + h_{g(310°C)} - h_{g(50°C)}\right)$

Where,

m_{H_2O} = mass of moisture in raw feed and coal feed

Mass of moisture in raw feed is 0.22% means $3.52 * 10^{-3}\ kg/kg - cli$

Mass of moisture in coal feed is $1.25 \times 10^{-3}\ kg/kg - cli\ [calculated]$

$m_{H_2O} = 3.52 * 10^{-3}\ Kg/Kg - cli + 1.25 \times 10^{-3}\ kg/kg - cli = 4.77 \times 10^{-3}\ kg/kg - cli$

From Thermodynamics Properties of water [37],

$H_{fg(50°C)} = 2381.94\ kJ/kg$, $h_{g(50°C)} = 2591.27\ kJ/kg$ and $h_{g(310°C)} = 3098.25\ kJ/kg$.

Then,

$Q_9 = 4.77 \times 10^{-3}\ Kg/Kg - cli \times (2381.94 + 3098.25 - 2591.27)\ kJ/kg$

$= 13.78\ kJ/kg - cli = 3.31\ kCal/kg - cli$

4.3.2.10. Heat Loss due to Hot Air from Cooler

$Q_1 = m_{hot\ air} \times C_{P\ air} \times \Delta T$

$m_{hot\ air} = mass\ of\ vent[excess]\ air\ or\ hot\ air\ from\ Cooler = 2.54\ kg/kg - cli$

$C_{P\ air} = 1.016\ kJ/kg.°C$

$Where, T = 220\ °C\ and\ T_\infty = 21°C$

$Q_{10} = 2.54\ kg/kg - cli \times 1.016\ kJ/kg.°C \times (220°C - 21°C)$

$= 513.55\ kJ/kg - cli = 123.25\ kCal/kg - cli$

4.3.2.11. Heat Loss due to Dust

The dust that leaves the cooler is assumed to be recycled back to the apron conveyor and negligible amount of dust exit the bag filter.

$$C_{p,i} = a_i T^0 + b_i T^1 + c_i T^2 + d_i T^3 \quad \ldots \ldots (4.13)$$

Where a, b, c, and d are raw meal heat capacity expansion coefficient and T is temperature of clinker discharge which is 310 ^{0}C.

Table 4.17: Raw meal Coefficient [35]

A	0.206
B	1.01×10^{-4}
C	-0.3710^{-7}
D	0

$$C_{P\ dust} = 0.206 + 1.01 \times 10^{-4} \times 310 - 0.3710^{-7} \times 310^2 + 0 \times 310^3 = 0.234\ kJ/kg.°C$$

$$Q_{11} = m_{dust\ preheater} \times C_{P\ dust} \times \Delta T$$

$$Where, m_{dust\ preheater} = mass\ of\ preheater\ dust = 0.16\ kg/kg - cli$$

$$Q_{11} = 0.16\ kg/kg - cli \times 0.234\ kJ/kg.°C * (310\ °C - 21\ °C) = 10.82\ kJ/kg - cli$$
$$= 2.59\ kCal/kg - cli$$

4.3.2.12. Heat Loss due to Clinker Discharge

The specific heat capacity of clinker at any section is obtained with the help of output temperature of clinker of just before discharging.

$$C_{p,i} = a_i T^0 + b_i T^1 + c_i T^2 + d_i T^3$$

Where a, b, c, and d are clinker heat capacity expansion coefficient and T is temperature of clinker discharge which is 86 ^{0}C.

Table 4.18: Clinker Coefficient [35]

A	0.1742
B	1.41×10^{-4}
C	1.28×10^{-7}
D	5.07×10^{-11}

$$C_P = 0.1742 + 1.41 \times 10^{-4} \times 86 + 2.28 \times 10^{-7} \times 86^2 + 5.07 \times 86c^3 = 0.19\ kJ/kg.°C$$

$$Q_{12} = m_{cli} \times C_{p_{cli}} \times (\Delta T)$$

$$Where, T = clinker\ discharge\ temperature\ 86\ °C$$

$$m_{cli} = 1\ kg/kg - cli$$

$$Q_{12} = 1\ kg/kg - cli \times 0.19\ kJ/kg.°C \times (86\ °C - 21°C) = 12.35\ kJ/kg - cli$$

$$= 2.95\ kCal/kg - cli$$

4.3.2.13. Surface Heat Losses

Table 4.19: surface temperature of selected unit processes ($°C$)

Days	Cooler	Kiln	C-1	C-2	C-3	C-4	C-5	C-6	Swirl	Mixing
1	82.6	294.0	56.0	50.4	64.2	73.4	92.0	129.4	123.4	110.0
2	81.5	283.2	43.7	47.5	66.0	72.7	84.1	98.6	94.7	126.7
3	89.6	282.1	66.5	52.9	67.3	87.3	85.7	109.7	118.5	97.2
4	83.1	279.5	58.1	48.3	66.9	80.9	92.6	119.2	125.0	130.9
5	82.1	280.5	53.9	47.9	57.8	86.2	86.7	102.8	120.8	136.0
Average	83.8	283.9	55.6	49.4	64.4	80.1	88.2	112.0	116.5	120.2

Source: Measured data using portable temperature measurement [Beta 140], October 2017

A. Kiln

i. Radiation Heat Loss

Radiation heat loss from the kiln surface is calculated for each meter length of the Kiln in Table-B2 Appendix-B and the total result is:

$$Q_{13\,R_K} = \frac{\delta \times \varepsilon \times A_{kiln}(T_S^4 - T_\infty^4)}{\dot{m}_{clinker}} \dots \dots \dots \dots (4.14)$$

$Where,$

$\delta = Stephen\ Boltzman's constant\ (5.67 \times 10^{-8}\ W/m^2.K^4)$

$\varepsilon = Emissivity\ factor\ (0.9\ for\ rough\ oxidized\ steel)$

$A_{kiln} = \pi \times D_{kiln} \times L_{kiln} = \pi \times 4.6\ m \times 1\ m = 14.45\ m^2$ At each meter of the kiln surface.

$\therefore\ Q_{13\,R_K} = 136.43\ kJ/kg - cli = 32.64\ kCal/kg - cli$

ii. Convection Heat Loss

Convection heat loss from the kiln surface is calculated using the air property of the kiln surface for each meter length of the kiln in Table-A1 appendix-A and the total result is:

$$Q_{13C_K} = \frac{h_{con} \times A_{kiln} \times (T_S - T_\infty)}{\dot{m}_{clinker}} \dots \dots \dots \dots (4.15)$$

$$where\ h_{con} = \frac{k_{air}}{D_{kiln}} Nu \dots \dots \dots \dots (4.16)$$

The properties of air for the kiln surface are taken at the film temperature [24].

$$T_f = \frac{T_s + T_\infty}{2} \dots \dots \dots \dots (4.17)$$

Properties of air at the film temperature are listed in Table-A1 Appendix-A.

Thermal conductivity (k)

Prdental number (Pr)

Kinematic viscosity (v)

Coefficient of volume expansion, $\beta = \frac{1}{T_f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.$ (4.18)

From the above data the Rayleigh number becomes [37]:

$$R_{aD} = \frac{g\times\beta\times(T_s - T_\infty)\times D^3\times Pr}{v^2} \ldots\ldots \text{(4.19)}$$

The Prdental number is taken from air property table and the Nusselt numbers is calculated from [37] equation 4.20:

$$Nu = \left[0.6 + \frac{0.387\times R_{aD}^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\right]^2 \ldots\ldots \text{(4.20)}$$

Then, $Q_{13C_K} = \frac{h_{con}\times A_{kiln}\times(T_s - T_\infty)}{m_{clinker}} = 47.826\ kJ/kg - cli = 11.44\, kCal/kg - cli$

B. Preheater

The length of cone is calculated from the Pythagoras theorem:

$$l_{con}^2 = h_{con}^2 + r_{con}^2 \ldots\ldots \text{(4.21)}$$

Area cylinder is calculated as:

$$A_{cyl} = side\ area * top\ area = \pi \times D_{cyl} \times h_{col} + \frac{\pi \times D_{cyl}^2}{4}$$

Area of cone is calculated as $A_{con} = \pi \times D_{con} \times l_{col}$

Table 4.20: Specification of Preheater [Source: Specification of pyro-processing system of MCF PL-2]

