Evaluation of Thermal Energy Consumption and Efficiency of Mugher Cement Plant

M.Sc. Thesis

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Evaluation of Thermal Energy Consumption and Efficiency of Mugher Cement Plant

A Thesis Submitted to Thermal and Aerospace Engineering Program of School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University in partial fulfillment of the requirements for the award of the degree of ***Master of Science in Thermal Engineering.***

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Approval by Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defense by Firomsa Dadi have read and evaluated his thesis titled "Evaluation of Thermal Energy Consumption and Efficiency of Mugher Cement Plant" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Masters of Science in Thermal Engineering.

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Declaration

I hereby declare that this M.Sc. Thesis entitled "Evaluation of Thermal Energy Consumption and Efficiency of Mugher Cement Plant" in partial fulfillment of the requirements for the award of the degree of Masters of Science in Thermal Engineering is an authentic record of my own work carried out from September 2018 to December 2019 under supervision of Dr. Gezahegn Habtamu, Assistant Professor of Thermal Engineering program, Adama Science and Technology University.

The matter embedded in this thesis has not been submitted for the award of a degree or diploma in any other university. All relevant resources information used in this paper has been duly acknowledged.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief. This has been submitted for examination with our approval. Masters of Science Thesis has been submitted for examination with my approval as the thesis advisor.

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Main Advisor Signature

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Co-Advisor Signature

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ABSTRACT

This study deals with the Evaluation of Thermal Energy Consumption and Efficiency of Mugher Cement Plant. The study includes thermal energy input and thermal energy output through sections of the factory. Mass balance of the system is done by raw data obtained from factory and energy balance of the system is evaluated by mass and temperature on system. The temperature on thermal system surface and material is measured by Dual Laser Infrared Thermometer. From energy balance, the specific energy consumption and efficiency of factory was found to be 3.277GJ/ton & 50.02% respectively. Total thermal energy consumption of the factory was 3547.57kJ/kg-clinker and around 49.98% of the total energy consumption was wasted from the factory, through hot exhaust gas from pre-heater and clinker cooler also from surface of the factory by convection and radiation heat. Those factors bring the plant to low performance.

The factory have no waste heat recovery to reduce energy consumption therefore there is a waste of 1773.11kJ per kg of clinker. If a factory installs a waste heat recovery system on pre-heater and clinker cooler, it can generate 5608 kW electrical power by exhaust flue gas and reduce power interruption due to electric power shortage as a country.

Keywords: Specific thermal energy consumption, Mass balance, Energy balance, Rotary kiln, Pre-heater, Pre-calciner, Cooler efficiency and Waste heat recovery system.

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LIST OF ABBREVIATION

ABBREVIATION	**DESCRIPTION**
AQC	Air Quench Clinker Cooler (Chamber)
C_{1A} and C_{1B}	First Cyclone A and B
C_2	Second Cyclone
C_3	Third Cyclone
C_4	Fourth Cyclone
C_5	Fifth Cyclone
C_6	Sixth Cyclone
CCR	Central Control Room
GCV	Gross Calorific Value
GC	Great cooler (Clinker cooler)
HFO	Heavy Furnace Oil
HPD	Hour per Day
LOI	Loss on Ignition
Mt	Million ton
NSP	New Suspension Pre-heater
PH	Pre-heater
PC	Pre-calciner
RMF	Raw Mill Factor
RK	Rotary kiln
SEC	Specific Energy Consumption
SH	Specific Heat
TAD	Tertiary Air Duct
TPH	Ton per Hour
TPY	Ton per Year
TTPY	Thousand Tons per Year
VRM	Vertical Raw Mill
WHRS	Waste Heat Recovery System

LIST OF SYMBOLS AND UNIT

Description	**Symbol**	**Unit**
Area	A	m^2
Dynamic viscosity	μ	kg/ms
Convective heat transfer coefficient	h	$W/m^{2}\ ^{0}C$
Heat lost	Q	kJ
Heat loading of rotary kiln	Q_{load}	$kJ/m^2/hr$
Temperature of surface	T_S	^0C
Temperature of shell	T_{Sh}	^0C
Temperature	T	^0C
Thermal conductivity	K	$W/m\ ^0C$
Stefan Boltzmann constant	σ	W/m^2k^4
Specific heat capacity	C_p	kJ/kg^0C
Time	t	S
Waste heat from cyclone surface	Q_{CS}	kW
Waste heat by convection	Q_{CV}	kW
Waste heat by radiation	Q_R	kW

CHAPTER ONE

INTRODUCTION

Ethiopia is a developing country in which the number of cement industry is increased from time to time. All of those industries get energy from fuel and electricity for the production process. Cement production is one of the most energy-intensive industrial processes in the world *(Schuer et al., 1992).*Thermal energy is the highest consumed energy from the total energy consumption because of pyro-processing. A combustion process in a rotary kiln is called pyro-processing and the product of burned feed material is called Clinker. Pyro-processing (Clinker formation), was taking place in a rotary kiln by fuel burning to generate thermal energy. Rotary kiln is a cylindrical shape unit that is the heart of a cement plant. Thermal energy is generated 100 % for non-pre-calciner and 40 % for pre-calciner rotary kiln cement plant *(Hiromi et al. 2013).*

Cement manufacturing process can be classified as a dry process and wet process. For a dry process, heat is generated in a rotary kiln by combustion of fuel with air to increase the temperature of feed raw material. For wet-process the process is the same as the dry process, but the moisture content of material for the wet process is higher than the dry process. By comparison of thermal energy consumption between dry and wet process, a wet process consumes more thermal energy but less electrical energy consumption. Theoretically, for producing one ton (1000 kg) of clinker it requires a minimum of 1.6 GJ, of thermal energy *(Liu et al., 1995).* This indicates that cement plant consuming the high thermal energy to produce 1000 kg of clinker.

Specific energy consumption (SEC) is the ratio of thermal energy consumed to the quantity of clinker produced by plant. Specific energy consumption is depending upon the harder raw material and quality of fuel. So the property of raw material and fuel quality determines the performance of the plant. Another way of determining the performance of the cement plant is the technology status which means using new generation technology like clinker cooler which highly recovers heat from clinker and waste heat management.

The major component for determining the performance of cement production is pre-heater, cooler, pre-calciner, rotary kiln and capacity of Induced Draft Fan for cooling clinker. Now a day's several cement plant technologies are being modified for increasing production and decreasing energy consumption. Number of cyclone of a pre-heater and pre-calciner is also determining the performance of the cement industry on thermal energy consumption. As a number of cyclone pre-heater is increased the energy consumption of the cement plant decreases by increasing temperature of feed material.

Thermal energy generated in a rotary kiln is not fully converted to the purpose of the plant. The purpose of the rotary kiln is to make clinker. On the energy balance, almost 40 % is lost through pre-heater flue gas, rotary kiln shell and cooler exhaust gas *(Engin and Ari, 2005).* A lot of researchers approximately studied thermal energy balance on the cement plant to identify useful and wasteful energy. Generally, a cement plant is one among the most thermal energy consuming plants and its performance is studied seriously for improving cost of production through reducing thermal energy consumption.

1.1 Mugher Cement Factory Profile

Mugher Cement Factory is the largest cement plant, located in the centre of Ethiopia and found 84 km away from North-West of Addis Ababa, capital city. The plant has three production lines. The first plant started operation in 1984, the second plant started production in 1990 and the third plant started production in 2011, respectively. The first and the second plant have production capacity of 1000 tons of clinker per day for each. The total production capacity of the two factories is 600,000 tons of clinker per annum and the third plant produces 3000 tons of clinker per day and 900,000 tons of clinker per annum. The average annual operation date of Mugher cement Factory is 300 days.

The average production capacity of Mugher cement plant is 1.7 million ton of clinker per year *(Larionov et al., 2017)* which is sharing around 16.83 % of the total clinker produced in the country. The plants use both electrical and thermal energy. All plant's used heavy furnace oil (HFO) or coal as a thermal energy source when they were installed. Now a day's all plant lines were modified to operate on bituminous coal instead of heavy furnace oil as the thermal energy source. The coal is imported from South Africa. Today in Ethiopia the number of cement plants is increased due to an increase in demand for cement. Table 1.1 shows the list of cement plants in Ethiopia.

Table 1.1 Ethiopian cement plant capacity and their thermal energy demand in MTPY *(Larionov et al., 2017)*

Plant	***Cement capacity (M. ton/Year)***	***Clinker capacity (M.ton/year)***	***Thermal energy demand (M. GJ/year)***
Mugher Cement	2.2	1.7	5.9
Dangote Cement	2.5	1.9	6.8
Derba Midroc Cement	2.5	1.8	6.3
Habesha Cement	1.2	0.9	3.1
National Cement	1.2	0.9	3.2
Messebo Cement	2.1	1.7	6.3
Other	1.6	1.3	4.6
Total	**13.3**	**10.2**	**36.2**

The end production process of plant is clinker and cement. Cement is the process of mixing and grinding material of clinker with pumice and gypsum at requier proportion and cement type. Mugher Cement plant is producing two types of cement depending upon clinker quantity, Gypsum and Pumice. These are

1. Pozzalana Portland Cement (PPC) – is a mixture of 65 % clinker, 30 % pumice and 5 % gypsum
2. Ordinary Portland Cement (OPC) – is a mixture of 95 % clinker and 5 % gypsum

A type of cement produced is determining the thermal energy consumption of the plant. The OPC is consuming high thermal energy because mass of clinker needed is higher than PPC cement.

1.2 Statement of problem

Mugher Cement Factory modified its production system recently (Since 2017) for use of bituminous coal as source of thermal energy in place of heavy furnace oil. The factory energy consumption, energy efficiency and energy saving potential areas where not studied since it starts running on coal as thermal energy source. In addition coal fire plants have several disadvantage such as emission of CO_2 (A greenhouse gas), generation of waste heat and several harmful substance.

Cement production process is most intensive in thermal energy consumption. Total input thermal energy generated by burning fuel is not fully consumed by the clinker production. Almost half is wasted from the plant system through a rotary kiln shell, Pre-heater cyclone, pre-calciner surface, clinker cooler surface and tertiary air duct shell by convection and radiation heat transfer modes. Also, the hot flue gas exhaust through clinker cooler stack and pre-heater stack is shared waste heat from cement plant. The other case of waste heat in the cement plant is the exhaust clinker which is at cooler outlet the temperature of clinker is above the design. This thesis analyzes the Evaluation of Thermal Energy Consumption and Efficiency of Mugher Cement Plant and identifying sections where thermal energy waste occurred and, also analyzes the heat recovery system without negatively affecting the plant production.

1.3 Objective

1.3.1 General objective

The objective of this research is to study in detail the thermal energy consumption performance, energy efficiency and energy conserving opportunities in Mugher Cement Factory system.

1.3.2 Specific objectives

The specific objectives of thesis include:

1. To conduct thermal energy performance of Mugher cement plant
2. To determine the energy balance of the plant and its thermal efficiency
3. To identify high thermal energy consuming systems and ways of saving energy consumptions without affecting its production
4. To conduct economic analysis for the identified energy saving opportunities

1.4 Scope, limitation and significance

1.4.1 Scope

The scope of this paper includes the following in the production of dry Portland cement by rotary kiln and using combustion coal for their thermal energy source:

- Measurements of temperature of the system such as ambient air, cooler surface, clinker, pre heater, kiln shell temperature with portable instruments
- Analyzing mass and heat balance on rotary kiln.
- Formulation of action plan for thermal energy conservation
- Cost benefits analysis of energy efficient measures.

1.4.2 Limitation

The main limitations in this work are 1) Among the three production lines of the plant the first and second line are not working for a long month's so only third line of the plant was considered in this thesis research. 2) Greenhouse gas emission of the factory was not included in this study.

1.4.3 Significance of the thesis

Today many cement plant is constructed in our country and they consume large amount of thermal energy by burning coal or oil which is costing to these companies. Performance analysis of thermal system is the key way in identifying how much thermal energy is consumed, how much consumed energy is converted to clinker production, area of waste energy and how action should be taken to conserve energy in these companies. The study helps Mugher Cement Factory to be aware of its coal consumption profile and take energy saving measures, so that it can reduce the imported coal consumption and save the environment from pollution too.

1.5 Methodology

The study covers production process, combustion process, mass balance, energy balance of the system, performance of the plant and ways of waste energy recovery. The temperature on the surface on pre-heater, pre-calciner, rotary kiln and clinker cooler surface, ambient air and clinker is measured to determine heat balance and the performance of a plant. Feed raw material, air flow rate, coal flow rate and primary air flow rate data was taken from installed portable gauge on a system. Online air calculator is used to determine exact property of air such as density, dynamic viscosity, Prandntl number, specific heat capacity, and thermal conductivity. To realize this work document review, data collection and data analysis have been adopted.

1.5.1 Document review

A review of latest documents and studies related to the specific subject was made. The review covered the documents related to pre-heater, pre-calciner, kiln, clinker cooler operation and clinker composition.

1.5.2 Data collection

Mostly, direct measurement approach data collection was used for thermal energy balance. Thermal data collection was somewhat complex and difficult to measure because some parts of a system are very hot. Collected data include: flow rate and temperature of solid materials (raw materials, clinker and coal), temperature of thermal unit surfaces like rotary kiln, clinker cooler, pre-heater, pre-calciner and temperature of ambient air. Surface and material temperature was measured by using portable Dual Laser Infrared Thermometer, whereas the pre-heater gas stream temperature and pressure drop on each stage was taken from the installed thermocouple and central control room (CCR). Daily coal consumption and clinker production data is taken from production manger office. Coal property and clinker property data is taken from, plant laboratory. Plant design data (dimension and production capacity) for pre-heater cyclones, pre-calciner, tertiary air duct, rotary kiln, and clinker cooler were taken as references.

1.5.3 Data Analysis

Collected data are used for analyzing the thermal energy consumption and energy & mass balance of the factory. Then, the actual thermal energy consumption of the plant was compared to its design standard and world bench mark to identifying the loss area and plant performance.

1.6 Research organization

This thesis is organized in to nine chapters. The first chapter presents the introduction of the study i.e about background, statement of the problem, objective, scope, limitation, and methodology. The second chapter presents literature review. Chapter three present about cement production process. Chapter four present about thermal energy and raw material flow process in cement production. Chapter five about mass and energy balance of clinker material. Chapter six present about results and discussions. Chapter seven study about area of waste energy and ways of improvement. Chapter eight study about economic analysis of Mugher cement factory on waste heat. Finally chapter nine contains the drawn conclusions and recommendations of the thesis.

CHAPTER TWO

LITERATURE REVIEW

2.1 Energy consumption in cements plant

In terms of total energy consumption, the cement industry occupies a top position in the ranks of energy consumed industries *(Moustafa, 2012).* The total energy costs (thermal and electrical energy) make up about 30 to 40 % of the total production costs of cement. This is why efficient energy utilization has always been a matter of priority in the cement industry *(Mogens et al., 1983).* The energy sources in a cement plant are classified as primary sources, like fuel oil, coal, natural gas and electricity. The two most energy-intensive processes in cement manufacture are pyro-processing and grinding. Pyro-processing consumes thermal energy in the form of fuel oil, coal or natural gas combustion, while grinding consumes electrical energy. Figure 2.1 shows energy distribution in the cement plant for both thermal and electrical energy.

I) Electrical energy: The major electrical energy consumption areas in cement factory are raw mill drives, rotary kiln drive, cooler lane drive, belt drive, fans and conveying systems, crushing, cement grinding, packing, pump, light and welding process. Electrical energy consumption rise significantly for dry cement kin. Average electrical energy consumption is approximately 110-120 kWh/ton in cement plant, shown in Table 2.1

Table 2.1 Specific electrical energy consumptions by cement plant *(Philip, 2001)*

Section/Equipment	***Electrical energy consumption (kWh/ton)***	***Share (%)***
Quarrying and pre blending	6	5
Raw milling	28	24
Blending	7	6
Burning and cooling	25	22
Finish milling	44	38
Conveying, packing and loading	6	5
Total	**116**	**100**

II) Thermal Energy: Fuels such as coal and heavy fuel oil (HFO) are used in the cement plant as a source of thermal energy. The major use of thermal energy is in the kiln and pre calciner is used for pre heating and burning raw material (limestone + clay) for clinker formation. Clinker is formed at a temperature of minimum 1450 ^{0}C in a rotary kiln. Phase change from solid to liquid by heating of raw material feed to rotary kiln from pr-heater is occurred for produce quality clinker. Now a day's Mugher cement factory used bituminous coal after a year of 2017 as thermal energy source.