Parameters	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**
Diameter, D(mm)	5600	8000	8000	8000	8200	8200
Column height, $h_{col}(mm)$	6800	1000	1000	1000	1000	2300
Cone height, $h_{con}(mm)$	4000	3300	3900	3450	3900	5000
Length for cylinder part (m^2)	4883	5186	5186	5587	5659	6466
Area for cylinder part (m^2)	144.3	75.4	75.4	75.4	78.6	112
Area for cone part (m^2)	86	130.3	130.3	140.4	145.8	166.6
Total area (m^2)	230.6	205.7	215.8	208.2	224.4	278.6

Table 4.21: Areas for different position of pyro-processing [Source: Specification of pyro-processing system of MCF PL-2]

Position	Area (m^2)
Swirl chamber	169.0
Mixing chamber	703.7
Grate cooler	102.7
Kiln hood	21.8

i. Radiation Heat Loss

Radiation heat loss from the six stage cyclone preheater surface is calculated for each cyclone preheater in table-B2 Appendix-B and the total result is:

$$Q_{13\,R\,PH} = \frac{\delta \times \varepsilon \times A_{PH} \times (T_S^4 - T_\infty^4)}{\dot{m}_{clinker}}$$

$$Where, \delta = Stephen\ Boltzman's constant\ (5.67 \times 10^{-8}\ W/m^2.K^4)$$

$$\varepsilon = Emissivity\ factor\ (0.9\ for\ rough\ oxidized\ steel)$$

$$Q_{13\,R_{PH}} = 16.322\ kJ/kg - cli = 3.91\ kCal/kg - cli$$

ii. Convection Heat Loss

$$Q_{13\,C_{PH}} = \frac{h_{con} \times A_{PH} \times (T_S - T_\infty)}{\dot{m}_{clinker}} \qquad where\ h_{con} = \frac{k_{air}}{D_{ph}} Nu$$

The properties of air at the film temperature of:

$$T_f = \frac{T_s + T_\infty}{2}$$

Properties of air at the film temperature are tabulated in table-A3 Appendix-A. From the tabulated data the Rayleigh number becomes:

$$R_{aD} = \frac{g \times \beta(T_s - T_\infty) \times D^3 \times Pr}{v^2}$$

A vertical cylinder can be treated as a vertical plate when [37]:

$$D \geq \frac{35L}{G_{rL}^{1/4}},$$

$$Where\ G_{rL}\ is\ Grashof\ number$$

$$G_{rL} = \frac{g * \beta(T_S - T_\infty) L_c^3}{v^2}$$

The Prdental number is taken from air property table and the Nusselt numbers is calculated from [37] equation 4.22 and 4.20:

$$Nu = 0.1 \times R_{aL}^{\frac{1}{3}} \quad \dots\dots\dots\dots\dots\dots\dots\dots. \quad (4.22)\ \ for\ C-1\ upto\ C-5$$

$$Nu = \left[0.825 + \frac{0.387 R_{aD}^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right]^2 \quad for\ C-6$$

Then,

$$Q_{13\,C_{PH}} = \frac{h_{con} \times A_{PH} \times (T_S - T_\infty) \times 3.6}{\dot{m}_{clinker}} = 10.689\ kJ/kg - cli = 2.56\ kCal/kg - cli$$

C. Pre-calciner

i. Radiation Heat Loss

Radiation heat loss from the swirl chamber and mixing chamber surface is calculated for each in table [B2] appendix [B] and the total result is:

$$Q_{13\,R_{PC}} = \frac{\delta \times \varepsilon \times A_{PH} \times (T_S^4 - T_\infty^4) \times 3.6}{\dot{m}_{clinker}}$$

$$Q_{SC} = 3.677\ kJ/kg - cli \quad and \quad Q_{MC} = 14.964\ kJ/kg - cli$$

$$Q_{13\,R_{PC}} = 18.641\ kJ/kg - cli = 4.46\ kCal/kg - cli$$

ii. Convection Heat Loss

$$Q_{SC,MC} = \frac{h_{conv} \times A_{SC,MC} \times (T_S - T_\infty) \times 3.6}{\dot{m}_{clinker}} \quad Where, \quad h_{conv} = \frac{k_{air}}{L_{SC,MC}} Nu$$

Properties of air at the film temperature are tabulated in table-A2 appendix-A from the tabulated data the Rayleigh number becomes:

$$R_{aD} = \frac{g \times \beta(T_s - T_\infty) \times D^3 \times Pr}{v^2}$$

A vertical cylinder can be treated as a vertical plate when [37]:

$$R_{aD} = \frac{g \times \beta \times (T_s - T_\infty) \times D^3 \times Pr}{v^2}$$

A vertical cylinder can be treated as a vertical plate when [37]:

$$D \geq \frac{35L}{G_{rL}^{1/4}},$$

$Where\ G_{rL}\ is\ Grashof\ number$

$$G_{rL} = \frac{g \times \beta \times (T_s - T_\infty) \times L_c^3}{v^2}$$

The Prdental number is taken from air property table and the Nusselt numbers is calculated from [37] equation 4.22 and 4.20:

$$Nu = 0.1 \times R_{aL}^{\frac{1}{3}} \quad for\ for\ the\ swirl\ chamber$$

$$Nu = \left[0.825 + \frac{0.387R_{aD}^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right]^2 \quad for\ the\ mixing\ chamber$$

$$Then, h_{con} = \frac{k}{L_{SC.MC}} Nu$$

$$Q_{13\ C_{PC}} = \frac{h_{conv} \times A_{SC,MC} \times (T_S - T_\infty) \times 3.6}{\dot{m}_{clinker}}$$

$$Q_{sc} = 2.198\ kJ/kg - cli \qquad and \quad Q_{MC} = 9.660\ kJ/kg - cli$$

$$Q_{13\ C\ PC} = Q_{sc} + Q_{MC} = 2.198\ kJ/kg - cli + 9.660\ kJ/kg - cli = 11.858\ kJ/kg - cli$$
$$= 2.84\ kCal/Kg - cli$$

D. Kiln Hood

i. Radiation Heat Loss

$$Q_{13R_{KH}} = \frac{\delta \times \varepsilon \times A_{k.hood} \times (T_S^4 - T_\infty^4) \times 3.6}{\dot{m}_{clinker}}$$

$$A_{k,hood} = 5.86\ m \times 3.71\ m = 21.8\ m^2$$

$$Q_{13\ R\ KH} = 0.499\ kJ/kg - cli = 0.12\ kCal/kg - cli$$

ii. Convection Heat Loss

For horizontal surface facing up [37] the characteristic length and Rayleigh number in this case are:

$$L_C = \frac{A_s}{P} = \frac{L \times W}{2(L + W)} = \frac{5.86\ m \times 3.71\ m}{2(5.86 + 3.71)m} = 1.136\ m \qquad and,$$

$$R_{aLc} = \frac{g \times \beta \times (T_s - T_\infty) \times D^3 \times Pr \times L_c^3}{v^2} = 2.23 \times 10^3$$

$$Nu = 0.15 \times R_{aLc}^{\frac{1}{3}} = 290.160 \qquad and \quad h_{con} = \frac{k_{air}}{L_C} Nu = 7.486$$

$$Q_{13C_{KH}} = \frac{h_{con} \times A_{k.hood} \times (T_s - T_\infty)}{\dot{m}_{clinker}} = 0.442\ kJ/kg - cli = 0.11\ kCal/kg - cli$$

E. Cooler

i. Radiation Heat Loss

$$Q_{13\,R\,C} = \frac{\delta \times \varepsilon \times A_{cooler} \times (T_S^4 - T_\infty^4)}{\dot{m}_{clinker}}$$

$$A_{cooler} = 27.68\,m \times 3.71\,m = 102.69\,m^2$$

$$Q_{13R_C} = 1.18\ kJ/kg - cli = 0.28\ kCal/kg - cli$$

ii. Convection Heat Loss

For horizontal surface facing up in Appendix-C, table-C1 the characteristic length and Rayleigh number in this case are:

$$L_C = \frac{A_s}{P} = \frac{L \times W}{2(L+W)} = \frac{27.68\,m \times 3.71\,m}{2(5.86+3.71)m} = 1.639\,m \qquad and,$$

$$R_{aLc} = \frac{g \times \beta \times (T_s - T_\infty) \times Pr \times L_c^3}{v^2} = 1.749 \times 10^3$$

$$Nu = 0.15 \times R_{aLc}^{\frac{1}{3}} = 7.642 \qquad and \qquad h_{con} = \frac{k_{air}}{L_C} Nu = 0.130$$

$$Q_{13C_C} = \frac{h_{con} * \times \times (T_s - T_\infty)}{\dot{m}_{clinker}} = 0.022\ kJ/kg - cli = 5.222 \times 10^{-3}\ kCal/kg - cli$$

Table 4.22: Summery of Thermal Energy Audit for pyro-processing of Line-2

Description	Results kCal/kg.cli	Ratio %	Description	Results kCal/kg.cli	Ratio %
Heat inputs			**Heat outputs**		
Heat input from combustion of coal	**747.08**	**90.06**	**Heat input from infiltration air**	**0.43**	**0.052**
Heat input from sensible heat by coal	**1.01**	**0.122**	**Heat required for clinker formation**	**411.2**	***49.57***
Heat input from raw material feed	**9.44**	**1.14**	**Heat loss by the exhaust gas**	**200.34**	**24.15**
Heat input from organic substance in kiln feed	**44.21**	**5.33**	**Heat loss due to evaporation**	**3.31**	**0.40**
Heat input from cooling air	**27.78**	**3.35**	**Heat loss due to hot air from cooler**	**123.25**	**14.86**
			Heat loss due to dust	**2.59**	**0.31**
			Heat loss due to clinker discharge	**2.95**	**0.36**
			Radiation from kiln	**32.64**	**3.93**
			Convection from kiln	**11.44**	**1.38**
			Radiation from preheater	**3.91**	**0.47**
			Convection from preheater	**2.56**	**0.31**
			Radiation from pre-calciner	**4.46**	**0.54**
			Convection from pre-calciner	**2.84**	**0.34**
			Radiation from kiln hood	**0.12**	**0.014**
			Convection from kiln hood	**0.11**	**0.013**
			Radiation from cooler	**0.28**	**0.034**
			Convection from cooler	**0.005222**	**0.00063**
			Uncounted losses	**27.08**	**3.2646**
Total heat input	**829.52**	**100.00**	**Total heat output**	**829.52**	**100.00**
Energy efficiency for pyro-processing system			η_{th}	***49.57%***	

As shown from the table 4.22: 90.06% which is 747.08 $kCal/kg\ of\ cli$ of the total heat input to the pyro-processing system is from combustion coal, 0.122% which is 1.01 $kCal/kg\ of\ cli$ of total heat input is from sensible heat by coal, 1.14% which is 9.44 $kCal/kg\ of\ cli$ of total heat input is from raw material feed, 5.33% which is 44.21 $kCal/kg\ of\ cli$ of total heat input is from organic substance in kiln feed and the other 3.35% which is 27.78 $kCal/kg\ of\ cli$ of the total heat input from cooling air.

The total heat required for clinker formation is 49.57% which is 411.2 $kCal/kg\ of\ cli$ from total heat input. From this can concluded the thermal energy efficiency of pyro-processing system is 49.57%.

As shown from table 4.22: 24.15% which is 200.34 $kCal/kg\ of\ cli$ is loss due to the exhaust gas, 14.86% which is 123.25 $kCal/kg\ of\ cli$ is loss due to hot air from cooler, 10.3% which is 85.45 $kCal/kg\ of\ cli$ is loss due to surface the other 3.26% which is 27.08 $kCal/kg\ of\ cli$ is uncounted losses.

4.4. Economics Analysis of the Quantified Thermal Energy Losses

The economic analysis is done for the energy that consumes in the process for heating false air, cooling air and heat losses in the form of radiation and convection in the pyro-processing.

Table 4.23: Amount of heat losses consumed in different form

No	Form of heat consumption	Amount ($kCal/kg\ of\ cli$)
1	False air	27.78
2	Cooling air	0.43
3	Pre heater losses	85.45
4	Pre calciner (swirl chamber and mixing chamber) losses	
5	Kiln losses	
6	Cooler losses	
Total		113.66

To know how much coal uses the industry to losses,

$113.66\ Kcal/Kg - cli\ \ or\ 473.58\ Kj/Kg - cli\ thermal\ energy\ calculated\ as\ follows:$

$Since, Q = m_{coal} * CV_{coal}$

$473.58\ Kj/Kg - cli = m_{coal} * 27068.18\ Kj/Kg - cli$

$$m_{coal} = \frac{473.58\ Kj/Kg - cli}{27068.18\ Kj/Kg - cli} = 0.0175\ Kg/Kg - cli$$

$\dot{m}_{coal} = 0.0175\ Kg/Kg - cli * 131.25\ ton/hr = 2296.34\ Kg/hr$

From the above calculation can know how much of coal is consumed in a year if the factory operates for 24 hrs in a day and 330 $days$ in a year.

Then,

$$\dot{m}_{coal} = 2296.34\ Kg/hr * 24\ hrs * 330\ days = 18,187,032.708\ Kg/year$$
$$= 18,187.0327\ tone/year$$

And, the average cost for one tone of coal (South African) in the selected fiscal (audit) year is 36877.67 ETB per ton of coal.

From this can calculate the amount of birr lost the factory in a year.

$$Amount\ of\ ETB\ Lost = 18,187.0327\ \ ton/year * 3687.67\ ETB/ton$$
$$= 67,067,774.90\ ETB/year$$

4.5. Identified Thermal Energy Conservation Opportunities

The thermal energy conservation opportunities /ECOs/ for Pyro-processing system is identified from observation, inspection, informal interview, and detail energy audit conducted.

a. Housekeeping (No /Low Cost) Thermal Energy Conservation Opportunities

The following housekeeping or low cost thermal energy conservation opportunities help the factory considerably to reduce its thermal energy cost. These are:

1. Giving updated awareness on energy management to the factory workers.
   - ✓ Daily monitoring and analysis of key parameters.
   - ✓ Daily power consumption report sent all management cadre employees for their information and control action.
   - ✓ Celebration of annual Energy conservation week celebrations to educate all persons.
   - ✓ Formation of energy circle team.
2. Cleaning all machines in the factory regularly.
3. Carrying out energy audits at regular intervals and adopting necessary energy conservation activities through Zero / Low/ high cost investments.
4. Checking the proper functioning of Pyro-processing system.
5. Periodic removal of collapse of dust from the Pyro-processing system.

b. ECOs Identified from detail audit:

1. Process Controls and Optimization
2. Waste Heat Recovery for Power Production

c. Use of alternative fuels (Biomass in cement technology)

4.6. Technical and Economic Analyses for the Proposed ECOs

4.6.1. Process Control and Optimization

a. Technology/Measure Description [Technical Feasibility]

The clinker-making process is a countercurrent process, with the kiln located between two heat exchangers that recover the heat of the combustion gases and the hot clinker. Optimum control of the kiln system is key for a smooth and energy efficient process. Non-automated or non-optimum process control systems may lead to heat losses, unstable process conditions, and more operational stops. The latter effects lead to increased fuel demand of the system. Automated computerized control systems are effective measures to optimize combustion process and conditions and to maintain operating conditions in the kiln at optimum levels. Today, all modern kilns are equipped with such systems[38].

Both raw materials and the fuel mix can be improved through analysis of chemical and physical characteristics. Besides automating the weighing and blending processes, other parameters such as air and mass flow and temperature distribution can be controlled in order to optimize kiln operation.

Additional process control systems include the use of online analyzers that permit operators to determine the chemical composition of raw materials and the product, thereby allowing for immediate changes in the blend of these materials.

Improved process control also will help to improve the product quality and grind ability, such as reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding.

Process control of the Pyro-processing system can improve heat recovery, material throughout, and reliable control of free lime content in the clinker. As a result, the operating cost of an optimized kiln is usually reduced as a result of decreased fuel and refractory consumption, lower maintenance costs, and higher productivity[38].

Combustion management is of prime importance for pyro-processing system optimization and requires specific attention to the following items:

1. *Fuel grinding management*: fuel grinding should be managed to achieve optimally set fineness.
2. *Air ratio management*: to maintain an appropriate air ratio, the oxygen concentration in the combustion exhaust gas requires strict management.
3. *Exhaust gas management*: carbon dioxide and nitrogen oxides should be measured, and the measurement data should be used for combustion management.
4. *Kiln burner management*: the basic designs such as the fuel discharge angle of the burner, the primary air ratio, etc., should be reviewed to maintain the optimum combustion conditions.
5. *Cooler operation management*: heat recovery at the cooler greatly affects the combustion management of them kiln burner.