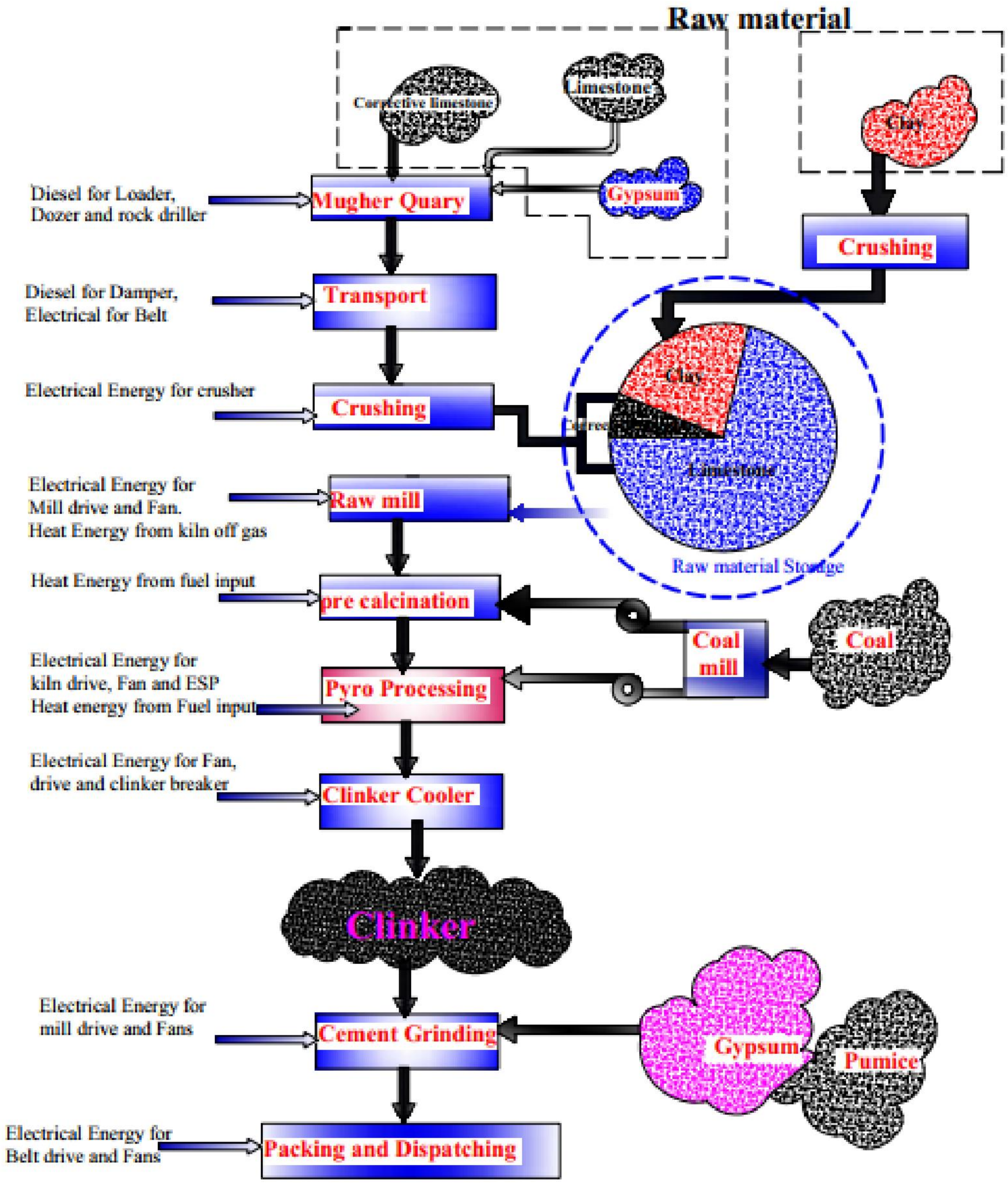


Figure 2.1 Electrical and Thermal energy flow in cement production process

2.2 Studies carried out in Ethiopian cement factory

The major energy use of cement factory is thermal energy which is obtained by burning coal. One measures of plant performance is its energy consumption compared to its design. In a cement plant the total energy generated from fuel is not fully used for clinker production, some of them waste from the system through different section. The following authors studied energy audit and thermal evaluation at some of Ethiopian cement factory.

Feleke (2014) study energy audit in Mugher cement factory, then the study shows thermal energy losses is higher and poor energy utilization. About 31 % of the heat is lost to surrounding which leaves the kiln system with clinker, cooler waste gases and pre-heater exhaust gases.

Tigist et al., (2015) carried out thermal energy audit and waste heat recover on 3000 ton per a day of cement plant, then their result shows that 25.23 % of the total heat input is released to the environment through the pre-heater and another 15.58 % waste through the cooler exhausts. The west heat recovery system (WHRS) can generate a gross power of 5.258 MW as long as the kiln is in operation.

Gebreslassie et al.,(2018) studied energy auditing performance in Messobo Cement Factory to quantify the energy losses in the system and to identify potential areas for improvement. Based on their energy analysis performed, the most energy intensive process is found to be the burning system. They found plant specific heat consumption is 844.5kcal/kg-clinker, with around 45.83 % system efficiency. According to their study result, the major heat losses for the processes occurred in pre - heater exhaust gases and grate cooler vent air that accounted as 176.7 kcal /kg-clinker and 199.3kcal/kg-clinker respectively. With these considerations of heat loss, they estimate a theoretical power that can be harnessed from the pre-heater exhaust gas and the cooler vent is 14048.3 kW and 16172 kW, respectively.

2.3 International studies carried out on cement industries

Shaleen et al., (2002) conducted research on energy balance and cogeneration in a cement industry. They used the data recorded from plant in India with a production capacity of one million ton per annum. They found that about 35 % of the input energy was lost with the waste heat streams. A steam cycle was selected to recover heat from the streams using a waste heat recovery steam generator and they were estimated that about 4.4 MW of electricity could be generated.

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 in Turkey cement plant. Their study indicated that with an input heat of 3686 kJ/kg of clinker, which is 95.47 % for input heat, the energy utilized for clinkering was 1795kJ/kg-clinker with an efficiency of 48.7 % with almost 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 and radiation). For the heat loss through hot flue gas and cooler exhaust, a waste heat recovery steam generation system was proposed which recovered 1 MW energy.

Wang et al., (2013) stated that in a cement production plant, 85 % of total energy is consumed in a rotary kiln to produce the clinker. Due to convection and radiation effects on the external surface of the rotary kiln, the heat loss can reach up to 15 %. They have conducted an experimental study for a prototype rotary kiln and examined the influence of working conditions on the performance of the heat recovery unit. It is found that increasing the temperature of the working fluid tends to reduce heat losses through the ambient.

Ziya et al., (2010) developed a mathematical model to examine the performance of a heat recovery unit for the rotary kiln. It was found that 73 % of waste heat could be recovered with the proposed heat exchanger geometry and transferred to the working fluid. From their study specific thermal energy consumption in cement industries is found to be from 4 to 5 GJ/ton

Karamarkovic et al., (2013) studied in a magnesium production company, the heat losses from the rotary kiln and exhaust gases are 26.35 % and 18.95 % of the input energy, respectively. To reduce the heat loss, they have proposed an annular duct heat exchanger. The annular heat exchanger can reduce the fuel consumption of the kiln by 12 % and increases the energy and efficiency of the system by 7.53 %.

Ramesh et al., (2013) studied the specific thermal energy consumption in cement industries in India and the consumption varies from 2.95 to 4 GJ/ton of clinker. The higher specific energy consumption is due to the harder raw material and poor quality of fuel.

Rasul et al., (2005) conducted a research base data from Indonesian Portland cement plant. They presented a simple model to evaluate the thermal performance of the cement industry. The developed model was based on the mass and energy balance. The results obtained were that burning efficiency was 52.7 %, cooler efficiency was 45 %, and the heat recovery efficiency was

51.2 %. There was high heat loss at the cooler of 19 % and it is mostly due to convection and radiation.

Adem and Recep (2014) performed thermodynamic analysis of the kiln to achieve effective and efficient energy management scheme. The actual data taken from a cement plant located in Gaziantep, Turkey, are used in numerical calculations to obtain energy balance for the system. They calculated that 12.5 MW of energy is lost from the surface of the kiln which accounts for the 11.3 % of the total energy input to the unit. The specific energy consumption for clinker production is determined to be 3735.45 kJ/kg clinkers.

Kabir et al., (2010) analyzed a pyro-processing unit of a typical dry process cement plant. In order to enhance the energy performance of the unit, they considered conservation of heat losses from the system. Application of waste heat recovery steam generator and secondary kiln shell were suggested. They showed that power and thermal energy savings of 42.88 MWh per year and 5.30 MW can be achieved, respectively.

Atmaca et al., (2012) employed energy and exergy analysis on a pyro-processing unit in Turkey. They found that the rate of heat loss is reduced from 22.7 MW to 17.3 MW by the application of insulation to the system. They determined that 1056.7 kW of electricity can be generated by using the waste heat, and annual emission rates have been reduced by 8.2 %.

Madlool et al., (2011) reported that the specific energy consumption in cement production varies from technology to technology. The dry process uses more electrical but much less thermal energy than the wet process. In industrialized countries, primary energy consumption in a typical cement plant is up to 75 % fossil fuel and up to 25 % electrical energy using a dry process. Pyro-processing requires the major share of the total thermal energy use. This accounts for about 93 to 99 % of total fuel consumption. About 29 % of the expense is spent on energy, 27 % on raw materials, 32 % on labor and 12 % on depreciation in a cement industry. Therefore, cement industry is characterized by intensive industry throughout its production stages and the calcination of its raw materials.

Moustafa et al., (2012) reported the share of energy consumed in a cement clinker kiln plant attains 70 to 78 % of the overall energy consumed in the process of cement production as a whole. The residual (22 - 30 %) is the share of electrical energy. On the other hand, for the burning of the clinker kiln plant, thermal energy represents 92 – 96 % of the required energy and the electrical energy accounts for only 4 - 8 %. Therefore, potentials for reducing specific heat consumption in the kiln plant deserve priority

Tripathy et al., (1992) study shows that the efficiency of the clinker production was estimated to be 41.83 %. With a heat recovery system, the study showed that an estimated power of 1.14 MW could be generated with a simple payback period of 48 months.

Caputo et al., (2011) studied on performance modeling of radiant heat recover, the external surface of the kiln easily reaches temperatures of the order of 400 ^{0}C and owing to the large size of these kilns (the length may exceed 250 m, and diameter 4 to 6 m), heat losses from the surface are very high which is about 8-15 % of the total heat input.

Prasanth and Sudhakar, (2016) studied on analysis of heat lost from cement kiln by energy balance method. Their result shows that a major heat loss occurred is kiln exhaust gas 19.15 %, hot air from cooler stack 5.61% and radiation from kiln shell surfaces is 10.47 %. These results indicate that the presence of waste heat, which is 51 % of the overall heat of the process.

Stanley et al. (2017) studied on plant production capacity of 1700 tons of clinker per day. The average specific power consumption of the case study plant was 111 kWh/ton of cement with an average peak demand of 9.7 MW. According to their research evaluation the potential that the plant has generating electrical power from the hot waste gases vented into the atmosphere is 3.4 MWh. This results to a net potential to generate 2.89 MWh of electrical power after factoring in the auxiliary power consumption by waste heat recovery plant system at 15%. This ultimately gave a reduction of 33 % in the electricity power bill of the case study plant. In their study they use steam rankine cycle for the power generating and the plant installation simple payback period is 2.7 years.

Ahmet et al., (2016) reported that energy efficiency of a cement production process is quite small due to large amounts of heat loss from the systems. Rotary kilns widely used in the cement industry to produce clinker. The surface temperature of rotary kiln reaches up to 300 ^{0}C. In their study, considering the higher temperature difference and higher surface area of the rotary kiln with dimensions of 4.8 m diameter and 70 m length, then if heat losses to environment become recovered the is possible to generate electric power up to 350 kW.

2.4 Conclusion from literature review

The following conclusions are drawn from the literature reviewed:

- Cement plant is the most energy intensive industry on the world.
- Mass and energy balance models are developed to determine the thermal performance of cement plant system.
- The waste heat from cement plant is occurred on kiln surface, hot flue gas from pre-heater and clinker cooler by large mass.
- The specific fuel consumption in clinker production is used as an important energy performance indication in cement plant.
- Thermal energy consumption is much higher than electricity consumption in cement industries and thermal efficiency of the plant is less than 55%.
- Waste heat recovered from a cement plant can reduce energy consumption.

2.5 Research gap

The following research gaps are identified for carrying out the present study.

- No detail energy consumption and performance study was conducted at Mugher cement factory after the factory shifts its energy source from heavy fuel oil to bituminous coal.
- The waste heat from the surface of pre-heater, pre-calciner, tertiary air duct and kiln shell is considered as uncountable heat loss without true value.

This paper work is proposed to identify the potential thermal energy loss areas, to analyze the energy performance of factory and adapt a mechanism that makes possible energy saving.

CHAPTER THREE

MUGHER CEMENT MANUFACTURING PROCESS OVER-VIEW

3.1 Introduction to cement

Cement is considered one of the most important building materials around the world. Cement is a binder, a substance used for construction that sets, hardens, and adheres to other materials to bind them together. Cement is produced from clinker and gypsum or pumice by mixing and grinding them. Clinker manufacturing is a blending of raw material like limestone, sandstone and clay in different proportion by mechanical and thermal energy process (*Ahmet, 2015).*

3.2 Mugher cement factory manufacturing flow

Mugher cement production process flow (From raw material to final product) is discussed from section **A to N**.

A) Raw material

The location area of Mugher cement plant has a deposit of Limestone, Clay, Gypsum and Sand stone (Corrective Limestone). The raw material deposit location of limestone, clay, sand stone and gypsum are found at 3 km, 1 km, 5 km and 12 km distance from the factory respectively and transported from Quarry by truck to the crusher and by belt conveying from crusher to raw material storage after size reduction. Pumice or a volcanic ash is a cement raw material found to the west of a great rift valley at a place called Derba Arrerti and Koka which are 165 km and 200 km respectively from the plant and transported to the factory by trucks.

B) Hammer Crusher

Except pumice other raw materials from quarry is feed to a hammer crusher after brought from quarry by truck for size reduction. Two type of hammer crusher: double hammer crusher and single hammer crusher are used for reduce the size of mines or raw material at a range of 25 mm to 75 mm size. Reduced material is transported to store by a belt conveyer. The crushed limestone is stored in the stockpile through stacker conveyors.

C) Raw material storage room

The raw material transported from crusher is stored in storage room for few days to remove moisture from the raw material.

D) Proportioning

Limestone, sandstone (corrective lime stone) and clay are mixed in proportion at the required quantity for the quality of clinker product and type of cement produced. Corrective limestone added to the material when the limestone quality is low. Raw material exit from proportioning is transported to raw mill by belt convening. The mass balance of raw material is controlled by belt speed mechanism.

E) Raw Mill

Raw mill is a machine used for grinding raw material. Material size reduction is completed and fine material is sucking by Induced Draft (ID) Fan to raw mill silo. Two types of raw mill are there: horizontal and vertical raw mill. Both of them have the same purpose for size reduction and derived by electrical energy but with different model and capacity. Both type of raw mill is found in Mugher cement plants, which have a capacity of 60 to 300 TPH. Raw mill involves mixing the extracted raw materials to obtain the correct chemical configuration, and grinding them to achieve the proper particle size to ensure optimal fuel efficiency in the kiln and strength in the final cement product. To remove the moisture content from raw material during grinding hot gas from pre heater is used. Raw material moisture at inlet and outlet is approximately 4% and ≤1% respectively. Storage silos are used to store the raw material after output from the mill. Process flow diagram of cement production is described in Figure 3.2 from raw material to the final product.

F) Coal Mill

Coal is the source of thermal energy for cement factory. The coal that is to be burnt in the kiln and pre-calciner section is dry and finely grinds by coal mill. While entering to the coal mill the moisture content in the coal is around 15% whereas it becomes 2% at the outlet. Hot flue gas exit from pre-heater is supplied by duct to coal mill for moisture remove during grinding. After grind it stored in storage silos of coal. The fined coal is feed to rotary kiln and pre-calciner burner.