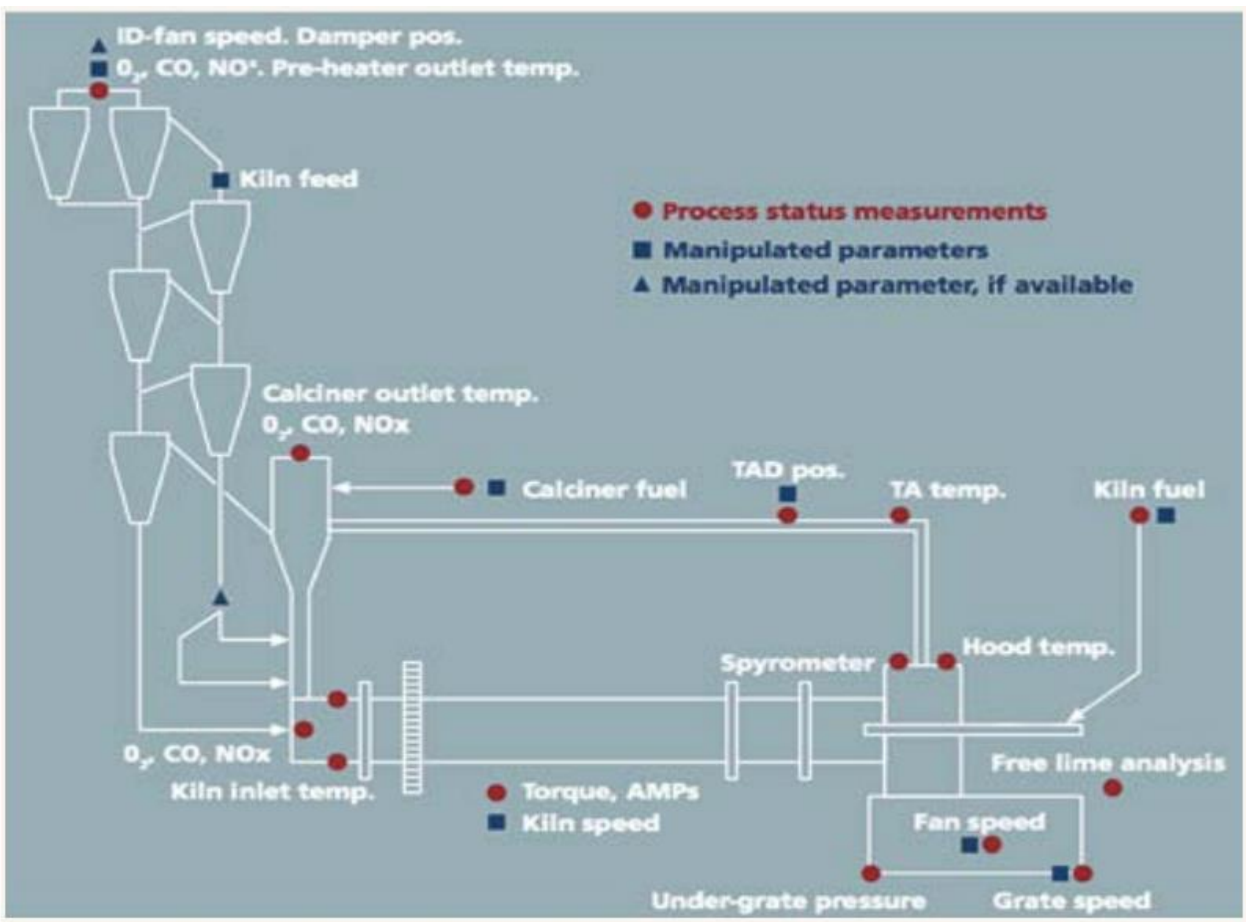

Figure 4.4: Schematic description of control points and parameters in pyro-processing system control and management system

b. *Energy Performance [Economics feasibility]*

i. Saving Analysis

Thermal energy savings from process control systems may vary between 2.5 percent and 10 percent, and the average savings are estimated at 6.25 percent[9].

By assuming 6.25 percent of the total thermal energy loses will be recovered by the adequate process control and optimization, the saved energy will be 28.9965kCal/kg.cli. This saves 4258.1765 tons of raw coal which is equivalent with 16,128,567.32 Birr per year. Another basic saving while we conduct process control and optimization is environmental saving. Emissions of greenhouse gases will reduce.

ii. Implementation Cost

Capital costs are estimated at between \$0.34 million and \$0.47 million (for a plant with 2 million tons per year of production capacity) and the average implementation cost is estimated \$0.405 million [9].

Therefore: the total cost of process control and optimizations for pyro-processing system will be \$405,000.00 (11,137,500.00 ETB). From this, we can decide as it is an economically feasible measure.

iii. Payback Period

The payback period can be estimated as follows.

$$\text{Simple payback period} = \frac{\text{Implementation Cost}}{\text{Cost Saved}} = \frac{11{,}137{,}500.00\ \text{ETB}}{16{,}128{,}567.32\ \text{Birr per year}} = 0.69\ \text{year}$$

$$= 0.69\ \text{year}\ \times 12\ \text{months}/year = 8.28\ months\ \cong 8\ months$$

4.6.2. Waste Heat Recovery for power Production

a. Technology/Measure Description [Technical Feasibility]

From the Thermal Energy Balance Sheer table show that 39.01% of total heat input is available as waste heat from exist gases of preheater and clinker cooler. The quantity of heat from preheater exit gases ranges from 750 to 1,050 MJ per ton of clinker at a temperature range of 300 to 400 degrees Celsius. The quantity of heat from the clinker cooler ranges from 330 to 540 MJ per ton of clinker at a temperature range of 200 to 300 degrees Celsius from the exhaust air of the grate cooler. A portion (or in some cases all) of this heat is used to dry raw materials and coal. In certain cases, it may be cost effective to recover the remaining portion of the heat in these exhaust streams for power generation[39].

Because raw material drying is important in a cement plant, heat recovery has limited application for plants with higher raw material moisture content. Often drying of other materials such as slag or fly ash requires hot gases from the preheater or cooler; in that case, opportunities for waste heat recovery will be further decreased.

Power production with residual hot gases from the preheater and hot air from the cooler require a heat recovery boiler and a turbine system. Power generation can be based on a steam cycle or an organic Rankine cycle (that is, the conversion of heat into work). In each case, a pressurized working fluid (water for the steam cycle or an organic compound for the organic Rankine cycle) is vaporized by the hot exhaust gases in a heat recovery boiler, or heater, and then expanded through a turbine that drives a generator[39].

Steam Rankine Cycle—The most commonly used Rankine cycle system for waste heat recovery power generation, the steam Rankine cycle, uses water as the working fluid and involves generating steam in a waste heat boiler, which then drives a steam turbine. As shown in Figure 4, in the steam waste heat recovery cycle, the working fluid—water—is fist pumped to elevated pressure before entering a waste heat recovery boiler. The water is vaporized into high pressure steam by the hot exhaust from the process and then expanded to lower temperature and pressure in a turbine, generating mechanical power that drives an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where the expanded vapor is condensed to low-pressure liquid and returned to the feed water pump and boiler.

The steam turbine technology is best known from power plants. While in modern power plants, electric efficiency is raised to 45 to 46 percent, the relatively low temperature level from the cooler (200 to 300 degrees Celsius) limits the efficiency in waste heat recovery systems in cement kilns to a maximum of 20 to 25 percent[39].

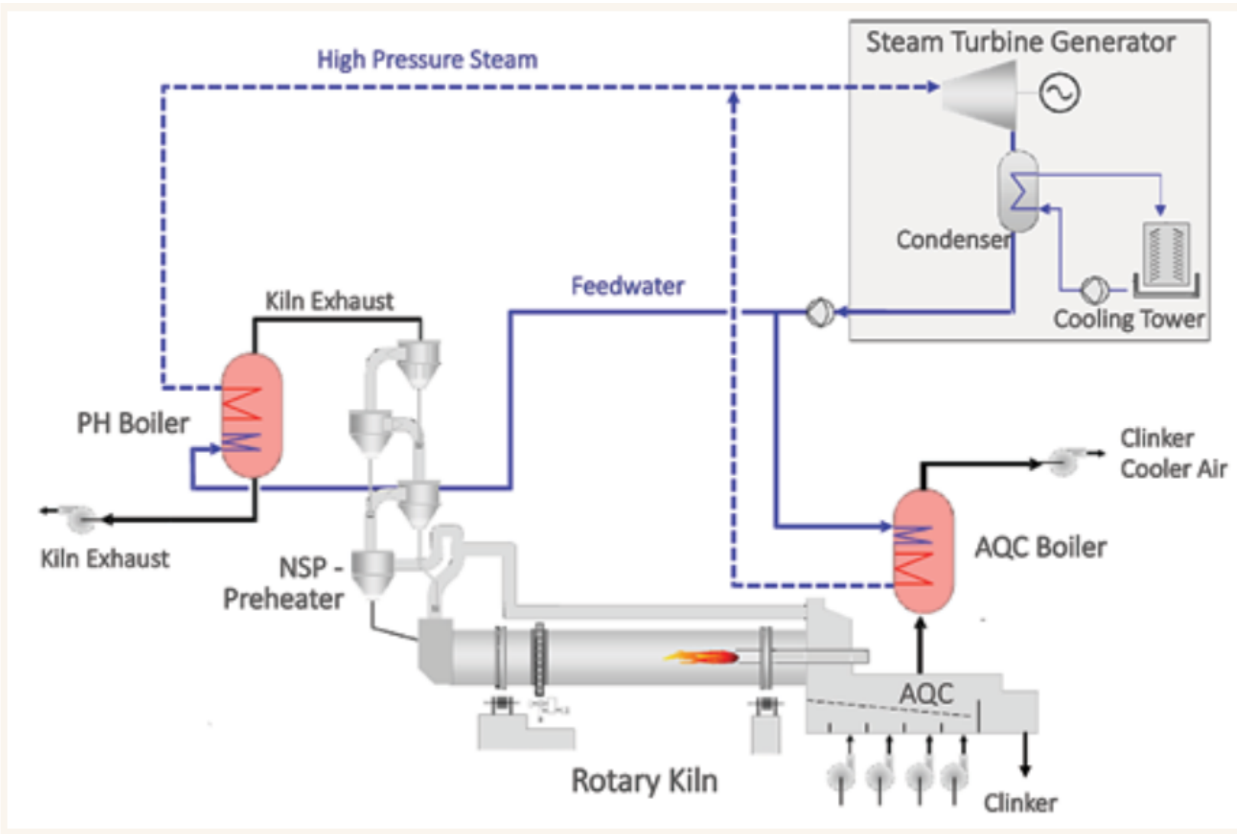

Figure 4.5: Typical Waste Heat Recovery System Using Steam Rankine Cycle

Steam cycles are, by far, the most common waste heat recovery systems in operation in cement plants. These systems are generally characterized by the following:

- Are most familiar to the cement industry and economically preferable where source heat temperature exceeds 300 degrees Celsius.
- Are based on proven technologies and simple to operate.
- Are widely available from a variety of suppliers.
- Are less costly to install than other systems on a specific cost basis ($ per kW).

b. Energy Performance [Economics feasibility]

i. Saving Analysis

Power generation potential is up to 22 kWh per ton of clinker; based on the chosen process and kiln technology, 8 to 10 kWh per ton of clinker can be produced from cooler exhaust air, and 9 to 12 kWh per ton of clinker can be produced from the preheater gases if the moisture content in the raw material is low and if it requires only a little hot gas/air for drying. Thus, in total, up to 22 kWh per ton of clinker, by using up to 25 percent of the thermal energy loses from waste heat from exist gases of preheater and clinker cooler for power consumption of a cement plant, can be produced by using these technologies without changes in pyro-processing operation[39].

By assuming 25 percent of the total thermal energy loses will be recovered by the waste heat recovery for power production, the saved energy will be 80.8975kCal/kg.cli. This saves 12,944.62 tons of raw coal which is equivalent with 47,735,485.839 Birr per year.

ii. Implementation Cost

Capital costs are estimated at between $0.74 million and $1.27 million (for a plant with 2 million tons per year of production capacity) and the average implementation cost is estimated $1.005 million[39].

Therefore: the total cost of waste heat recovery for power production of pyro-processing system will be $1,005,000.00 (27,637,500.00 ETB). From this, we can decide as it is an economically feasible measure.

iii. Payback Period

The payback period can be estimated as follows.

$$\text{Simple payback period} = \frac{\text{Implementation Cost}}{\text{Cost Saved}} = \frac{27{,}637{,}500.00\ \text{ETB}}{47{,}735{,}485.839\text{Birr per year}} = 0.58\ \text{year}$$

$$= 0.58\ \text{year} \times 12\ \text{months}/year = 6.96\ months\ \cong 7\ months$$

4.6.3. Use of Alternative Fuels (Biomass in Cement Technology)

Biomass is biological material derived from living, or recently living organisms. In the context of biomass for energy this is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material[40].

Messebo cement factory is working to partially replace its fuel consumption with biomass (sesame husk), which have been considered as waste and ignited at farmlands in woreda kafta Humera Sesame husk is considered to be carbon-neutral or green energy because the crop grown to replace the combusted sesame husk is considered to absorb CO_2 from the atmosphere while growing, thereby in effect 'canceling out' the CO_2 emissions associated with the combustion of the cultivated crop each year, the net effect on the atmospheric carbon balance is zero[41].

Farming information

The sesame farm lands are concentrated around Humera town. The farm areas are accessible only during dry seasons through rural roads. Kafta Humera wereda is the main producer of the sesame crops in Tigrai region. The total area covered by sesame crop in this wereda is about 223,918 hectares. The average yield found is 3 quintals of sesame seed per hectare. The weight of the stalks is on average 2 tons per hectare. Therefore, 223,918hectare×2tons/hectare= 447,836 tons could be collected per annum in Kafta Humera Wereda. The stalk is currently mowed from the middle but we can train the farmers to cut it from the bottom[40].

Collection

Depending on the agricultural residue, collection can be a major component of the densification process. For example, materials such as sesame stalks tend to be widely dispersed in the fields as the stalks are cut and stacked in piles. As a result, it must be collected and transported to central location (baling plant). For the time being the plant is collecting the straw from the fields for commissioning. But later on the plant have a plan to outsource the collection and baling jobs to micro and small enterprises (MSE) which is expected to create a very huge job opportunity to the region[40].

Process flow diagram

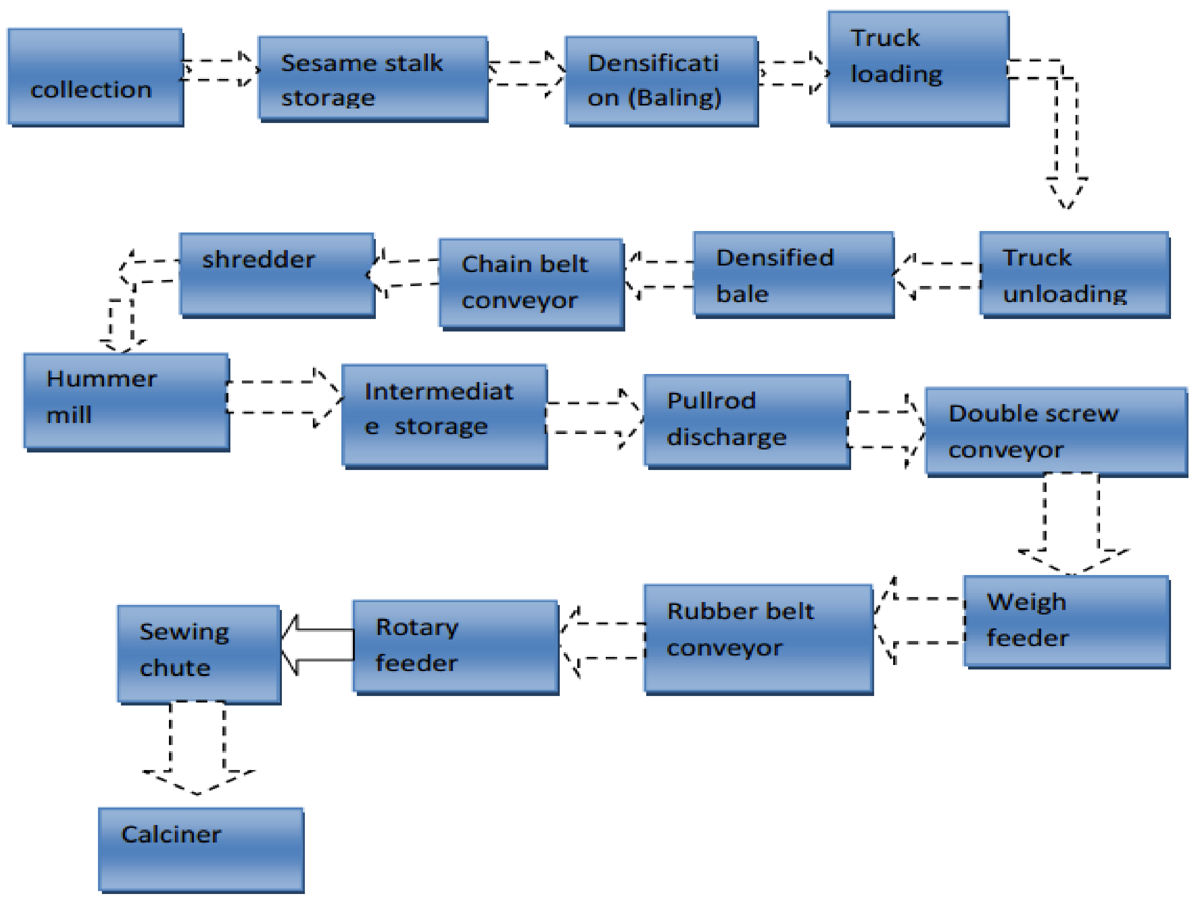

Figure 4.6: process flow diagram of Sesame husk for partial replacement of the raw coal