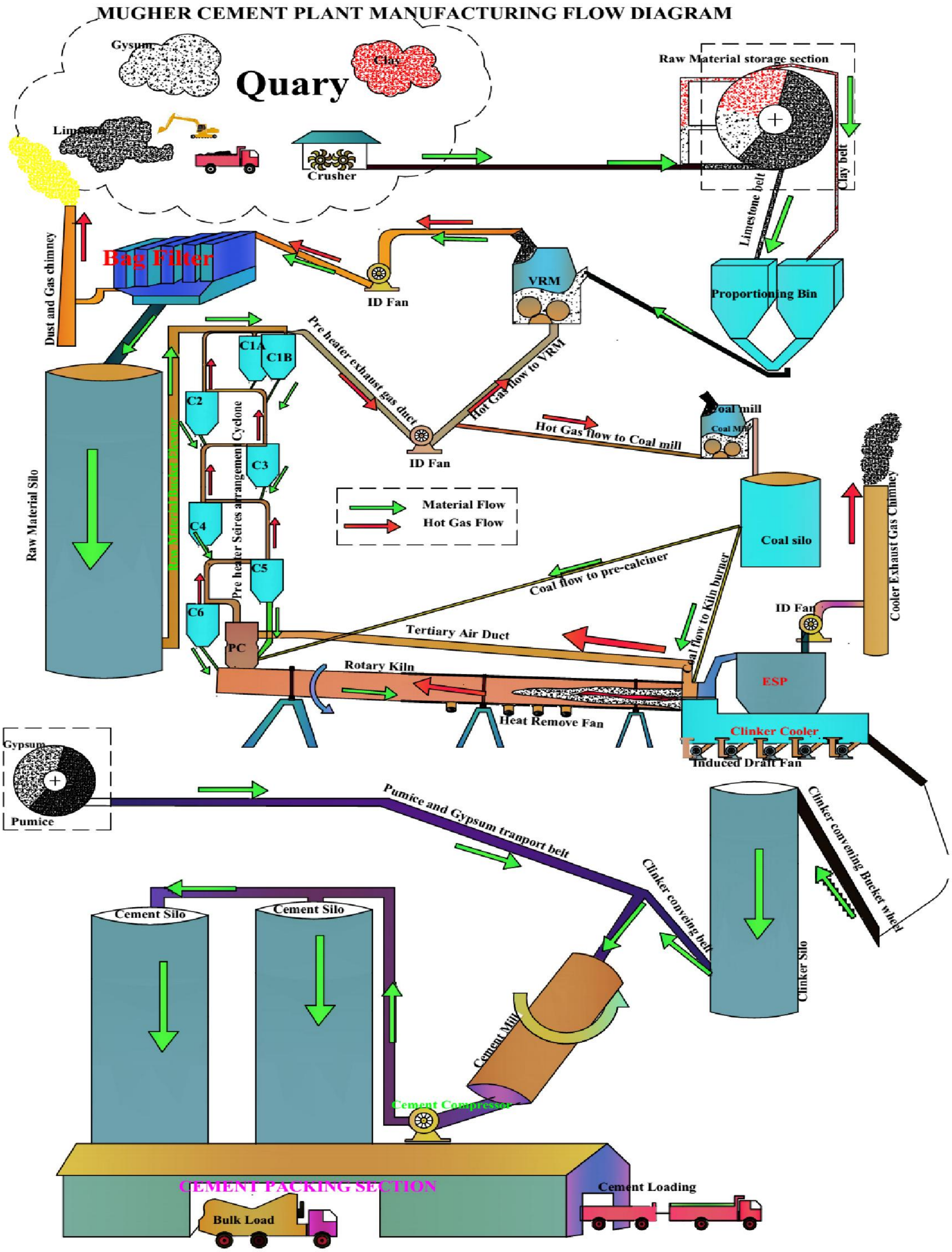


Figure 3.1 Process flow diagram of the Mugher cement plant

G) Pre-heater

Blended raw materials from silo is feed into the upper end of the pre heater tower and then passed through the end of the rotary Kiln. The pre-heater tower is constructed from a series of counter current flow cyclones. The hot gas is flow from rotary kiln to upper pre-heater. Heat exchange is occurred between material flow and hot gas. So when the materials pass through the cyclone the temperature of raw material is increased from first cyclone to the bottom cyclone.

H) Pre-calciner

The latest pre-heater towers contain a combustion chamber. This chamber is commonly known as pre-calciner. After material combusted in pre-calciner they feed to the rotary kiln inlet hood. In pre heater rotary kiln the feed enters the rotary kiln approximately 30 – 40 % calcined where as in the pre-calciner kiln this feed can be up to 90 % calcined *(Philip, 2001).*

I) Rotary Kiln

Rotary kiln is a cylindrical body used for burning raw material of Limestone and Clay mixed feed from top of pre-heater. Rotary kiln position is 3.5 degree inclined from horizontal plane or surface. Mugher cement rotary kiln is 66 m long with diameters ranging of 4.4 m. Refractory bricks are used to cover its internal surfaces to prevent heat transfer. The Kiln is slowly rotated with about 1 to 4 RPM, and the raw material is tumbled through increasingly hotter zones. Maximum combustion is take place and the raw material will be melt and combined together to form a clinker. The clinker is discharged as red hot from the end of the rotary kiln and passed through clinker coolers. Hot clinker is transported through clinker cooler by lane movement. There are different types of rotary kiln depends on their size and capacity. The size and the capacity of the rotary kiln are determining their thermal energy consumption. Each of them can be shown in Table 3.1

Table 3.1 Specific fuel consumption with different types of rotary kiln *(Philip, 2001)*

Type of Kiln	*Maximum capacity(TPD)*	*Specific fuel(kcal/kg)*	*Length: Diameter*
Shaft kiln	200	900-1000	__
Long wet kiln	2,000	1200-1500	32-38
Long dry kiln	2,000	900-1200	32-38
Pre-heater kiln	2,000	800- 900	14-16
Pre-calciner kiln	11,000	700-850	11-16

Figure 3.2 Photograph of rotary kiln

J) Clinker

Clinker is obtained when the raw material is feed in to rotary kiln and burned by air and coal at a temperature of 1350 to 1500 ^{0}C. Clinker is a coarse-grained material composed of clay and limestone. Clinker is the principal ingredient in cement production and is a mixture of approximately 80 % limestone and 20 % clay ***(Lafarge, 2008).*** To make cement, clinker is mixed with gypsum and pumice at a percentage of 3 to 6 by weight (*Ahmet, 2015).*

K) Clinker Cooler

In order to produce the quality cement and conveyors, the clinker inlet from rotary kiln hood has cooled to 70 -100 ^{0}C. Mugher cement factory use ETA clinker cooler. ETA cooler is also kwon as Great cooler and it have a shape of rectangular. In clinker cooler the process of cooling is taking place with the help of ambient air supplied by cooler fans to recover the thermal energy from clinker. After taking heat from clinker partial part of hot air is supplied into kiln as secondary air for complete combustion and partial part is supplied to pre-calciner as tertiary air and remaining will be vent through Electro Static Precipitator (ESP). Eleven Induced Draft fans are used for air supplying to clinker cooler. Cooled clinker is conveyed by Bucket wheel and stored in clinker silo for cement production.

L) Air supply Induced Draft Fan (ID Fan)

ID Fan are cooling air fans located in front entrance of the cooler, whose operating pressure, is used as reference value for the control of the speed for the lanes. There are eleven fans are there. Five fans sited in one side and six fans are sited in another side.

M) Cement Mill

This is the final stage in the process of cement making. To make cement the pyro-process product clinker is mixed with a raw material of Pumice and Gypsum according to type of cement produced. The mixture of clinker, pumice and gypsum is ground in a Cement mill. The output product of the mill is called Cement. After final milling, the product is sent to cement storage silos, where it is stored and supply to the customer. Two type of cement is produced at Mugher cement factory depending on quantity of clinker and additive raw material. Those two types are

1. Pozzalana Portland Cement (PPC)

PPC cement is contains 65 % clinker, 30 % pumice and 5 % gypsum. PPC type cement is used for simple construction.

2. Ordinary Portland cement (OPC)

OPC cement is contains 95 % clinker and 5 % of gypsum. OPC type cement is used for special construction like bridge, high way, big tower…etc. The price of OPC is higher than the PPC because of high clinker content, which is related to thermal energy consumption for clinker production. Therefore a type of cement produced is determining the thermal energy consumption of the plant because they depend up on clinker percentage. Cement is the composed of different compounds as shown in Table 3.2

Table 3.2 Composition of dry cement manufacturing process (*Madlool et al., 2011*)

Compounds	Composition (%)
CaO	65 ± 3
SiO_2	21 ± 2
Al_2O_3	5 ± 1.5
Fe_2O_3	3 ± 1

N) Cement loading

To supply product for the customer cement is loaded in 50 kg bags packed and by bulk loading truck.

CHAPTER FOUR

THERMAL ENERGY AND RAW MATERIAL FLOW PROCESS IN CEMENT PRODUCTION

Thermal energy flow process in cement plant takes place from vertical raw mill to clinker cooler outlet. At raw mill the heat needed to remove moisture and at cooler outlet heat is recovered by cooling from clinker.

4.1 Vertical raw mill

Thermal energy is used in raw mill is to dry a material before feed in to grinding table. The moisture content of raw material can affect plant performance through fuel consumption. If the moisture content of material feed in to rotary kiln is high, it requires high amount of fuel burned to increase sensibility of the raw material. The hot gas exhaust from pre-heater cyclone is flow to vertical roller mill by Induced draft Fan to dry the material (Figure 4.1). Hot gas flow from pre-heater temperature riches up to 350 ^{0}C. The heat requirement to dry a material is depend up on material flow rate, capacity of raw mill and moisture content of material.

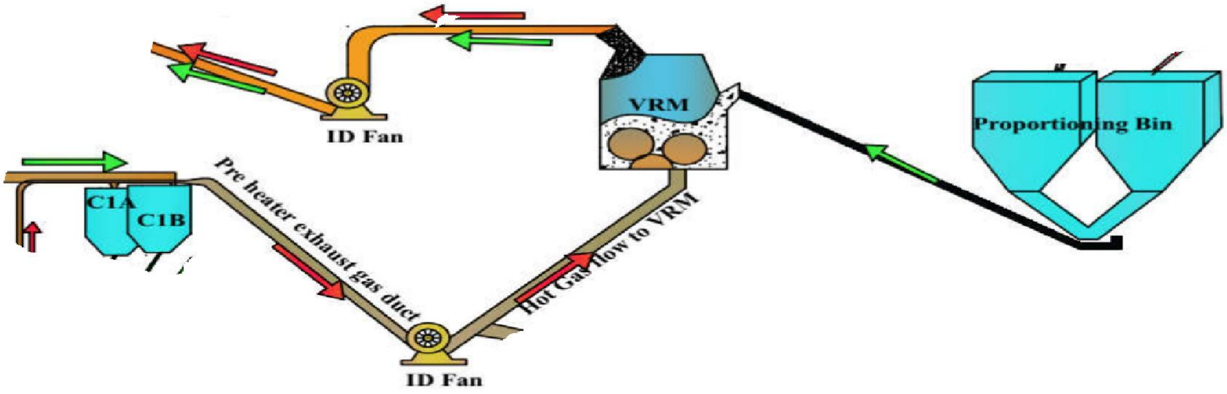


Figure 4.1 Hot gas flow to vertical raw mill to dry material feed.

Capacity of raw mill measured in a unit ton per day or per hour (TPD or TPH), however some time it relates to capacity of clinker production of plant. Hot gas exhaust from pre-heater is related to clinker production so heat content of flue gas is depend on energy generated in rotary kiln and gas flow. The capacity of VRM is obtained by **equation 4.1.**

$$M_{VRM} = M_{Clinker} \text{ x } RMF \text{ x } \frac{24}{Op.hr} \quad (4.1)$$

Where: M_{VRM} – Capacity of vertical raw mill (kg-raw material/kg-clinker)

$M_{Clinker}$ – Clinker produced (TPH or TPD)

RMF – Raw mill to clinker factor

Op. hr – Working hour of raw mill per a day

24 - Total hour of a day

Raw mill factor is the ratio of raw material feed to rotary kiln to fine clinker produced, which have a constant value of 1.57 at Mugher cement factory. Moisture content of material is varying every season. Mugher cement plant material moisture content by weight is 4% in average. To determine moisture content of a raw material equation 4.2 is made.

$$\dot{M}_M = \frac{\dot{M}_{VRM} \text{ x } (\dot{W}_{RM}\%)}{(\dot{W}_{RM} - \dot{W}_M)\%} - \dot{M}_{VRM} \quad (4.2)$$

Where: $\dot{M}_M$ – Mass of moisture content (kg of moisture per hour or day)

$\dot{W}_{RM}$ – Weight of raw material in percentage, assuming as 100 %

$\dot{W}_M$ – Weight of moisture in raw material by percentage

Heat required to remove the moisture before feeding to grinding table of vertical raw mill can be calculated by rearranging equation 4.1 and 4.2

$$Q_{VRM} = \dot{M}_M \text{ x } \dot{H} \quad (4.3)$$

Where: Q_{VRM} – Heat requirement for vertical raw mill (kJ/kg-clinker)

$\dot{H}$ - Heat of moisture removes (3980.5kJ/kg-moisture)

4.2 Thermal energy on pre-heater cyclone

Pre-heaters are used in cement production plants to pre heat the raw mix by moisture remove before it is feed into the kiln. Raw material is feed to rotary kiln from the top of pre-heater first cyclone. During feeding the temperature of raw material from silo is around 70 ^{0}C *(Central Control Room).*

Preheating cyclones: Cyclones are conical vessels that tangentially intake the raw mix producing a vortex. Hot pre-heater waste gases are also removed through a bypass. Removal of this gas allows higher specific energy consumption. The sensible heat of this waste gas is a source of energy loss; although the cyclones minimize this loss by efficiently cooling the gas. When raw material is feed in to top of pre-heater cyclone, heat exchange occurred with hot gas. Flow direction of hot gas and raw material is countercurrent. The hot gas flow from rotary kiln to first cyclone of pre-heater temperature is 350 to 900 ^{0}C which have high sensible heat.

4.3 Heat transfer Analysis in Rotary kiln

4.3.1 Heat transfer in side rotary kiln

The main purpose of burning fuel in rotary kiln and pre-calciner is heating the raw material for clinker formation. Heat generated in the rotary kiln is transferred from the flame to the material flow in to kiln. The heat transfer plays an essential role in the system. Since there is a temperature difference between two parts of a system, the heat will be transferred from burner flame to raw material to occur heat exchange.

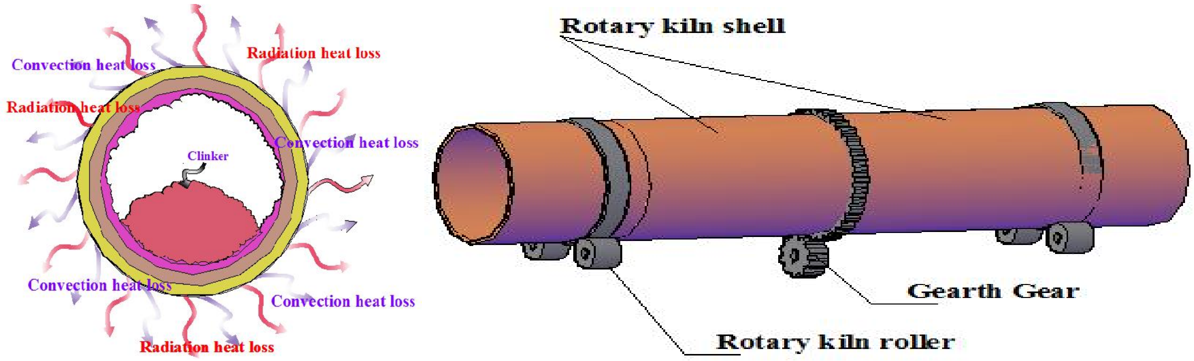


Figure 4.2 Rotary kiln shell and surface heat

Three modes of heat transfer take place in rotary kiln (*Philip, 2001*). Those heat transfer modes in a rotary kiln are

1. Conduction: The raw material on a burning process is direct contacting with the bed of the rotary kiln, and then the heat is transferred by conduction from material to kiln bed. Equation 4.4 is used to find conduction heat equation of the process.

$$Q_{cd} = \frac{K * A * \Delta T}{x} \ldots\ldots\ldots\ldots (4.4)$$

Where: Q_{cd} - Heat transfer by conduction (W)

K - Thermal conductivity of material (W/m/^{0}C)

A - Area occupied by material (m^2)

ΔT - Temperature difference between material and kiln bed (^{0}C)

x - Thickness of material (m)

2. Convection: The secondary air of hot gas from cooler is recovering heat from the clinker then transfer heat to the material by convection heat transfer mode.

$$Q_{cv} = h * A * \Delta T \ldots\ldots\ldots\ldots (4.5)$$

Where: Q_{cv} - Heat transfer by convection (W)

h - Convective heat transfer coefficient (W/m^2/^{0}C)

3. Radiation: The heat of flame is transferred to the wall of rotary kiln and raw material by radiation heat transfer mode.

$Q_{Rd} = \varepsilon * \sigma * A * (T^4 - T_S^4)$……………………….………………………….……… (4.6)

Where: Q_{Rd}- Heat transfer by radiation (W)

ε - Emissivity of material

σ- Stefan Boltzmann radiation constant (5.67×10^{-8} W/m^2/K^4)

T – Temperature of hot surface

T_S – Temperature of low surface

4.3.2 Heat transfer to outside surface of rotary kiln

Since the temperature difference is occurred between outside and inside of rotary kiln heat is transfer from internal to external. To analyze the heat transfer between internal temperature of the rotary kiln and its surrounds the following assumption is made:

- The system is one dimensional and composite structure of cylindrical
- Three modes of heat transfer are occurred.
- Rotary kiln assumed as a control volume

Composite of rotary kiln includes clinker material, Refractory material (Bricks) for insulation and steel wall (shell). Figure 4.3 shows composite and thermal resistance network system of a rotary kiln.