Advantage of use of sesame husk

- To ensure natural resource preservation and total emission reduction
- To enhance use of waste material (as a fuel)
- To insure environmentally sustainable waste management and important saving of agricultural wastes.
- To use of suitable alternative materials because it does not have any negative impact in emission.
- To encourage environmental, social, economically equally and friendly relationship.
- To improve Ethiopian's climate resilient green economy strategy.

- The company may obtain acceptance from international and financial institutions as well as from governmental institutions because it supports current globalization issues.
- To create job opportunity to the local community (small and micro enterprises)
- To reduce greenhouse gases emission.
- To obtain revenue from carbon trade.
- To insure socio economic and ecological sustainability.
- To reduce foreign currency.

Cost wise and environmental advantage

a. **fuel replacement**

The benefit of using sesame husk is not only to displace coal used in Messebo cement factory but it also helps full to environmental protection. The fuel displacement is step wise up to 60%, currently the plant installed all the machinery and equipment designed for 40% heat required[40].

Assuming the average specific energy consumption of Messebo cement factory for the pyro processing system to be 750 kCal/Kg of clinker and the heating value of imported coal to be 6000 kCal/Kg of coal, hourly fuel consumption of Messebo cement factory, with a production capacity of 125 tons of clinker per hour, is estimated at 15.63 ton/hour of imported coal. Replacing 40% this imported coal with sesame husk, would require about 9.26 ton/hour of sesame husk fuel (assuming a heating value of 4050 kCal/Kg). This is a considerable amount of fuel to handle on an hourly basis[40].

Considering 40% of fuel consumption of kiln line-2, equivalent to 6.25 ton/hour of coal is replaced with 9.26 ton/hour of sesame husk. Assuming the average sesame husk cost to be Birr 1900 per ton the hourly sesame husk fuel cost would, therefore, be approximately birr 17,594.

Considering the current price of coal to be birr 4450 per ton of coal, the cost of the substituted 40% of coal on hourly base would be approximately birr 27,813.

The estimated net saving from fuel replacement is, therefore, Birr 10,219 per hour. Since line-2 has the capacity to produce 3000 ton of clinker per day and accordingly 125 ton of clinker per hour Messebo cement factory can earn birr 8.18 per quintal of clinker.

b. Reduction of CO_2 gas as greenhouse gas (GHG)

As a result of substituting 40% consumption of coal of line-2 with sesame husk Messebo can reduce carbon dioxide emitted from combustion of fossil fuel coal. The CO_2 emission factor of coal is about 96kg/GJ and the average heating value of imported coal is 6000 kCal/Kg of coal and the amount of 40%coal replaced by sesame husk is estimated to be 45,000 tons/year. The estimated CO2 emission reduction would, therefore, be about 108,452 tons of CO_2 per year.

Revenue from CDM

The reduction of CO_2 emissions can enable Messebo cement factory to apply for revenue from the CDM (Clean Development Mechanism)[40].

With 40% fuel switching, a minimum of 45,000 ton/year of coal can be displaced and about 108,452 tons of CO2 per year can be reduced.

With this reduction, revenue from the CDM (at US$14/tone of CO2) would be about US$ 1,518,328 per year.

4.7. Energy Action Plan

Energy action plan is important to implement the suggested ECMs. Based on this fact, the identified technically and economically feasible ECOs are categorized in to short term, medium term and long term action plans. Performing ECMs based on their own action plan helps the organization to provide the savings gained from ECMs with very short payback period to ECMs with medium and long payback periods. So as to improve the energy efficiency of MCF PL-2, energy action plan for the identified recommended technically, economically and environmentally feasible measures should be designed.

Short term Action Plan

This plan requires no/or least capital investment or least improvement to avoid energy wastages and minimizing non-essential energy users and can be accomplished in a short period of time on a regular basis never less than once a year. This plan can be implemented quickly without the need for additional studies to improve the system efficiency.

Medium Term Action Plan

This term action plan can be implemented at the factory level with small investment and once to achieve efficiency improvement through modifications of existing equipment's and other operations and is generally of low individual cost.

Long Term Action Plan

The long term plan is done once to achieve efficiency improvement through innovation, planning and engineering input. More capital investment which thoroughly studied is required to finalize the long term action plan.

Energy Action Team

To supervise, monitor and report the energy utilization of the factory, Energy action team must be established in the factory. The tasks performed by this team include;

- Assess performance and setting goals,
- Look for any energy conservation opportunity improvements,
- Formulate action plans for implementing efficiency improvement,
- Coordinating the implementation of the action plan,
- Supervising and controlling the implementation,
- Evaluate and report performance.

This team must be led by an energy team leader or manager, and consists of all professionals who have brief knowhow about all energy related information of the factory.

Table 4.24: Action Plan of ECMs

No.	Recommended ECOs	Energy action term
1	Daily power consumption report sent all management cadre employees	Short term
2	Cleaning all machines in the factory regularly.	Short term
3	Periodic removal of collapse of dust from the Pyro-processing system	Short term
4	Checking the proper functioning of Pyro-processing system	Short term
5	Carrying out energy audits at regular intervals	Medium term
6	Formation of energy circle team	Medium term
7	Daily monitoring and analysis of key parameters	Medium term
8	Celebration of annual Energy conservation week	Medium term
9	Process Controls and Optimization	Long term
10	Waste Heat Recovery for Power Production	Long term
11	Use of alternative fuels (Biomass in cement technology)	Long term

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATION

5.1. Conclusions

The specific energy of the factory was determined using different data collected by inspection through walk, interviewing of the factory workers, referring to the nameplate of the major energy consuming systems, referring to the factory data record books and log sheets, and direct measurement using portable measuring instruments.

The factory uses thermal energy inefficiently. As a result, this thesis dealt with the unwise energy consuming end use devices of MCF PL-2 and attained its objectives. The end use devices were examined for their energy performance during the assessment time and ECOs for the major energy (heat loss area) consuming systems (pre-heater, pre-calciner, kiln and grate cooler) are identified.

The above heat loss area is quantified using the both mass and thermal energy balance approach. The Clinker capacity of the production line is 131.25 ton/hour and total coal feed to both burners are 22.5 ton/hour. The result, obtained by performing energy balance in all parts of the pyro-processing systems, shows that huge amount of energy loss from surface of kiln systems (6.56%), kiln exhaust (24.15%) and cooler exhaust (14.86%). The annual losses are calculated in terms of cash to be 67,067,775 ETB.

The thermal energy conservation measures suggested among various ECOs identified are;

1. Housekeeping (No /Low Cost) Thermal Energy Conservation Opportunities
2. Process Controls and Optimization
3. Waste Heat Recovery for Power Production
4. Use of alternative fuels (Biomass in cement technology)

5.2. Recommendation

This thesis recommended many major ECOs from the conducted detail energy audit for different system units, many housekeeping thermal energy conservation measures and use alternative fuels so as to help the factory reduce its thermal energy cost. Therefore, from the research findings it can be said that the factory should implement and monitor the recommended ECOs based on the listed on the paper. In addition to these, it is better for the factory if it seeks advice from other energy audit teams to get benefit and become market competitive.

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APPENDIX

Appendix A: Air property

Table A1: Air property of kiln surface

Position (m)	Surface temp. $T_s(°C)$	Film. Temp. $T_f(°C)$	$k(W/m.K)$	Pr	$\beta(1/K) \times 10^{-3}$	$v(m^2/s) \times 10^{-5}$
1	164.4	92.7	0.03092	0.706	2.733	2.244
2	222.8	121.9	0.03293	0.704	2.531	2.563
3	294.1	157.6	0.03529	0.703	2.322	2.981
4	301.7	161.4	0.03554	0.703	2.301	3.026
5	307.6	164.3	0.03573	0.703	2.286	3.060
6	188.7	104.9	0.03176	0.705	2.646	2.378
7	250.5	135.8	0.03386	0.704	2.446	2.723
8	245.3	133.2	0.03369	0.704	2.461	2.692
9	275.2	148.1	0.03466	0.703	2.374	2.868
10	290.7	155.9	0.03518	0.703	2.331	2.961
11	305.5	163.3	0.03566	0.703	2.291	3.048
12	297.4	159.2	0.03539	0.703	2.313	2.999
13	312	166.5	0.03587	0.703	2.275	3.086
14	284.9	153.0	0.03498	0.703	2.347	2.926
15	252.5	136.8	0.03392	0.704	2.440	2.735
16	254.6	137.8	0.03399	0.704	2.433	2.747
17	240.2	130.6	0.03352	0.704	2.477	2.662
18	222.6	121.8	0.03292	0.704	2.532	2.562
19	188.4	104.7	0.03175	0.705	2.647	2.378
20	176.2	98.6	0.03126	0.706	2.690	2.309
21	197.2	109.1	0.03205	0.705	2.616	2.424
22	266.3	143.7	0.03438	0.704	2.399	2.816
23	336.1	178.6	0.03666	0.703	2.214	3.230
24	328.3	174.7	0.03641	0.703	2.233	3.183
25	332.5	176.8	0.03655	0.703	2.223	3.208
26	329.7	175.4	0.03646	0.703	2.230	3.191

27	327	174.0	0.03636	0.703	2.236	3.175
28	275.3	148.2	0.03467	0.704	2.374	2.869
29	220.5	120.8	0.03289	0.704	2.539	2.551
30	330.5	175.8	0.03647	0.703	2.228	3.195
31	319.2	170.1	0.03611	0.703	2.256	3.128
32	330.4	175.7	0.03647	0.703	2.228	3.195
33	350.1	185.6	0.03710	0.703	2.180	3.319
34	355.5	188.3	0.03727	0.703	2.167	3.354
35	360.1	190.6	0.03742	0.703	2.157	3.383
36	363.3	192.2	0.03752	0.703	2.149	3.403
37	354.5	187.8	0.03724	0.703	2.170	3.347
38	338.5	179.8	0.03674	0.703	2.208	3.246
39	347.6	184.3	0.03702	0.703	2.186	3.303
40	346.2	183.6	0.03698	0.703	2.189	3.294
41	346.2	183.6	0.03698	0.703	2.189	3.294
42	346.9	184.0	0.03694	0.703	2.188	3.286
43	346	183.5	0.03686	0.703	2.190	3.293
44	285.3	153.2	0.03500	0.703	2.346	2.929
45	247.4	134.2	0.03375	0.704	2.455	2.704
46	279.3	150.2	0.03480	0.704	2.362	2.893
47	278.3	149.7	0.03477	0.704	2.365	2.887
48	291.6	156.3	0.03520	0.703	2.329	2.965
49	306.5	163.8	0.03570	0.703	2.289	3.054
50	310.9	166.0	0.03584	0.703	2.277	3.080
51	302.1	161.6	0.03555	0.703	2.300	3.028
52	312.6	166.8	0.03589	0.703	2.273	3.089
53	307.1	164.1	0.03571	0.703	2.287	3.058
54	291	156.0	0.03518	0.703	2.330	2.962
55	334	177.5	0.03659	0.703	2.219	3.216
56	312.5	166.8	0.03589	0.703	2.273	3.089
57	259.9	140.5	0.03401	0.703	2.418	2.779
58	296.2	158.6	0.03535	0.703	2.316	2.993
59	211.3	116.2	0.03254	0.705	2.569	2.502

60	315	168.0	0.03597	0.703	2.267	3.104
61	310.2	165.6	0.03581	0.703	2.279	3.075
62	305	163.0	0.03564	0.703	2.293	3.045
63	299.6	160.3	0.03564	0.703	2.307	3.013
64	294.3	157.7	0.03529	0.703	2.321	2.982
65	287.7	154.4	0.03508	0.703	2.339	2.943
66	297.7	159.4	0.03541	0.703	2.312	3.002
67	270	145.5	0.03449	0.704	2.389	2.838
68	237.2	129.1	0.03320	0.704	2.486	2.644
69	224.4	122.7	0.03298	0.704	2.526	2.572
70	230.9	126.0	0.03177	0.704	2.506	2.608

Table A2: Air properties of different position of pyro-processing

Position	**Surface temp.** $T_s(°C)$	**Film. Temp.** $T_f(°C)$	$\mathrm{K(W/m.K)}$	**Pr**	$\beta(1/K) \times 10^{-3}$	$v(m^2/s) \times 10^{-5}$
C-1-1	55.6	38.3	0.02693	0.709	3.211	1.671
C-1-2	55.6	38.3	0.02693	0.709	3.211	1.671
C-2	49.4	35.2	0.02673	0.709	3.243	1.644
C-3	64.4	42.7	0.02723	0.709	3.166	1.714
C-4	80.1	50.55	0.02777	0.708	3.089	1.79
C-5	88.2	54.6	0.02805	0.708	3.051	1.828
C-6	112	66.5	0.02898	0.708	2.944	1.956
Swirl chamber	116.5	68.75	0.02917	0.707	2.925	1.982
Mixing chamber	115	68	0.02911	0.707	2.931	1.973
Grate Cooler	80.9	50.95	0.02780	0.708	3.085	1.793
Kiln hood	119.9	70.45	0.02931	0.707	2.912	2.001

Appendix B: Convection and radiation heat losses

Table B1: Heat losses of kiln surface

Position (m)	Surface temp. $T_s(°C)$	$R_{aD} \times 10^{11}$	Nu	h_{conv} $(W/m^2.K)$	Q_{conv} $(J/Kg-cli$	Q_{rad} $(J/Kg-cli$
1	164.4	5.247	866.786	5.826	331.217	602.88
2	222.8	5.227	865.329	6.195	495.572	1071.136
3	294.1	4.790	840.798	6.450	698.357	1940.943
4	301.7	4.736	837.702	6.472	720.215	2055.365
5	307.6	4.697	835.432	6.489	737.281	2147.379
6	188.7	5.281	868.426	5.996	398.620	768.007
7	250.5	5.088	857.750	6.314	574.438	1368.038
8	245.3	5.121	859.533	6.295	559.764	1308.571
9	275.2	4.925	848.451	6.393	644.234	1675.685
10	290.7	4.813	842.142	6.441	688.612	1891.221
11	305.5	4.710	836.226	6.483	731.138	2083.139
12	297.4	4.771	839.741	6.461	707.908	1990.065
13	312	4.665	833.607	6.500	749.891	2217.815
14	284.9	4.856	844.571	6.422	671.905	1808.454
15	252.5	5.075	857.033	6.320	579.985	1391.386
16	254.6	5.064	856.394	6.328	586.017	1416.191
17	240.2	5.150	861.137	6.275	545.292	1251.961
18	222.6	5.228	865.341	6.193	494.937	1069.165
19	188.4	5.274	868.031	5.991	397.600	735.62
20	176.2	5.279	868.477	5.902	363.121	672.439
21	197.2	5.281	868.410	6.051	422.640	837.584
22	266.3	4.989	852.244	6.370	619.412	1559.911
23	336.1	4.488	823.147	6.560	819.466	2633.017
24	328.3	4.547	826.626	6.543	797.085	2493.121
25	332.5	4.516	824.807	6.554	809.301	2567.778
26	329.7	4.538	826.077	6.548	801.284	2517.834
27	327	4.768	839.552	6.636	793.205	2470.328
28	275.3	4.930	848.912	6.398	645.023	1677.019