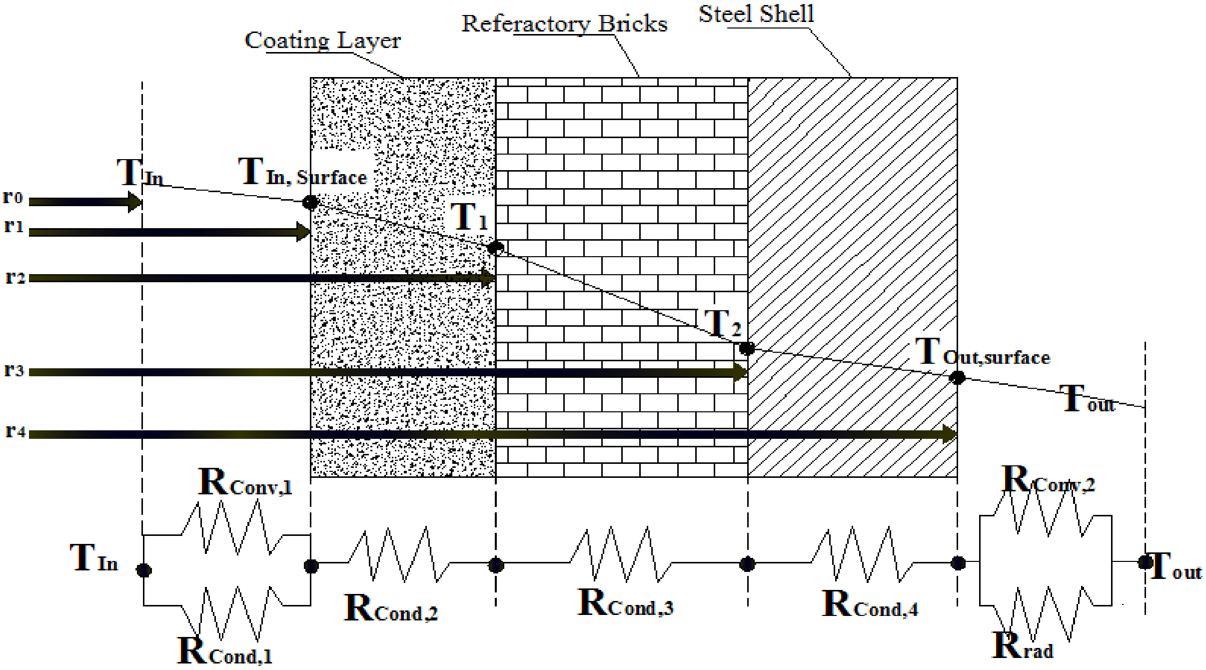


Figure 4.3 Structure and thermal resistance network of rotary kiln

The rate of heat transfer between the heat of inside rotary kiln system and its surroundings is calculated by equations 4.7:

$$Q_{total} = \frac{T_{In}-T_{Out}}{R_{total}} \quad (4.7)$$

Where: Q_{total} – Rate of heat transfer

R_{total} - Total thermal resistance of the system

T_{In} – Internal temperature (Inside rotary kiln)

T_{Out} – Outside temperature (Ambient temperature)

A total thermal resistance is summation of all convective, conductive and radiation thermal resistance and each of resistance thermal networks is show on Figure 4.3. Each of thermal resistance is calculated by equation ***4.8a** to **4.8p***.

1. Heat transfer from Clinker material motion inside rotary kiln to coating layer by convection and conduction

A) Heat transfer from clinker material to coating layer by convection:

Hot flue gases from clinker cooler and burner flame is in the opposite direction of material, against the inclination of the rotary kiln. Clinker material move by rotary motion and gravity from inlet to outlet of the rotary kiln and thermal resistance for heat transfer is formulated as:

$$R_{conv,1} = \frac{1}{2*\pi*r_1*L_1*h_1} \quad (4.8a)$$

Where: $R_{conv,1}$ – Convective thermal resistance of clinker material

r_1 – Internal radius from center of rotary kiln to coating surface

L_1, L_2, L_3, L_4 – Length of rotary kiln for all equation of 4.8a to 4.8n

h_1 – Convective heat transfer of material

B) Heat transfer through clinker material sliding in rotary kiln by conduction.

Clinker material is sliding inside a rotary kiln for transporting and calcinations process. During this process the heat of material is transferred to coating material on a rotary kiln by conduction form and thermal resistance is calculated:

$$R_{cond,1} = \frac{1}{2*\pi*L_1*K_1}*\ln\frac{r_1}{r_0} \quad (4.8b)$$

Where: $R_{cond,1}$ – Conductive thermal resistance of clinker material

K_1 – Thermal conductivity of clinker material

r_1 – Internal radius from center of rotary kiln to coating (r_0 + material thickness)

r_0 - Internal radius from center of rotary kiln to material sliding on coating

2. Heat transfer through coating layer by conduction.

Coating is clinker material accumulated or stored on bed of rotary kin. Heat transfer rate take place by conduction form and thermal resistance is calculated:

$R_{cond,2} = \frac{1}{2*\pi*L_2*K_2}*\ln\frac{r_2}{r_1}$ ………………………………………………………………… (4.8c)

Where: $R_{cond,2}$ – Conductive thermal resistance of coating

K_2 – Thermal conductivity of coating

r_2 – Internal radius from center of rotary kiln to bricks (r_1 + coating thickness)

3. Heat transfer though Bricks by conduction

Refractory bricks insulated on kiln shell to reduce waste heat to environment and conductive thermal resistance is calculated:

$R_{cond,3}= \frac{1}{2*\pi*L_3*K_3}*\ln\frac{r_3}{r_2}$ ……………………………………………………………...….. (4.8d)

Where: $R_{cond,3}$ – Conductive thermal resistance of bricks

K_3 – Thermal conductivity of bricks

r_3 – Internal radius from center of rotary kiln to steel shell (r_2 + bricks thickness)

4. Heat transfer through kiln shell by conduction

Conductive thermal resistance of kiln shell is calculated as:

$R_{cond,4}= \frac{1}{2*\pi*L_4*K_4}*\ln\frac{r_4}{r_3}$ ………………………………………………………………… (4.8e)

Where: $R_{cond,4}$ – Conductive thermal resistance of steel shell

K_4 – Thermal conductivity of bricks

r_4 – Internal radius from center of rotary kiln to kiln shell (r_3 + steel shell thickness)

5. Heat transfer from kiln shell to ambient (environment) air by free and forced convection

A) The heat transfer from kiln shell to ambient air free is excluding a burner zone. Convective thermal resistance between kiln shell and ambient air is calculated as:

$R_{conv,2}= \frac{1}{2*\pi*r_5*L_4*h_2}$ ………………………………………………………………… (4.8f)

Where: $R_{conv,2}$ – Convective thermal resistance from steel shell to ambient air

r_5 – Internal radius from center of rotary kiln to ambient air (r_4 + boundary thickness)

h_2 – Convective heat transfer of ambient air and calculated from Nussalt number and thermal conductivity of air

$$h = \frac{Nu*K}{D} \quad \text{(4.8g)}$$

Where: D – Hydraulic diameter of rotary kiln

K – Thermal conductivity of air

N_U – Nussalt number,

The average Nusselt number correlation for free convection occurred on cross flow cylinder is proposed by Churchill and Bernstein:

$$Nu = \left\{0.6 + \frac{0.387*Ra^{1/6}}{\left[1+\left(\frac{0.559}{Pr}\right)^{9/16}\right]^{8/27}}\right\}^2 \quad \text{(4.8h)}$$

$$Ra = Gr * Pr = \frac{g*\beta*\Delta T*L_C{}^3}{\nu^2} * Pr \quad \text{(4.8i)}$$

$$Gr = \frac{g*\beta*\Delta T*L_C{}^3}{\nu^2} \quad \text{(4.8j)}$$

Where: Ra - Rayleigh number

Gr - Grashof number

g - Gravitational acceleration, m/s^2

T_s - Temperature of the surface, ˚C

T_a - Temperature of the air sufficiently far from the surface, ˚C

ν -Kinematic viscosity of the fluid, m^2/s

β - Coefficient of volume expansion, 1/K

$$\beta = \frac{1}{\frac{T_s + T_a}{2}} \quad \text{(4.8k)}$$

$$Pr = \frac{\nu}{\alpha} = \frac{\mu*Cp}{K} \quad \text{(4.8l)}$$

Where: Pr - Prandtl number

α - Thermal diffusivity

Cp – Specific heat

μ -Dynamic viscosity of air

B) The heat transfer from kiln shell to ambient air by forced convection is the region of burner (Burner zone). In this zone air flow by cooling fan is applied to remove heat on a rotary kiln shell. Convective heat transfer coefficient can be calculated by:

$h = \frac{NU*K}{D}$……………………………………………………………*Nu, for forced convective*

The average Nusselt number correlation of forced convection for cross flow over a cylinder is proposed by Churchill and Bernstein:

$$Nu = \frac{h*D}{K} = 0.3 + \frac{0.62*Re^{1/2}*Pr^{1/3}}{\left[1+\left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}}*\left[1+\left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5} \quad \text{(4.8k)}$$

Where: Re - Reynolds number and calculated from equation 4.8m

$$Re = \frac{\rho_a*\mathcal{V}*D}{\mu} \quad \text{(4.8m)}$$

Where: ρ_a – Density of air

$\mathcal{V}$ - Flow rate of air by cooling fan of kiln shell

μ - Dynamic viscosity of air at mean temperature

D – Diameter of rotary kiln

6. Heat transfer from shell of rotary kiln to ambient air by radiation

$$R_{rad} = \frac{1}{2*\pi*r_5*L_4*h_{rad}} \quad \text{(4.8n)}$$

Where: R_{rad} – Radiation thermal resistance from steel shell to ambient air

h_{rad} – Radiation heat transfer of ambient air and calculated by:

$$h_{rad} = \sigma*\varepsilon*(T^2_{out,surface} + T^2_{out})(T_{out,surface} + T_{out}) \quad \text{(4.8o)}$$

Where: $T_{out,surface}$ – Temperature of outside rotary kiln shell (steel shell)

Then the total thermal resistance network of the system is:

$$R_{total} = R_{conv,1} + R_{cond,1} + R_{cond,2} + R_{cond,3} + R_{cond,4} + R_{conv,2} + \frac{R_{Conv,2}*R_{rad}}{R_{conv,2}+R_{rad}} \quad \text{(4.8p)}$$

4.3.3 Rotary kiln performance Evaluation

Heat loading of rotary kiln: is the amount of heat accumulated or generated in the kiln during burning of the fuel.

$$Q_{load} = \frac{\dot{m}_c * GCV}{\pi * (\frac{D}{2})^2} \quad \text{……………………………………………………………………………..…. (4.9)}$$

Where: Q_{load} - Heat loading of rotary kiln (kJ//m^2/hr)

$\dot{m}_{coal}$ - Coal feed rate to kiln (kg/hr

GCV - Gross Calorific Value of Coal (kJ/kg-coal)

D - Effective kiln diameter (m)

Material Retention Time in rotary Kiln: is the time taken of materials transported inside a rotary kiln from inlet to outlet. Material retention time is depending up on length, speed and slope of rotary kiln *(Philip, 2001).* Retention time of material can be calculated:

$$T_{ret} = \frac{1.77 * L * \sqrt{\theta}}{S * D * N} * F \quad \text{…………….……………………………………………………….…….….... (4.10)}$$

Where: T_{ret} - Material retention time (minute)

L - Kiln length (m)

Θ - Angle of response of material (degree) which is 36 to 40 degree.

F - Factors which is equal to 1, for constant rotary kiln diameter.

N - Kiln speed (RPM)

D - Effective diameter (m)

S - Slope, (degree)

Rotary Kiln effective Volume: is the total internal volume of a rotary kiln and calculated by:

$$V_{ef} = \frac{\pi * D^2 * L}{4} \quad \text{……………………………………….………………………………….... (4.11)}$$

Where: V_{ef} - Effective volume of rotary kiln (m^3)

Volumetric loading of kiln: Volume of kiln occupied by clinker per a day.

$$V_{Kiln} = \frac{Clinker\ production\ (TPD)}{V_{ef}} \quad \text{………………..………………………………..………… (4.12)}$$

Where: V_{ef} – Volumetric loading of kiln (TPD/m^3)

Rotary kiln percentage of filling: is a volume of a kiln which occupied by clinker material.

$$\Phi = \frac{3.2 * kilncapacity\ (TPD)}{D^3 * N * S} \quad \text{……………………………………….…………...………… (4.13)}$$

Where: ϕ - Percentage of filling (%)

D - Rotary kiln effective diameter (m)

Kiln speed

Kiln speed means rotation of kiln with respect to time in minute. Kiln speed is one of the mechanisms to control production quantity and coal consumption. Typically cyclone pre-heater kilns rotate at 2 - 2.5 rpm (50-70 cm/sec circumferential speed) and have material retention times of 20 – 40 minutes. Pre-calciner kilns rotate at 3.5 - 4.5 rpm (80 - l00 cm/sec) *(Philip, 2001)*

4.4 Nozzle

The shell loses large amounts of heat through radiation and convection. Additionally, air is pumped over the shell surface using nozzles on the burning zone side. This is done in order to cool the outer shell to create material build-up, which in turn protects the refractory used inside the kiln. The build-up is a consequence of the material melting at the high temperatures and cooling down against the surface. It is known that cooling of the kiln shell can increase the refractory's life time by up to two times that of refractory without cooling *(Duda, 1985).*

4.5 Burner

Energy is added to the system, through the direct firing burner located at the lower part of the rotary kiln and pre-calciner. Fuel flow from the burner ignites and burns with mixed air of secondary air from clinker cooler and primary air from ambient.

4.6 Coal analysis

Coal is a hydrocarbon which is used as thermal energy source for Mugher cement factory and imported from South Africa.

Bapat (2014), Coal is a combustible carbonaceous rock, containing many kinds of organic and inorganic material, formed from accumulated vegetable matter that has been altered by decay and various amounts of heat and pressure over millions of years.

Amy and Peter (2016), Coal provides 90 % of the energy consumed by cement plants around the world, despite the environmental harm caused by its combustion. It takes 200 – 450 kg of coal to produce one ton of cement. Quality of coal is determined by gross calorific value, ultimate and proximate analysis.

1. Ultimate analysis: Ultimate analysis of coal is the determination of coal composition from carbon, hydrogen, sulpher, nitrogen, ash and oxygen in different percentage.

Ultimate Analysis = %C + %H + %N + %S + %O = 100%.. (4.14)

Table 4.1 Ultimate analysis of bituminous coal composition *(Plant Laboratory)*

S/no	***Coal composition***	***Symbol***	***Composition by %***
1	Carbon	C	82.5
2	Hydrogen	H	4.3
3	Nitrogen	N	1.91
4	Sulfur	S	0.70
5	Oxygen	O	10.59
	Total		**100%**
	Gross calorific Value (kcal/kg)		**6465**

2. Proximate Analysis: Proximate analysis involves quantitative determination of coal composition as a percentage (%) of moisture, volatile matter, fixed carbon and ash in coal.

Proximate Analysis = % volatile matter + % fixed carbon + % ash + % moisture

Table 4.2 Proximate analysis of bituminous coal composition *(Plant Laboratory)*

S/no	***Coal composition***	***Symbol***	***Composition by %***
1	Volatile matter	Voli	25.99
2	Fixed carbon	FC	57.22
3	Ash	Ash	14.89
4	Moisture	Moist	1.9
	Total		**100%**

3. Gross calorific value (GCV): Gross calorific value is the heat evolved in its complete combustion under constant pressure at a temperature of 25 ^{0}C when all the water initially present as liquid in the fuel and that present in the combustion products are condensed to liquid state *(Philip, 2001).* Theoretical gross calorific value can be calculated by Dulong's formula:

$GCV = [80.8*\%C + 34.5*\% (H – O/8) + 22.4\%S]$ (kcal/kg)…………………………….…………….......... (4.15)

Specific heat capacity of coal: One of the basic parameters necessary to describe the accumulation element of a coal on energy equation is the specific heat capacity.

Bartosz et al., (2013) develop a correlation to determinate the specific heat capacity of coal as a function of the temperature and volatile matter content on dry, ash-free basis for $T_{coal} \leq 100^0C$

$C_{p,coal} = 1015.32 + 812.26*V^{daf}$ (J/kg/k)………………..…………..………..…..……………(4.16)

Where $C_{p,coal}$ - Specific heat capacity of coal at constant pressure in dry, ash basis,%

V^{daf} - Volatile matter content

Coal Firing: Coal firing for cement kilns is a direct firing involves grinding of coal and feeding directly to the burner. In kiln primary and secondary air is used as oxidizer. For pre-calciner primary and tertiary air is used as oxidizer. To complete combustion of coal in cement factory, the total primary air required is 15 to 30 % *(Philip, 2001).*

Combustion process of coal: Combustion of a coal is occurred when the oxygen in the air is brought into contact with the coal and if a sufficient temperature to start a burning is present. A combustion processes are takes place in the following stages:

Mixing → Ignition → Chemical Reaction → Diffusion of Products

Combustion analysis of coal: Calorific components of the coal burnt in cement rotary kilns are composed of hydrocarbons element such as: carbon (C), hydrogen (H), sulphur (S), nitrogen (N) and oxygen (O). When burnt in a cement kiln these hydrocarbons react chemically with oxygen provided by combustion air, releasing thermal energy to heat the rotary kiln and byproduct:

Fuel + oxygen → product + Heat

$$C + O_2 \longrightarrow CO_2$$

$$2H + 1/2O \longrightarrow H_2O$$

$$S + O_2 \longrightarrow SO_2$$

$$N + 1/2O_2 \longrightarrow NO$$

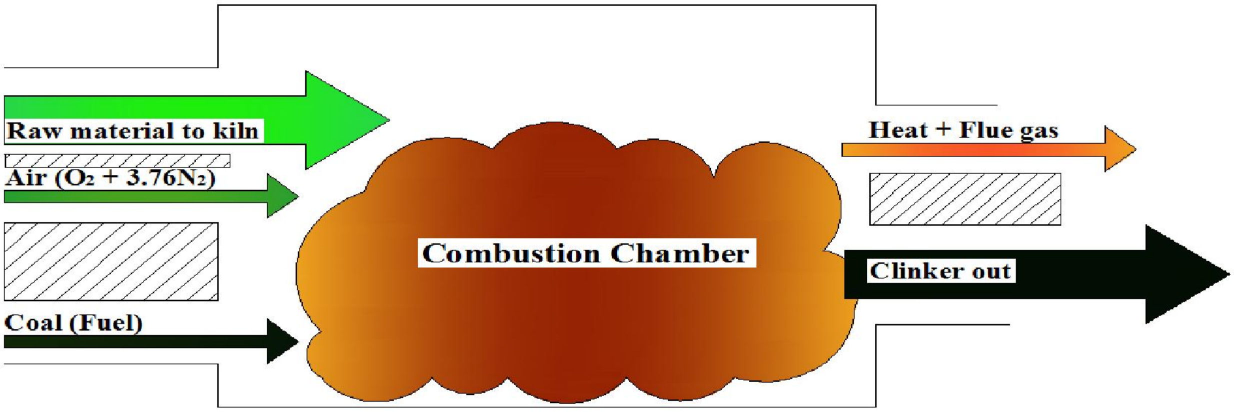


Figure 4.4 Combustion process

Burning Temperature of clinker material: To burn raw material at desired temperature equation 4.17 is developed *(Kurt, 1986)*

$T = 1300 + 4.51C_3S - 3.74C_3A - 12.64C_4AF$……………………………………………… (4.17)

Where: T - Temperature required to burn material

C_3S - 4.071CaO - 7.600SiO_2 - 6.718Al_2O_3 - 1.430Fe_2O_3 - 2.852SO_2

C_3A - 2.650Al_2O_3 -1.692Fe_2O_3

C_4AF - 3.043Fe_2O_3

Flame temperature:

$T_{flame} = \frac{HV}{1.11 * A_{combustion} * C_{p-gas}}$ ………………..…………………………………….…. (4.18)

Where: HV - $HeatingValueoffuel\ (kJ/kg)$

$A_{combustion}$ - $Combustionairrequired\left(\frac{kg-air}{kg-coal}\right)$

$C_{p\text{-}gas}$ – $specific\ heatofcombustiongas \approx 0.92$

From Dulong formula heating value of coal can calculated by:

HV = 145.44 *%C + 620.28 * %H +40.5 * %S – 77.54 * %O ……………………………. (4.19)

Theoretical combustion air requirement: Air is the composition of different gas, mostly nitrogen and oxygen. Oxygen is an oxidizer used for coal combustion and around 21% environmental air by weight is oxygen. To determine combustion air needed to burn a unit weight of coal equation (4.20) can be used when ultimate analysis is available. *(Kurt, 1986)*

$M_{combustion\ air} = (1 + \frac{E}{100})$ [0.11594%C + 0.34783 x (%H - %O/8) + 0.0438%S]……..…….. (4.20)

Where: $M_{combustion\ air}$ - Combustion air required (kg-air/kg-coal)

E - Percentage of excess air in coal (≈ 5%)

C - Percentage of carbon in coal

H - Percentage of hydrogen in coal

S - Percentage of sulpher in coal

O - Percentage of oxygen in coal

Product of combustion of coal: Product of coal combustion is heat and by-product like carbon dioxide, sulpher dioxide, water vapor, nitrogen dioxide and ash. Mathematically combustion product is determined by equation ***4.21a to 4.21e:***

CO_2 from coal = 0.0367 x %C ……………………………….……….…………….….. (4.21a)

SO_2 from coal = 0.02 x %S ………………….…………..………..………………….. (4.21b)

H_2O from coal = 0.09 x %H ………………………...……………………….…..... (4.21c)

N_2 from coal = $[\frac{\%N}{100} + 3.3478\,(0.0267\,x\,\%C + 0.01\,x\,\%S + 0.08\,x\,\%H - 0.01\,x\,\%O)]$ ……………………………………………………………………………………… (4.21d)

Subtotal = $[CO_2 + SO_2 + H_2O + N_2]$……………………………………………………… (4.21e)

Weight of combustion air required per clinker production: To determine weight of combustion air required per clinker production rate can calculated by equation 4.22, *(Kurte, 1986)*

$W_{\text{combustion air}} = M_{\text{clinker}}$ x SCC x $M_{\text{Combustion air}}$……………………………………………………… (4.22)

Where: $W_{\text{combustion air}}$ – Weight of combustion air (kg/hr)

M_{clinker} - Mass of clinker from Kiln output (kg-clinker/hr)

SCC – Specific coal consumption (kg-coal/kg-clinker)

$M_{\text{combustion air}}$ - Combustion air required (kg-air/kg-coal)

4.7 Amount of feed required to produce one ton of clinker

The result obtained here in does not include any dust losses. The assumption also made is that all the coal ash enters the clinker and none leaves the kiln with the exit gas. To get the total feed to produce one kilogram of clinker the following equation is developed, *(Peray, 1979):*

$M_{\text{Rawfeed}} = 0.01784 * CaO\% + 0.0209 * MgO\% + 0.0135 * Al_2O_3\% + 0.01075 * SiO_2\% + 0.01 * Fe_2O_3\%$……………………………………………………………………… (4.23a)

$M_{\text{feed}} = M_{\text{Rawfeed}} * (\frac{100-LOI}{100})$ ……………………………………………………………… (4.23b)

Where: $M_{\text{Raw feed}}$ - Mass percentage of raw material composition (kg-kg-clinker)

M_{feed} – Theoretical Raw material feed for 1kg of clinker production (kg-feed/kg-clinker)

LOI – Loss on ignition *(From limestone and clay)*

4.8 Clinker cooler heat transfer

The temperature of clinker coming out of the kiln hood is approximately 1400 ^{0}C and above. A grate cooler can be regarded as a simple heat exchanger through which the clinker passes across the cooling air flow and direct heat transfer takes place between hot clinker and cold cooling air. Ambient air is blown into the cooler by ID Fan to exchange heat between the hot clinker and ambient air. A desired maximum recuperation of heat from the clinker cooler use in the kiln system for specific quantities of secondary and tertiary air demands that these combustion air quantities drawn from the cooler have the highest possible temperature *(Raziuddin et al, 2013).*

Secondary air temperature: the temperature of secondary air is around 849 ^{0}C *(Central control room*). Maximizing secondary air temperature involves optimizing clinker bed depth and cooling air distribution to the recuperating zone. When clinker is exit from cooler the temperature is drop to approximately 90 to 65 ^{0}C according to design.

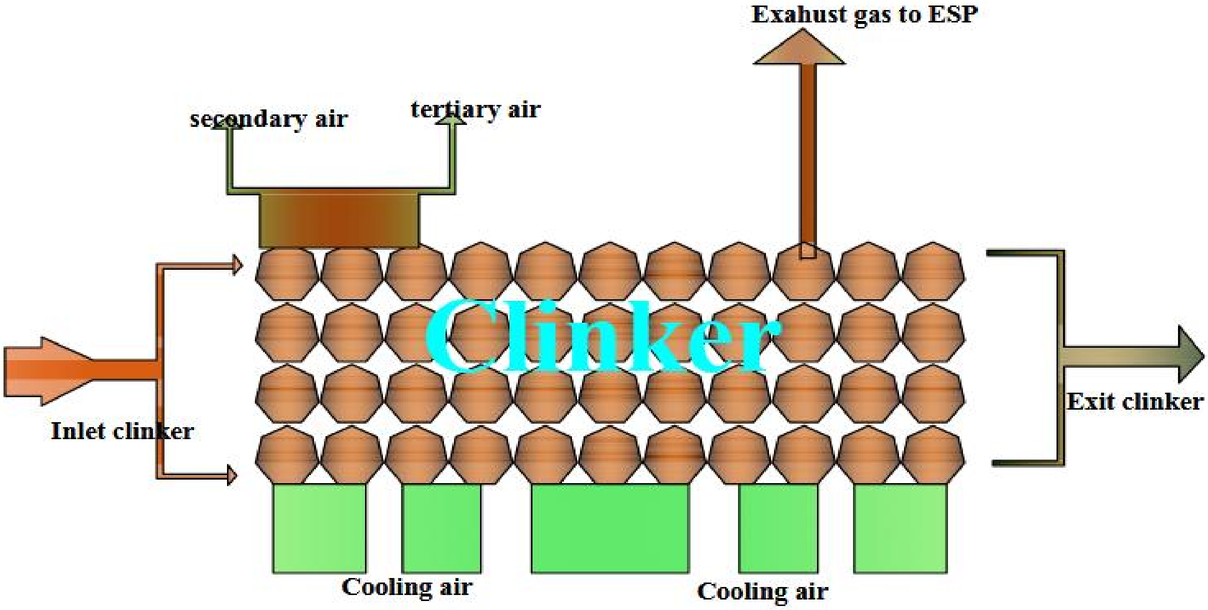


Figure 4.5 Clinker flow and heat transfer process in cooler

4.9 Specific energy consumption of cement plant

Specific energy consumption is the ratio of thermal energy generated by coal to clinker production.

$$SEC = \frac{Thermal\ Energy\ generated\ by\ Coal}{Clinker\ production} \quad \text{(4.26)}$$

Where: SEC – Specific energy consumption

For a cement plant the SEC is vary from process to process, clinker cooler and pre-heater technology.

CHAPTER FIVE

MASS AND ENERGY BALANCE OF CLINKER MATERIAL

5.1 Mass and volume of combustion product

Thermal energy consumption of rotary kiln is calculated from calorific value and specific coal consumed per clinker production of the plant. Specific coal consumption is the ratio of total coal consumed to total clinker production. Production capacity of plant is measured by ton per hour or ton per a day. Appendix Table 1.1shows data taken from plant which is production clinker and coal consumption for selective 15 day's per 24 hour plant fully operation.

$$\text{Specific coal consumed} = \frac{\text{Mass of coal consumed by pricalciner and Kiln burner (TPH)}}{\text{Total clinker production in TPH}} \quad \ldots\ldots\ldots\ldots\ldots (5.1)$$

Thermal energy generated by combustion of coal is a product of specific coal consumption and gross calorific value of coal. Therefore thermal energy generated from coal is calculated:

$$Q_{Coal} = SCC \text{ x } GCV \quad \ldots\ldots\ldots\ldots\ldots (5.2)$$

Where: Q_{Coal} – Thermal energy generated from coal (kJ/kg-clinker)

SCC – Specific coal consumption (kg-coal/kg-clinker)

GCV – Gross calorific value of coal (kJ/kg-coal)

Mass of coal combustion product per clinker:

Product of coal combustion is heat and by product like carbon dioxide, water as a form of vapor, sulpher dioxide and nitrogen. Mass of that byproduct is calculated from ultimate properties of a coal based on atomic and molecular weight. Mathematically coal combustion product on each is determined by ***equation 5.3a to 5.3e***:

$$CO_2 \text{ from coal} = 0.0367 \text{ x } \%C \text{ x Mass of SCC} \quad \ldots\ldots\ldots\ldots\ldots (5.3a)$$

$$SO_2 \text{ from coal} = 0.02 \text{ x } \%S \text{ x Mass of SCC} \quad \ldots\ldots\ldots\ldots\ldots (5.3b)$$

$$H_2O \text{ from coal} = 0.09 \text{ x} \%H \text{ x Mass of SCC} \quad \ldots\ldots\ldots\ldots\ldots (5.3c)$$

$$N_2 \text{ from coal} = [\frac{\%N}{100} + 3.3478\,(0.0267\,x\,\%C + 0.01\,x\,\%S + 0.08\,x\,\%H - 0.01\,x\,\%O)] \text{ x Mass of SCC} \quad \ldots\ldots\ldots\ldots\ldots (5.3d)$$

$$\text{Subtotal} = [CO_2 + SO_2 + H_2O + N_2] \quad \ldots\ldots\ldots\ldots\ldots (5.3e)$$

Where: SCC = Specific coal consumption.

Total kiln exhaust gas by mass per clinker production:

The total kiln exhaust gas per kg of clinker is the summation of CO_2 from limestone calcinations, coal combustion, moisture in the raw material feed and water vapor from coal combustion.

Balance equation of limestone calcinations process is:

$CaCO_3$ (solid) $\xrightarrow{\qquad\qquad}$ CaO (solid) + CO_2 (gas)……………………………...……… (5.4)

Where: $CaCO_3$ – Calcium carbonate as solid state

CaO – Calcium oxide as solid state

CO_2 – Carbon dioxide as gas state

To produce 1kg of clinker 1.57 kg of raw material is required according to plant design factor. Raw material composition of clinker is 80% calcium carbonate and 20% clay. So from clinker production mass ratio 1.256kg $CaCO_3$ and 0.31kg of clay is required to produce 1kg of clinker.

$$CaCO_3(s) \xrightarrow{\qquad\qquad} CaO\ (s) + CO_2\ (g)$$

$$100\ \text{gm /mol} \xrightarrow{\qquad\qquad} 56\ \text{gm /mol} + 44\ \text{gm/mol}$$

Mass of $CO_2 = 1.256 * 0.44 = 0.55$kg

Therefore mass of CO_2 from calcinations of calcium carbonate is 0.55 kg/kg-clinker and moisture content of raw material is 2 % then, the total exhaust gas from rotary kiln summarized by Table 5.1. The excess air of the plant is range from 3% to 7% (*Central Control Room),* and the value used for analyzing is 5% which is average. So mass of excess air can be calculated:

$$\text{Mass of excess Air (kg/kg-clinker)} = \frac{\%\ \text{Excess Oxygen x Combustion,Calcination}\ and\ Drying}{(\%\text{Oxygen in Air b} - \%\text{Excess Oxygen})} \quad \text{……..… (5.5)}$$

Table 5.1 Show total exhaust gas during combustion and calcinations process

Coal ultimate Analysis	***Combustion product***	***Calcinations***	***Total***
%C = 82.5	0.366 kg CO_2/kg-cl	0.55kg CO_2/kg-cl	0.919kg CO_2/kg-cl
%H = 4.3	0.047 kg H_2O/kg-cl	0.02 kg H_2O/kg-cl	0.067 kg H_2O/kg-cl
%S = 0.7	0.002 kg SO_2/kg-cl	0.00	0.002 kg SO_2/kg-cl
%N = 1.91	0.008 kg NO_2/kg-cl	0.00	0.008 kg NO_2/kg-cl
%O = 10.59	-0.0128kg O/kg-cl	0.00	0.0128kg O/kg-cl
%Excess air ≈5%	0.668kg-air/kg-cl	0.00	0.668kg-air/kg-cl
%N = from air	1.1376kgN_2/kg-cl	0.00	1.1376kgN_2/kg-cl
Subtotal (kg/kg-clinker)	***2.232***	***0.57***	***2.802***

kg-cl = kilogram of clinker

Volume of exhaust gas from rotary kiln: The gases exhaust from cement kiln can be considered to as Ideal gases within 0.1% accuracy *(Whitehopleman).* According to Avogadro's law of ideal gas one mole of each gas occupies 22.4 dm^3, (1kmol = 22.4 m^3). The volume of each component of the exhaust gas can be calculated:

$$V_{\text{total gas}} = V_{CO2} + V_{H2O} + V_{SO2} + V_{N2} + V_{O2} \qquad (5.6)$$

$$V_X = \frac{\text{Mass of exahust gas} * 22.4}{\text{Molecar weight of exahust gas}} \qquad (5.7)$$

Where: $V_{\text{toal gas}}$ – Total exhaust gas

V_X – Volume of each exhaust gas from kiln (CO_2, H_2O, SO_2, N_2, O_2)

Table 5.2 Summary of exhaust product by mass and volume

Product type	***Volume based***		***Mass based***	
	Nm^3/kg-clinker	**Nm^3/hr**	**Kg/kg-clinker**	**TPH**
Carbon dioxide	0.466	61065	0.919	120
Water vapor	0.0833	10916	0.067	9
Sulpher	0.0006	77	0.002	0.26
Nitrogen	0.004	524	0.008	1
Oxygen	0.0179	2346	0.0128	2
N_2 (Excess air)	1.33	174283	1.67	219
O_2 (Excess air)	0.098	128419	0.14	18
Total	**1.964**	**257362**	**2.804**	**369.26**

The data obtained from central control room of the plant shows that the total gas passes through pre-heater which includes byproduct of combustion process such as CO_2, H_2O (Vapor), NO_X, SO_X & O_X and air delivered from the system. From the content of exhaust gas, CO2 (15%), H_2O (3%), NO_X (0.15%), SO_X (0.01%) & O_X (0.6%) by volume. The other 80% is excess air which is delivered from input material.