29	220.5	5.232	865.566	6.189	489.463	1048.613
30	330.5	4.534	825.859	6.548	803.368	2532.032
31	319.2	4.616	830.687	6.521	770.877	2336.648
32	330.4	4.533	825.802	6.547	803.053	2530.254
33	350.1	4.372	816.121	6.582	858.754	2897.949
34	355.5	4.326	813.310	6.590	873.824	3005.028
35	360.1	4.289	811.048	6.598	886.933	3098.447
36	363.3	4.264	809.504	6.603	895.986	3164.647
37	354.5	4.336	813.912	6.589	871.155	2984.989
38	338.5	4.466	821.819	6.564	826.174	2677.158
39	347.6	4.393	817.392	6.578	851.717	2849.309
40	346.2	4.405	818.110	6.577	847.894	2822.326
41	346.2	4.405	818.110	6.577	847.894	2822.326
42	346.9	4.432	819.780	6.583	850.533	2797.434
43	346	4.406	818.167	6.556	844.681	2818.486
44	285.3	4.851	844.294	6.424	673.087	1814.08
45	247.4	5.110	858.928	6.302	565.613	1332.372
46	279.3	4.901	847.309	6.410	656.384	1730.952
47	278.3	4.908	847.712	6.408	653.590	1717.359
48	291.6	4.811	842.027	6.443	691.208	1904.296
49	306.5	4.703	835.797	6.487	734.155	2130.001
50	310.9	4.672	833.976	6.498	746.762	2200.083
51	302.1	4.734	837.604	6.473	721.360	2061.515
52	312.6	4.663	833.453	6.503	751.717	2227.585
53	307.1	4.697	835.469	6.486	735.615	2139.472
54	291	4.814	842.165	6.441	689.397	1895.573
55	334	4.508	824.311	6.557	813.599	2594.82
56	312.5	4.662	833.390	6.502	751.403	2225.96
57	259.9	5.021	853.814	6.313	597.859	1480.124
58	296.2	4.776	840.027	6.455	704.277	1972.104
59	211.3	5.257	867.096	6.134	462.739	916.62
60	315	4.643	832.307	6.508	758.549	2266.82
61	310.2	4.679	834.419	6.496	744.731	2188.828

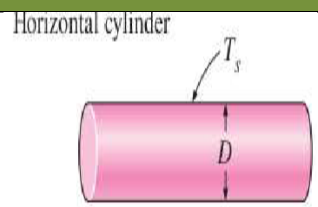
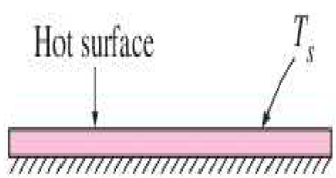
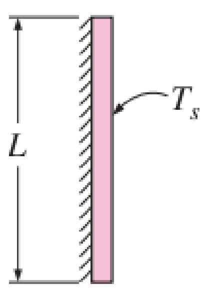
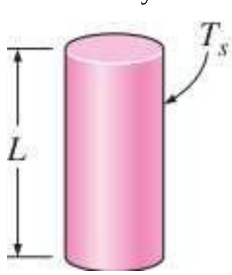
62	305	4.714	836.439	6.481	729.631	2106.483
63	299.6	4.753	838.665	6.498	717.662	2023.291
64	294.3	4.789	840.751	6.450	698.830	1943.896
65	287.7	4.835	843.383	6.432	680.017	1848.09
66	297.7	4.765	839.396	6.462	708.785	1994.574
67	270	4.964	850.848	6.380	629.734	1607.352
68	237.2	5.168	862.125	6.222	533.306	1219.439
69	224.4	5.221	865.008	6.202	500.074	1086.99
70	230.9	5.201	863.886	5.966	496.388	1152.988

Table B2: Surface heat losses of different position of pyro-processing

Position	**Surface temp.** $T_s(°C)$	R_{aD}	**Nu**	h_{conv} $(W/m^2.K)$	Q_{conv} $(J/Kg-cli$	Q_{rad} $(J/Kg-cli$
C-1-1	55.6	3.487×10^{12}	1516.451	3.781	827.501	1351.764
C-1-2	55.6	3.487×10^{12}	1516.451	3.781	827.501	1351746
C-2	49.4	8.306×10^{12}	2025.155	3.565	571.236	959.534
C-3	64.4	1.234×10^{13}	2512.891	4.390	1127.725	1657.68
C-4	80.1	1.413×10^{13}	2628.092	4.776	1611.787	2347.691
C-5	88.2	1.637×10^{13}	2758.079	4.941	2043.483	2999.557
C-6	112	1.245×10^{14}	5374.913	5.325	3679.99	5654.08
Swirl chamber	116.5	2.52×10^{12}	1361.893	4.966	2198.278	3677.063
Mixing chamber	115	1.077×10^{14}	5121.523	5.325	9660.551	14963.740
Grate Cooler	80.9	1.749×10^{10}	7.642	0.130	21.829	1180.909
Kiln hood	119.9	2.238×10^{9}	290.16	7.486	442.696	499.164

Appendix C: Correlations of different geometry

Table C1: Empirical correlation for average Nusselt number for natural convection over surfaces [37]

Geometry	Characteristic length	Range of R_{aD}	Nu
	D	$R_{aD} \leq 10^{12}$	$\left[0.6 + \frac{0.387R_{aD}^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\right]^2$
Horizontal plate 	A_S/P	$10^4 - 10^7$ $10^7 - 10^{11}$	$Nu = 0.54R_{aL}^{1/4}$ $Nu = 0.15R_{aL}^{1/3}$
Vertical plate 	L	$10^4 - 10^7$ $10^7 - 10^{11}$	$Nu = 0.54R_{aL}^{1/4}$ $Nu = 0.15R_{aL}^{1/3}$ For entire range $\left[0.825 + \frac{0.387R_{aD}^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}}\right]^2$
Vertical cylinder 	L		*A vertical cylinder can be treated as a vertical plate when: $D \geq \frac{35L}{G_{rL}^{1/4}}$

Appendix D: Heat capacity values

Figure D1: C_p of gases

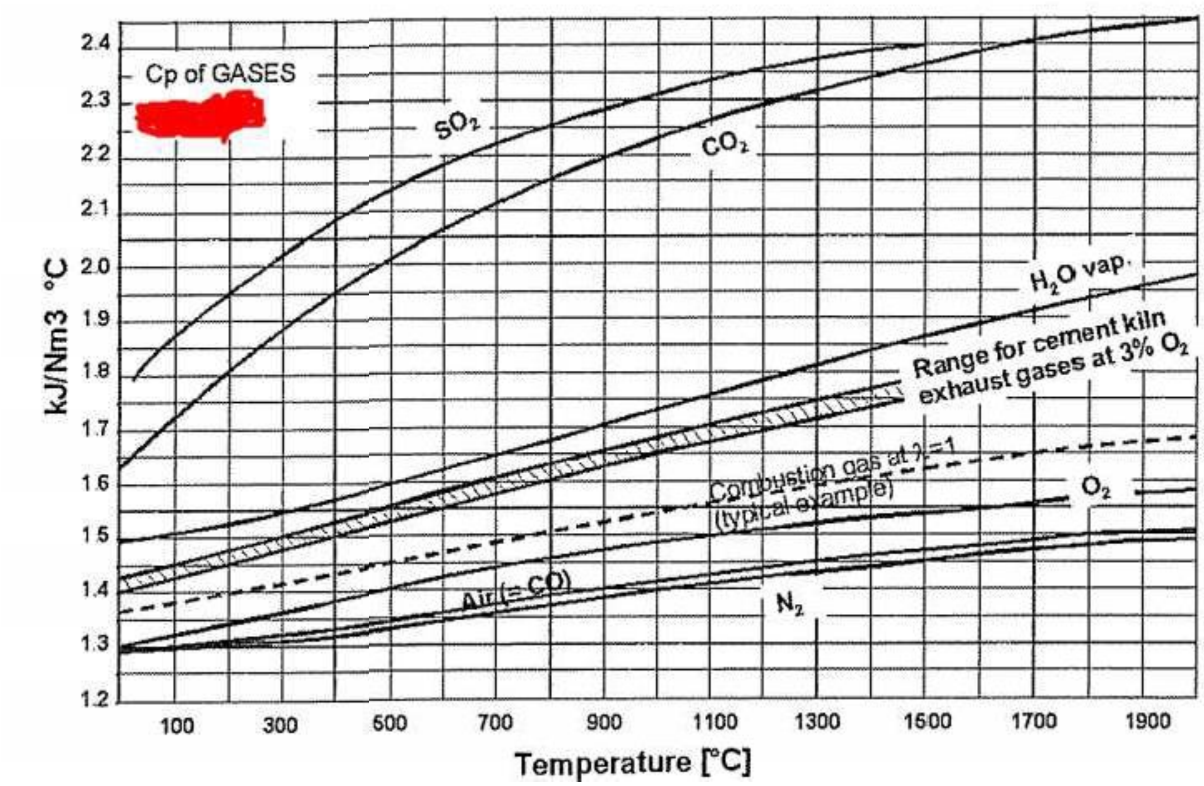


Figure D2: C_p of solid materials