5.2 Mass balance in VRM

Mass balance of VRM is includes input and output mass of hot gas, raw material feed to mill and fine product exit from VRM after grinding.

INPUT MASS = Mass of hot gas flow to VRM + Mass of raw material feed to VRM

OUTPUT MASS = Mass of Fine product exit from VRM

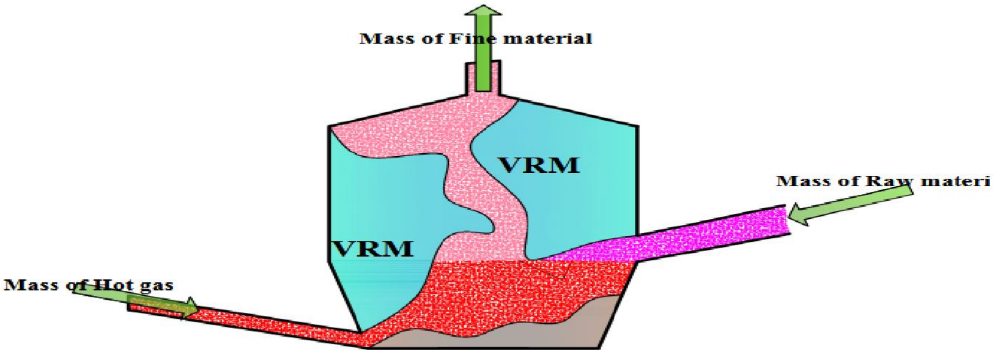


Figure 5.1 Mass balance of VRM

- Energy balance of VRM is include sensible heat of hot gas and sensible heat of raw material as input energy and sensible heat of fine product as heat of output energy.

5.3 Mass balance for clinker production

Mass balance of clinker material includes input mass (raw material feed, coal, primary air, clinker cooling air, coal coving air) and output mass (Clinker output, dust from pre-heater exhaust, exhaust gas from pre-heater and clinker cooler). Figure 5.2 shows mass of material entering to the system and leaving from the system.

Input mass (M_{In}) = Output mass (M_{Out})……………………...……..……………….……….... (5.8)

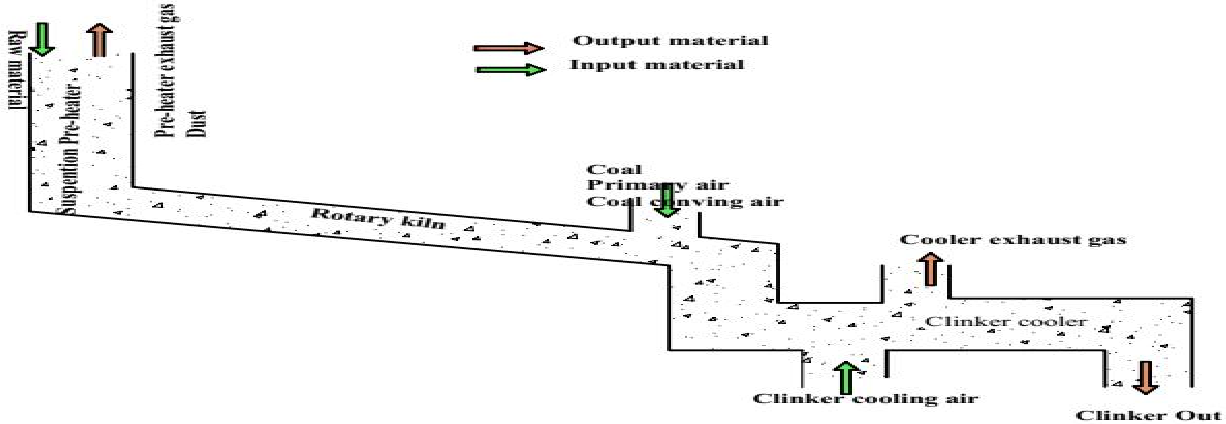


Figure 5.2 Input and out mass of the system

5.3.1 Input mass to a system

To analyze mass balance of clinker production the following assumption is made.

- Total mass of clinker is based on 1kg weight
- Mass of raw material feed to clinker factor is 1.57
- Primary air supply for combustion is 25 %
- Ambient temperature = 25 ^{0}C
- Density of all input air is the same

Input mass (M_{In})= Mass of feed material + mass of primary air + mass of coal + mass of coal convening air + mass of clinker cooler air + mass of moisture in feed………….………….….. (5.9)

1. Mass of feed material (M_{feed}): Is the total raw material feed to pre-heater for clinker production before calcinations process which is 1.57 constant factors. So 1.57 kg of raw material is required to produce 1 kg of clinker.

2. Mass of primary air ($M_{P,air}$): mass of primary is required 25 % by burner for complete combustion. The total mass of air for coal combustion is 1.405kg-air/kg-clinker.

3. Mass of coal (M_{Coal}): Is the required mass of coal to produce 1 kg of clinker. Mass of coal is equal to specific coal consumption.

4. Mass of coal convening air ($M_{con,air}$): Is a mass of air mixing with coal for transportation.

5. Mass of clinker cooling air ($M_{Cl,air}$): Air supplied to clinker cooler for clinker cooling at desired temperature. The air is compressed by eleven induced draft fan located at right and left side of grate cooler. The Volume of clinker cooling air flow to grate cooler is measured by portable installed gauge and the air flow rate value is direct taken from gauge. The flow rate unit is indicated on gauge by normal meter cube per hour (Nm^3/hr). Clinker cooling air supplied by each Induce Draft Fan is tabulated in Table 5.3.

$M_{Cl,air}$ = Volume flow rate of air * density of air

Where: $M_{Cl,air}$ - Mass of cooling air to clinker cooler

Table 5.3 Cooling air flow data taken from gauge on each Induced Draft Fan

Fan Model Number	*Average Air Velocity(m/s)*	*Temperature(℃)*	*Static Pressure(mbar)*	*Air Flow(OC)(m^3/h)*
2604	19.95	25	78.77	20610
2605	16.07	25	61.7	30444
2606	16.44	25	76.5	25652
2607	16.47	25	77.41	26243
2608	14.97	25	-	31888
2609	13.55	25	67.4	47655
2610	14.60	25	86.6	25356
2611	12.94	25	79.3	27112
2612	11.85	25	61.5	46448
2613	10.43	25	54.01	45735
2614	10.92	25	39.4	43000
Total cooling air flow			**Nm^3/h**	**371095**
			Nm^3/kg-clinker	**2.833**

Note: OC = Operation condition

6. Mass of moisture in feed material ($M_{F,mo}$): Raw material feed have 2 % moisture.

$$M_{F,mo} = (2 * 1.57\text{kg/kg-clinker}) /100$$

$$= 0.031\text{kg-moisture/kg-clinker}$$

5.3.2 Output mass of system during clinker production

Output mass (M_{Out}) = Mass of clinker + Mass of dust + Mass of Pre-heater exhaust gas + Mass of cooler exhaust gas + Mass of moisture evaporated …………………………………..…… (5.10)

1. Mass of clinker (M_{Cl}) = 1.00kg-clinker

2. Mass of dust (M_d): Mass of dust is depending on Loss on ignition (LOI) of clinker material. The loss of feed as exhaust gas from calcinations and dehydration of raw material is known as loss on ignition (LOI_{feed}). According to *Raid, (2013),* LOI is obtained by heated a clinker at a temperature of 900 to 1000 ^{0}C and the value is obtained from 0.1 to 2.5 %

Ton of clinker = (Ton of feed – Ton of dust) x (1-LOI_{feed})……………………………..…... (5.11)

Mugher cement plant uses limestone and clay in its raw mix design. However, sometimes when the limestone quality is low they add corrective limestone. Therefore loss on ignition is determined by considering the mix that contains only the two raw materials of clay and limestone.

Percentage of $LOI_{feed} = \frac{M_{limestone} x LOI_{limestone} + M_{clay} x LOI_{clay}}{Total mass of feed\ (TPH)}$……....…………………...…… (5.12)

Where: $M_{limestone}$ – Mass of limestone

$LOI_{limestone}$ – Loss on ignition of limestone

M_{clay} – Mass of clay

LOI_{clay} – Loss on ignition of clay

Table 5.4 The limestone and clay mixture *(Average production of plant per hour)*

Feed content	***Mass flow rate (TPH)***	***LOI (%)***	***Percentage (mass base)***
Limestone	165.9	41.68	80
Clay	41.5	9.90	20
Total	**207.4**	**51.58**	**100**

Rearranging the equation 5.11 and 5.12 gives:

Ton of dust = ton of feed – $\frac{Ton\ of clinker}{(1-\%\ LOI)}$……………………………………………... (5.13)

$= 207.12TPH - \frac{131.04TPH}{(1-0.3532)}$

= 5.79 TPH, 2.79% of feed = 0.044kg-dust/kg-clinker

3. Mass of exhaust gas from pre-heater ($M_{PH,Ex}$): Total exhaust gas from pre-heater

= 2.802kg-gas/kg-clinker

4. Mass of exhaust gas from clinker cooler ($M_{C,Ex}$) = Total mass of exhaust gas from clinker cooler

5. Mass of moisture evaporate ($M_{M,Ev}$): Total mass of moisture removed from material during calcinations.

5.4 Energy balance of a system

Heat balance of a system is the ways of identifying energy consumption from total input and output energy. Thermal energy is generated inside a kiln so heat generated is transferred to the material for the purpose of clinker or calcinations making. So the amount of heat input and output is known by Heat balance of rotary kiln.

5.4.1 Heat input for a clinker production system

1. **Heat generated by coal combustion:** The rotary kiln is fired with a bituminous coal with a gross calorific value (GCV) of 27088.35kJ/kg-coal, and specific coal consumption of 0.121kg-coal per kg of clinker. Therefore energy generated from coal combustion is calculated by:

$Q_1 = M_{Coal} * GCV$………………………………………………….……………..... (5.14)

Where: Q_1 – Heat generated from coal combustion

M_{Coal} – Mass of coal consumption per mass of clinker

GCV – Gross caloric value of coal

2. Sensible heat from coal

$Q_2 = M_{Coal}*C_{pCoal} * T_{Coal}$……………………………………………………..……... (5.15)

Where: Q_2 – Sensible heat from coal

M_{Coal} – Mass of coal consumption per mass of clinker

$C_{p,Coal}$ – Specific heat value of coal

T_{Coal} – Temperature of coal before burning process

3. Sensible heat of raw meal feed

$Q_3 = M_{Feed} * C_{p,Feed} * T_{Feed}$…………………..…………………….……….…..…… (5.16)

Specific heat capacity (SHC) of mixed material is the summation of specific heat capacity from mass fraction of each material.

Raw meal feed = Limestone (80%) + Clay (20%)

SHC of raw meal ($C_{p,Feed}$) = $0.8 * C_{p,CaCO3} + 0.2 * C_{p,Clay}$

Where: Q_3 – Sensible heat from raw material feed to pre heater

M_{Feed} – Mass of raw material feed per mass of clinker

$C_{p,Feed}$ – Specific heat capacity of mixed raw material

T_{Feed} – Temperature of feed material to pre-heater

$C_{p,CaCO3}$ – Specific heat capacity of Calcium carbonate (Limestone)

$C_{p,Clay}$ – Specific heat capacity of clay, 0.2 and 0.8 – Mass ratio of clay and limestone from feed material

4. Sensible heat of air form clinker cooler

$Q_4 = M_{Cl,air} * C_{p, Cl,air} * T_{Cl,air}$……………….…………………………….…….………. (5.17)

Where: Q_4 – Sensible heat from clinker cooling air

$M_{Cl,air}$ – Mass of clinker cooling air

$C_{p,Cl,air}$ – Specific heat capacity of clinker cooling air

$T_{Cl,air}$ – Temperature of clinker cooling air

5. Sensible heat from primary air

$Q_5 = M_{P,air} * C_{p, P,air} * T_{P,air}$ ………………………..……..……………..………… (5.18)

Where: Q_5 – Sensible heat from primary air

$M_{P,air}$ – Mass of primary air

$C_{p,P,air}$ – Specific heat capacity of primary air

$T_{P,air}$ – Temperature of primary air

6. Sensible heat from coal convening air

$Q_6 = M_{Conv,air} * C_{p, Conv,air} * T_{Conv,air}$ ………………………..……….……..……… (5.19)

Where: Q_6 – Sensible heat from coal convening air

$M_{Conv,air}$ – Mass of coal convening air

$C_{p,Conv,air}$ – Specific heat capacity of coal convening air

$T_{Conv,air}$ – Temperature of coal convening air

7. Sensible heat from moisture in the feed

$Q_7 = M_{F,mo} * C_{p, F,mo} * T_{F,mo}$ ……………………………………………………..……… (5.20)

Where: Q_7 – Sensible heat from moisture in feed

$M_{F,mo}$ – Mass of moisture in feed

$C_{p, F,mo}$ – Specific heat capacity of moisture in feed

$T_{F,mo}$– Temperature of moisture in feed

5.4.2 Heat output from rotary kiln with mass balance base

Output heat from the system by mass base includes:

1. Heat formation of clinker (Q_8)

Peray, (1979), develop the equation of the heat required for a clinker formation according to equation 5.21.

$Q_8 = 4.11(Al_2O_3) + 6.48(MgO) + 7.646(CaO) – 5.116 (SiO_2) – 0.59 (Fe_2O_3)$…..………….. (5.21)

Table 5.5 Percentage of clinker material compositions

S/No	Clinker composition	Percentage (%)
1	Al_2O_3	6.24
2	MgO	3.3
3	CaO	64.5
4	SiO_2	22.4
5	Fe_2O_3	3.56
	Total	**100**

$Q_8 = 4.11 * 6.24 + 6.48 * 3.3 + 7.646 * 64.5 - 5.116 * 22.4 - 0.59 * 3.56$

$= 1774.46$kJ/kg-clinker

2. Heat loss through the clinker at cooler outlet (Q_9)

$Q_9 = M_{Cl} * C_{P,\,Cl} * T_{Cl}$……………………….……………………………..….. (5.22)

Where: Q_9 – Heat loss from clinker at outlet of cooler

M_{Cl} – Mass of clinker

$C_{p,Cl}$ – Specific heat capacity of clinker

T_{Cl} – Temperature of clinker

The specific heat capacity of clinker at any temperature is obtained by correlation of *Raziuddin et al. (2013)*:

$Cpi = AT^0 + BT^1 + C\,T^2 + DT^3$…………………………………………….…….. (5.23)

Where: A, B, C and, D are clinker heat capacity expansion coefficient and given by Table 5.6

Table 5.6 Temperature constant

Constant	*Value*
A	0.1742
B	$1.41\text{x}10^{-4}$
C	$1.28\text{x}10^{-7}$
D	$5.07\text{x}10^{-11}$

Temperature of clinker exit from clinker cooler is varying by time. According to plant design temperature of clinker is around 65^0C plus temperature of ambient air. But due to cooler low efficiency the measured temperature is above design (see Table 5.7 and Figure 5.3).

Table 5.7 Temperature of clinker measured by Dual Leaser infrared thermometer

Measured time	***20/05/2019***			***21/05/2019***		
	8:30AM	9:30AM	11:30AM	8:30AM	9:30AM	11:30AM
Clinker Temperature (^{0}C)	176.4	88.7	196.9	202.0	174.4	120.4
Average (^{0}C)			***159.8***			

Figure 5.3 Measured temperature of outlet clinker by Dual Leaser Infrared Thermometer

3. Heat loss through the dust in exhaust gas

$$Q_{10} = M_d * C_{p,d} * T_d \dots \dots (5.24)$$

Where: Q_{10} – Heat lost by dust with exhaust gas

M_d – Mass of dust

$C_{p,d}$ – Specific heat capacity of dust

T_d – Temperature of dust

4. Heat loss through evaporation of moisture

$$Q_{11} = M_{M,Ev} * C_{P,M,Ev} * T_{M,Ev} \dots \dots (5.25)$$

Where: Q_{11} – Heat lost by evaporation of moisture

$M_{M,Ev}$ – Mass of evaporated moisture

$C_{p,M,Ev}$ – Specific heat capacity of evaporated moisture

$T_{M,Ev}$ – Temperature of evaporated moisture

5. Heat loss from exhaust gas

- ***From pre-heater exit***

$$Q_{12PH,\,EX} = M_{PH,Ex} * C_{P,\,PH,Ex} * T_{PH,Ex} \dots \dots (5.26)$$

Where: $Q_{12PH,\,EX}$ – Heat lost by hot exhaust gas from pre-heater

$M_{PH,Ex}$– Mass of hot exhaust gas from pre-heater

$C_{p,PH-Ex}$ – Specific heat capacity of hot exhaust gas from pre-heater

$T_{PH,Ex}$– Temperature of hot exhaust gas from pre-heater

➡ ***From cooler outlet gas***

$Q_{12C,\,EX} = M_{C,Ex} * C_{C,Ex} * T_{C,Ex}$ …………………………….………….……………… (5.27)

Where: $Q_{12C,\,EX}$ – Heat lost by hot exhaust gas from Cooler

$M_{C,Ex}$ – Mass of hot exhaust gas from Cooler

$C_{p,C-Ex}$ – Specific heat capacity of hot exhaust gas from Cooler

$T_{C,Ex}$ – Temperature of hot exhaust gas from Cooler

5.4.3 Thermal energy waste from a surface of plant

Thermal energy waste can also occurred on the external surface of the plant such as pre-heater cyclone surface, pre-calciner surface, Tertiary air duct surface, Rotary kiln shell and clinker cooler surface. This type of heat is considered as output thermal energy. The indication of the lost heat is in form of radiation and convection heat. Waste heat from plant is achieved by measuring temperature on each surface of system.

5.4.3.1 Heat lost from pre-heater cyclones

Raw material and hot gas in pre-heater cyclones flow countercurrent direction. The hot gas flow from rotary kiln to first cyclone of pre-heater temperature is from the range of 350 to 900 ^{0}C. In my study Mugher cement factory pre-heater have a six series cyclone which have different size and surface temperature. The first cyclone is pair (C_{1A} and C_{1B}) and located at the top of pre-heater. Pre-heater cyclone is the composite shape of frustum, cylinder, and rectangular duct. The main heat losses mechanisms from the pre-heater surface are radiation and convection. To calculate those waste heats the same equation used for all pre-heater cyclone, because of similar shape. But they have different size and different temperature distribution on each surface. The surface areas of shape of cyclone components are calculated by equation **5.28a** to **5.28d**:

- Lateral Surface area of frustum = $\pi*(r + R) * (\sqrt{((R - r)^2 + h^2})$………….……… (5.28a)
- Surface area of rectangular prism = $2(W*L + W*h + L*h)$…………..…....…..… (5.28b)
- Lateral surface of cylinder = $\pi * D * h$……………………………………........…… (5.28c)
- Squared surface area = $4*w*h$……………..…………………….…..………...… (5.28d)

Table 5.8 shows the dimension on each component which is taken from plant design and Figure 5.4 shows the pre-heater cyclone arrangement.

Table 5.8 Pre-heater part with their dimension *(Plant design data)*

Measurements	**C_{1A} and C_{1B}**	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**
Quantity	2	1	1	1	1	1
Length of material duct (m)	7	6	8	7.5	17.5	0.866
Height of frustum (m)	6	10	9.2	9	11.5	8.9
Smaller diameter of frustum (m)	1.78	1.78	1.78	1.78	1.78	1.78
Bigger diameter of frustum (m)	5.7	7.8	7.8	8.1	8.1	8.4
Height of cyclone (m)	10.45	7	8.8	8	6	10
Diameter of cyclone (m)	5.7	7.8	7.8	8.1	8.1	8.4
Gas duct length (m)	Chimney	16.45	13	14	16.19	14
Diameter of gas duct (m)		4.12	4.5	4.7	4.96	4.7

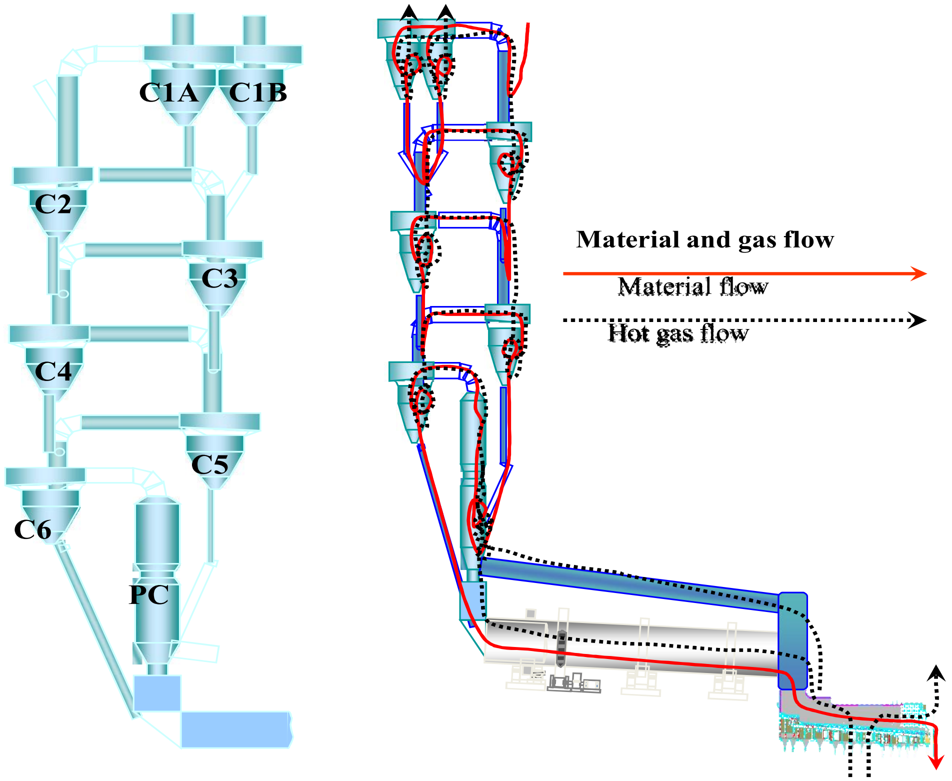


Figure 5.4 Pre-heater cyclone arrangements *(Plant design)*

Temperature on each cyclone surface to calculate waste heat is tabulated in Table 5.9, which is measured by Dual Leaser Infrared thermometer.

Table 5.9 Shows temperature measured from the surface of pre-heater cyclones plant

	Temperature distribution on surface of cyclone (C) part by ^{0}C			
	Frustum	***Gas Duct***	***Material Duct***	***Cyclone surface***
Cyclone (C1)	95	-	105	63
Cyclone (C2)	117	76	107	105
Cyclone (C3)	124	100	190	180
Cyclone (C4)	180	140	240	80
Cyclone (C5)	175	120	300	200
Cyclone (C6)	280	120	350	235

Heat losses from surface of PH cyclone

Equation to find heat loss from first cyclone is similar for six cyclones therefore the same equation is to be applied. First cyclone constructed from shape of cylinder, rectangular duct and frustum.

Heat lost from Frustum cyclone: For energy balance of a system analyzing the waste heat or lost from frustum is considered as output heat which in the form radiation and convection to enviroment. The quantity of waste heat from surface is depending on area of surface, air movement, materials property for emissivity. The ***area*** of each cyclone is calculated by equation **5.28a** to **5.28d** according to their shape. Frustum is a conic shape of cyclone so the area equation 5.28a is used. Figure 5.5 shows the shape of cyclone component and heat loss.

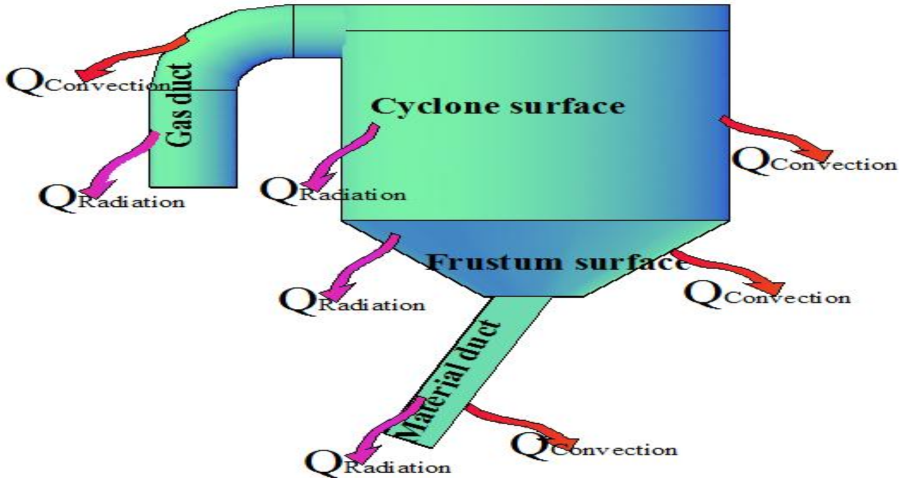


Figure 5.5 Shape of pre - heater cyclone and heat loss

A) Waste Heat by radiation occurred on frustum:

$Q_{FR} = \sigma * \varepsilon * A_S * (T_S^4 - T_A^4)$ ……………………………..……………..………………. (5.29)

Where: Q_{FR1} - Heat lost by radiation from first cyclone frustum shape

σ - Stefan Boltzman radiation constant (5.67×10^{-8} W/m^2/k^4)

T_S – Surface temperature of frustum

r – Small radius of frustum

R – Large radius of frustum

h – Height of frustum

A_S – Surface area of frustum……………...*All dimension of frustum is given in Table 5.8*

ε - Emissivity of cyclone material…. (0.3 for pre-heater, pre-calciner, TAD and cooler)

- Aluminum paint is applied to pre-heaters and grate coolers has a low emissivity of ≈ 0.3

B) Heat lost by convection occurred on frustum:

Heat lost by convection from surface of cyclone is occurred by free convection. Free convection heat losses depend up on dimensionless number of Grashof, Nussalt number and Rayleigh number, which is the product of the Grashof and Prandtl numbers.

Free convection heat loss:

$Q_{CV} = h * A_S * \Delta T$……………………………………………………….……….. (5.30)

$h = \frac{Nu*K}{L_c}$…………………………………………………….…………..………… (5.31)

$Q_{CV} = \frac{(Nu \ x \ K \ x \ A_S \ x \ \Delta T)}{L_C}$ ……………….……...…………..………...……..…………….………… (5.32)

Where: Q_{CV} - Free convective heat loss (W)

h – Convective heat transfer coefficient medium

A_S – Area on a surface

ΔT - Temperature difference

K – Thermal conductivity of air

N_U – Nussalt number

ΔT - Temperature difference of surface and air

L_c – Characteristic length of the surface to be heat is lost (m), calculated by:

$L_c = \frac{\text{Volume of surface body}}{\text{Area of surface body}}$…………………………………………………...*for frustum surfaces*

$$L_c = \frac{\frac{\pi}{3} * h(R^2 + r^2 + R * r)}{\pi(R+r) * \sqrt{(R-r)^2 + h^2}} \quad \text{.....} \quad (5.33)$$

- ***Grashof number (Gr):*** is a dimensionless number in air flow and heat transfer which approximates to the ratio of the buoyancy to viscous force acting on air movement on surface.

$$Gr = \frac{g * \beta * \Delta T * L_C{}^3}{\nu^2} \quad \text{.....} \quad (34)$$

Where: g - Gravitational acceleration, m/s^2

T_s - Temperature of the surface, ˚C

T_a - Temperature of the air sufficiently far from the surface, ˚C

ν -Kinematic viscosity of the fluid, m^2/s

β - Coefficient of volume expansion, 1/K

$$\beta = \frac{1}{\frac{T_s + T_a}{2}} \quad \text{.....} \quad (5.35)$$

- ***Prandtl number (Pr):*** Is a dimensionless number, named after the German physicist Ludwig Prandtl, defined as the ratio of kinematic viscosity to thermal diffusivity.

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\frac{\mu}{\rho a}}{\frac{K}{Cp}} = \frac{\mu * Cp}{K} \quad \text{.....} \quad (5.35)$$

Where: ν - Kinematic viscosity

α - Thermal diffusivity

Cp – Specific heat

μ -Dynamic viscosity of air

- ***Rayleigh number (Ra):*** Is a dimensionless number which is the product of the Grashof and Prandtl numbers

$$\mathrm{Ra} = \mathrm{Gr} * \mathrm{Pr} = \frac{g * \beta * \Delta T * L_C{}^3}{\nu^2} * Pr \quad \text{.....} \quad (5.36)$$

- ***Nusselt number (Nu):*** Is a dimensionless number which is estimated from Prandtl and Grashof Number for free convection.

$$Nu = \left\{ 0.825 + \frac{0.387 * Ra^{1/6}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}} \right\}^2 \quad \text{.....For vertical plate and cylindrical}$$

$$Nu = \left\{0.6 + \frac{0.387 * Ra^{1/6}}{\left[1+\left(\frac{0.559}{Pr}\right)^{9/16}\right]^{8/27}}\right\}^2$$ ……………………………..……….For horizontal cylindrical

$For\ forced\ convection\ occured\ on\ the\ rotary\ kiln\ at\ the\ region\ of\ burner\ zone\ the$

$nusselt\ number\ is\ obtained\ by$:

$$\text{Nu} = \frac{h * D}{K} = 0.3 + \frac{0.62 * Re^{1/2} * Pr^{1/3}}{\left[1+\left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} * \left[1 + \left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5}$$

$$\text{Re} = \frac{\rho_a * \mathcal{V} * D}{\mu}$$

Therefore the waste heat by forced convection from rotary kiln at the region of burning or flame zone is calculated by:

$$Q_{CV} = \frac{(Nu\ x\ K\ x\ A_S\ x\ \Delta T)}{D}$$

CHAPTER SIX

RESULTS AND DISCUSSION FOR THERMAL PERFORMANCE OF MUGHER CEMENT

6.1 Specific coal consumption

Mass of coal consumed and mass of clinker production used to find specific coal consumption. This mass is taken from *appendix Table 1A,* at the average production of 15 days and fully 24 hour plant operation.

$$\text{SCC} = \frac{\text{Mass of coal consumed in (pricalciner+Kiln burner)TPH}}{\text{Total clinker production in TPH}}$$

$$= 0.121\text{kg-coal/kg-clinker}$$

6.2 Mass balance through clinker production process

All mass founded in Table 6.1 is based up on 1kg of clinker production.

Input mass (M_{In}) = Output mass (M_{Out})

Input mass (M_{In})

$M_{In} = M_{feed} + M_{P,air} + M_{Coal} + M_{conv,air} + M_{Cl,air} + M_{F,mo}$

Output mass (M_{Out})

$M_{Out} = M_{Cl} + M_d + M_{PH,Ex} + M_{C,Ex} + M_{M,Ev}$

Table 6.1 Summary of input and output mass for clinker production

	Input mass	***Symbol***	***(kg/kg-cl)***	***Output mass***	***Symbol***	***(kg/kg-cl)***
1	Material feed	M_{Feed}	1.57	Clinker mass	M_{Cl}	1.00
2	Primary air	$M_{P,air}$	0.35	Dust	M_d	0.044
3	Coal	M_{Coal}	0.121	Pre-heater exhaust gas	$M_{PH,Ex}$	2.802
4	Coal convening air	$M_{Conv,air}$	0.045	Cooler exhaust gas	$M_{C,Ex}$	1.901
5	Clinker cooling air	$M_{Cl,air}$	3.66	Moisture evaporated	$M_{M,Ev}$	0.031
6	Moisture in feed	$M_{F,mo}$	0.031			
	Total	M_{In}	***5.78***	***Total***	M_{Out}	***5.781***

6.3 Energy balance through production process

The following tabulated data in Table 6.2 is used for calculating heat balance of cement factory.

Table 6.2 Heat balance data for Mugher cement factory

S/No		***Symbol***	***Unit***	***Value***	***Remark***
1	Gross calorific Value	GCV	kJ/kg-coal	27088.35	Laboratory
2	Mass of dust in exhaust gas	M_d	Kg/kg-cl	0.044	Correlation
3	Mass of clinker	M_{Cl}	Kg/kg-cl	1.00	CCR
4	Mass of coal convening air	$M_{Conv,air}$	Kg/kg-cl	0.045	CCR
5	Mass of moisture in feed	$M_{F,mo}$	Kg/kg-cl	0.031	CCR
6	Mass of pre-heater exit gas	$M_{PH,Ex}$	kg/kg-cl	2.802	Analytical
7	Mass of cooler exit gas	$M_{C,Ex}$	kg/kg-cl	1.901	Analytical
8	Mass flow of primary air	$M_{P,air}$	Kg/kg-cl	0.35	CCR
9	Mass of coal convening air	$M_{CL,air}$	Kg/kg-cl	3.66	Analytical
10	Raw meal feed	M_{Feed}	kg/kg-cl	1.57	Standard design
11	Specific coal consumption	M_{Coal}	kg/kg-cl	0.121	Production sheet
12	Specific heat of coal	C_{pCoal}	kJ/kg/^{0}C	1.262	Correlation
13	Specific heat of raw meal	$C_{p,Feed}$	kJ/kg/^{0}C	0.903	Correlation
14	Specific heat of air from cooler	$C_{p,cl,air}$	kJ/kg/^{0}C	1.0056	Air property
15	Specific heat of primary air	$C_{p,P,air}$	kJ/kg/^{0}C	1.007	Air property
16	SH of coal convening air	$C_{p,Conv,air}$	kJ/kg/^{0}C	1.007	Air property
17	SH of moisture in feed	$C_{p, F,mo}$	kJ/kg/^{0}C	4.19	Water property
18	Specific heat of clinker	C_{pcl}	kJ/kg/^{0}C	1.102	Correlation
19	Specific heat of dust	C_{pd}	kJ/kg/^{0}C	1.098	Analytical
20	SH of moisture	$C_{P,M,Ev}$	kJ/kg/^{0}C	4.19	Water property
21	SH of pre-heat exit gas	$C_{PH,Ex}$	kJ/kg/^{0}C		Gas property
22	Temperature of coal	T_{coal}	^{0}C	70	CCR
23	Temperature of raw meal	T_{Feed}	^{0}C	95	CCR
24	Temperature of cooler air	$T_{cl,air}$	^{0}C	27	Measured
25	Temperature of clinker	T_{cl}	^{0}C	159.8	Measured
26	Temperature of dust gas	T_d	^{0}C	280	CCR

27	Temperature of cooler exit gas	$T_{C,EX}$	^0C	280	CCR
28	Temperature of coal convening air	$T_{Conv,air}$	^0C	40	CC
29	Temperature of evaporation moisture	$T_{M,Ev}$	^0C	100	CCR
30	Temperature of preheat exit gas	$T_{PH,Ex}$	^0C	290	CCR
31	Temperature of primary air	$T_{P,\ air}$	^0C	25	Measured

6.3.1 Heat input for clinker production

Coal is the largest thermal energy source for clinker production. The other heat input is form sensibility of material flow to rotary kiln. Table 6.3 shows the general source of heat for clinker production and calculated by using *equation number 5.14 to 5.20.*

Table 6.3 Heat input for clinker production

S/No	*Type of heat source*	*Equation*	*Symbol*	*Q_{IN} (kJ/kg-cl)*
1	Heat generated from coal	M_{Coal} * GCV	Q_1	3277.69
2	Sensible heat from the coal	$M_{Coal}*C_{p,Coal}*T_{Coal}$	Q_2	10.69
3	Sensible heat of raw meal feed	$M_{Feed}*C_{p,Feed}*T_{Feed}$	Q_3	134.68
4	Sensible heat of air clinker cooling	$M_{Cl,air}*C_{p,\ Cl,air}*T_{Cl,air}$	Q_4	103.12
5	Sensible heat from primary air	$M_{P,air}*C_{p,\ P,air}*T_{P,air}$	Q_5	8.8
6	Sensible heat from coal convening air	$M_{Conv,air}*C_{p,\ Conv,air}*T_{Conv,air}$	Q_6	1.81
7	Sensible heat from moisture in feed	$M_{F,mo}*C_{p,\ F,mo}*T_{F,mo}$	Q_7	10.78
		Total		***3547.57***

kg-cl…………………………kilogram of clinker

6.3.2 Heat output

After coal combustion is processed in rotary kiln and some sensible heat is added to a process, the system is heat. From heat added to the system almost half of it is consumed to clinker production and the other is waste. In energy balance, the heat out can be classified as:

1. Heat output during clinker formation
2. Heat output from surface by temperature difference.

6.3.2.1 Heat output during clinker formation

Heat output during clinker formation is based on mass, specific heat capacity and temperature of material processed with clinker. By this type of heat, the energy consumption for clinker formation is useful, but the other is considered as waste heat. Table 6.4 shows summary of heat output which based on mass during clinker formation. Numerical values are calculated by using equation number 5.21 to 5.26 of chapter five.

Table 6.4 Heat output (waste) with mass based

S/No	***Type of heat out***	***Equation***	***Symbol***	***Q_{IN} (kJ/kg-cl)***
1	Heat formation of clinker	*Equation 5.21 and Table 5.5*	Q_8	1774.46
2	Heat loss by clinker exit	$M_{Cl} * C_{P,Cl} * T_{Cl}$	Q_9	176.1
3	Heat loss by dust in exhaust gas	$M_d * C_{p,d} * T_d$	Q_{10}	13.52
4	Heat loss by evaporation moisture	$M_{M,Ev} * C_{P,M,Ev} * T_{M,Ev}$	Q_{11}	13
5	Heat loss by exhaust gas from pre-heater	$M_{PH,Ex} * C_{P,PH,Ex} * T_{PH,Ex}$	$Q_{12PH,EX}$	669.46
6	Heat loss by exhaust gas from cooler	$M_{C,Ex} * C_{p\,C,Ex} * T_{C,Ex}$	$Q_{12C,EX}$	281.01
		Total		***2927.55***

kg-cl…………………………….kilogram of clinker

6.3.2.2 Heat output by form of waste from a surface of plant

A) Heat lost from pre-heater cyclone: The equation using to find waste heat on surface of all pre-heater cyclones is developed in chapter five with equation 5.28 to 5.39 according to pre-heater cyclone shape.

Prameters to calculate waste heat from pre-heater cyclone.

- Number of cycclone = 6
- First cyclone = 2 (Pair)
- Construction shape of cyclone: Cylinderical, frustum, circular and rectangular duct shape.
- All dimension are taken from plant design
- Temperature on each surface is measured by Dual laser Infrared thermometer
- Raw material flow from top cyclone to bottom cyclone

- Hot gas flow from bottom cyclone to top cyclone
- Emissivity of cyclone material = 0.3, *Aluminum oxide*
- Solar radiation neglected
- Ambient temperature = 25 ^{0}C *(Annual Average)*

Heat losses from surface of pre-heater cyclone

Heat lost from each pre-heater cyclone is calculated by similar equation of the first cyclone and the equation to calculate waste heat from the surface of pre-heater is given by Table 1B and Table 1C of page 88 and 90. The value is tabulated in Table 6.5 below.

Table 6.5 Shows summary of heat lost from per-heater cyclone

Pre-heater cyclones		***Pre-heater cyclone component***			
		Frustum	*Gas duct*	*Material duct*	*Cyclone surface*
First cyclone	Temperature (^{0}C)	95	-	105	63
	Waste heat (kW)	130.62	-	51.26	170.19
Second cyclone	Temperature (^{0}C)	117	76	107	105
	Waste heat (kW)	194.40	123.31	23.27	213.59
Third cyclone	Temperature (^{0}C)	124	100	190	180
	Waste heat (kW)	197.98	175.80	75.9	603.52
Fourth cyclone	Temperature (^{0}C)	180	140	240	165
	Waste heat (kW)	362.02	341.40	102.60	153.48
Fifth cyclone	Temperature (^{0}C)	175	120	300	200
	Waste heat (kW)	432.10	325.06	331.60	531.69
Sixth cyclone	Temperature (^{0}C)	280	120	350	235
	Waste heat (kW)	723.45	266.83	211.17	1100.61

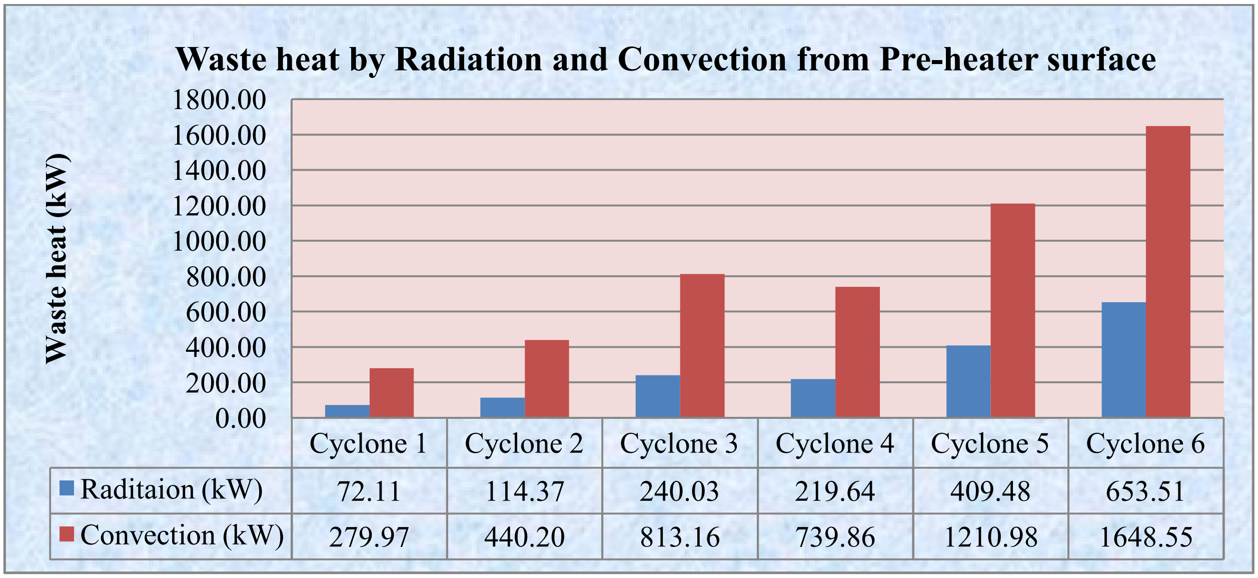
From the result of Table 6.5 the heat lost is increased from top of cyclone to bottom of cyclone. This result of hot flue gas is higher temperature at kiln exit and lower temperature at pre-heater exit and feed material temperature is increase from top to bottom by heat exchange with hot gas. Therefore the surface temperature of cyclone is increased from top cyclone to bottom cyclone.

Radiation and free convection heat lost:

The two ways of heat lost (By radiation and natural convection), from pre-heater cyclones are dependup on surface temperature of the system. As surface temperature increas from top to bottom,two of them increase form top to bottom. Therefore the waste heat occurred on pre-heater cyclone is proportionally to temperatur disstrebuted on a surface. Acording to a result of Table 6.6 and Figure 6.1 the occurnce of heat waste by free convection is higher.

Table 6.6 Summary of heat from heat waste from pre-heater cyclones by three ways

Pre-heater Cyclone	***Heat by Radiation (kW)***	***Heat by Free Convection (kW)***
Cyclone 1	72.11	279.97
Cyclone 2	114.37	440.20
Cyclone 3	240.03	813.16
Cyclone 4	219.64	739.86
Cyclone 5	409.48	1210.98
Cyclone 6	653.51	1648.55



	Cyclone 1	Cyclone 2	Cyclone 3	Cyclone 4	Cyclone 5	Cyclone 6
🟦 Raditaion (kW)	72.11	114.37	240.03	219.64	409.48	653.51
🟥 Convection (kW)	279.97	440.20	813.16	739.86	1210.98	1648.55

Figure 6.1 Waste heats from pre-heater cyclone by radiation, free convection

Figure 6.2 shows the total heat lost occurred on each cyclone that can increased from first cyclone to sixth cyclone.

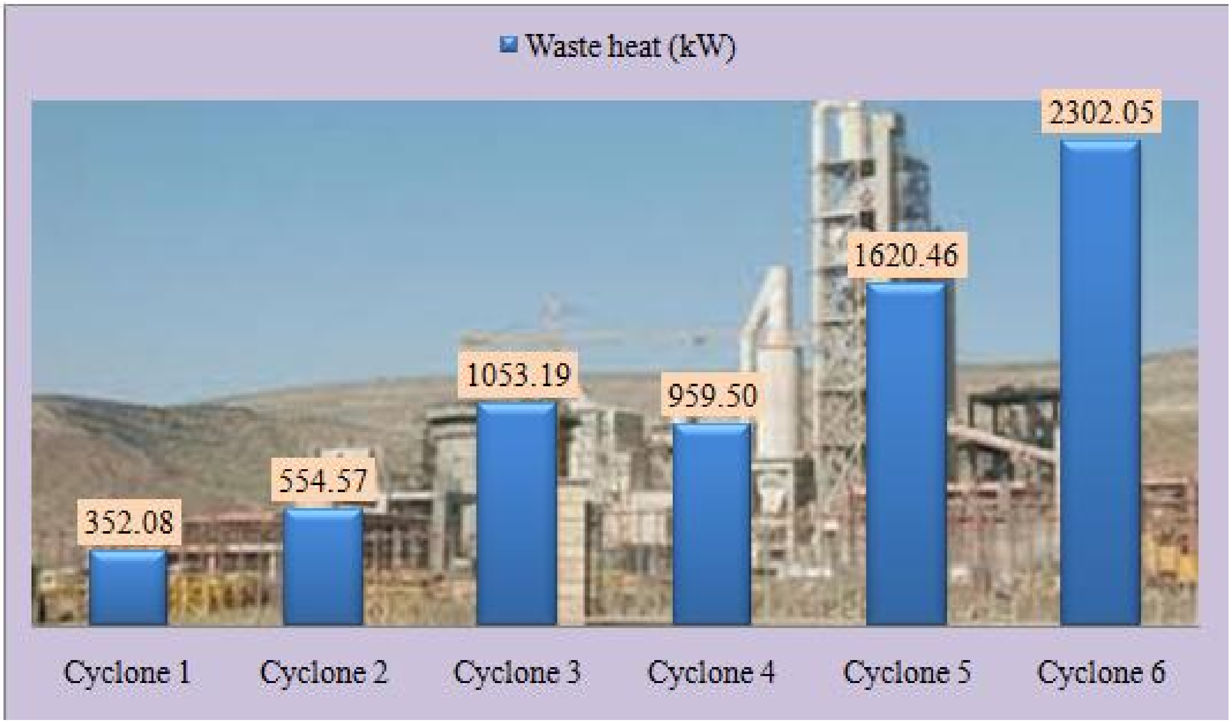


Figure 6.2 Total heat lost from each pre-heater cyclone

Comparison of heat lost from cyclone component:

As cyclone is constructed from four shapes the waste heat is occurred on all surfaces. The maximum heat lost is occurred on cylindrical cyclone surface and minimum heat lost occurred on material duct surface, which is shown by Table 6.7. Because of raw material and hot gas heat exchange is take place in cylinderical cyclone surface, that cause of high temperatue exposed to external surface. Also the larger surface area is a result for maximum heat lost.

Table 6.7 Summary of waste heat from cyclone-component

part of cyclone	***Waste Heat (kW)***	***Shared %***
Frustum	2040.55	30
Gas Line Duct	1232.41	18
Material Duct	795.80	12
Cyclone surface	2773.08	41

B) Heat lost from surface of pre-calciner

Pre-calciner is where combustion process is take place and 60% of fuel combustion is consumed for facilitating calcinations process of material before feed in to rotary kiln. In Table 6.8 design dimension of each shape for precalciner is given as:

Table 6.8 Dimension of pre-calciner

Measurement	*Height*	*Diameter*	*Gas duct length*	*Gas duct diameter*	*Frustum top and bottom diameter*	*Frustum length*
Pre-calciner	30m	7.86m	39.5m	4.7m	7.86m and 1.78m	2.44m

Due to combustion take place in pre-calciner the internal temperature reach up to 1200 ^{0}C *(CCR)* and surface temperature of external surface up to 250 ^{0}C. Table 6.9 show the temperature measured from the surface of pre-calciner.

Table 6.9 Temperature variation on the surface of pre-calciner

Gas line surface temperature	*Frustum average temperature*	*Cylindrical surface temperature*
190^{0}C	135^{0}C	140^{0}C

Heat lost from each pre-calciner surface is calculated by similar equation of the pre-heater cyclone. The value of waste heat is tabulated in Table 6.10 below.

Table 6.10 Shows summary of heat lost from pre-calciner

	By Radiation (kW)	*By Free convection (kW)*	*Total (kW)*	*Shared (%)*
Frustum	19.89	163.80	367.39	14
Gas Line	631.27	957.06	1588.33	59
Cylindrical surface	267.1	473.36	740.46	27

From Table 6.10 maximum waste heat is occurred at gas line section, because of hot gas pass through a line have high temperature.

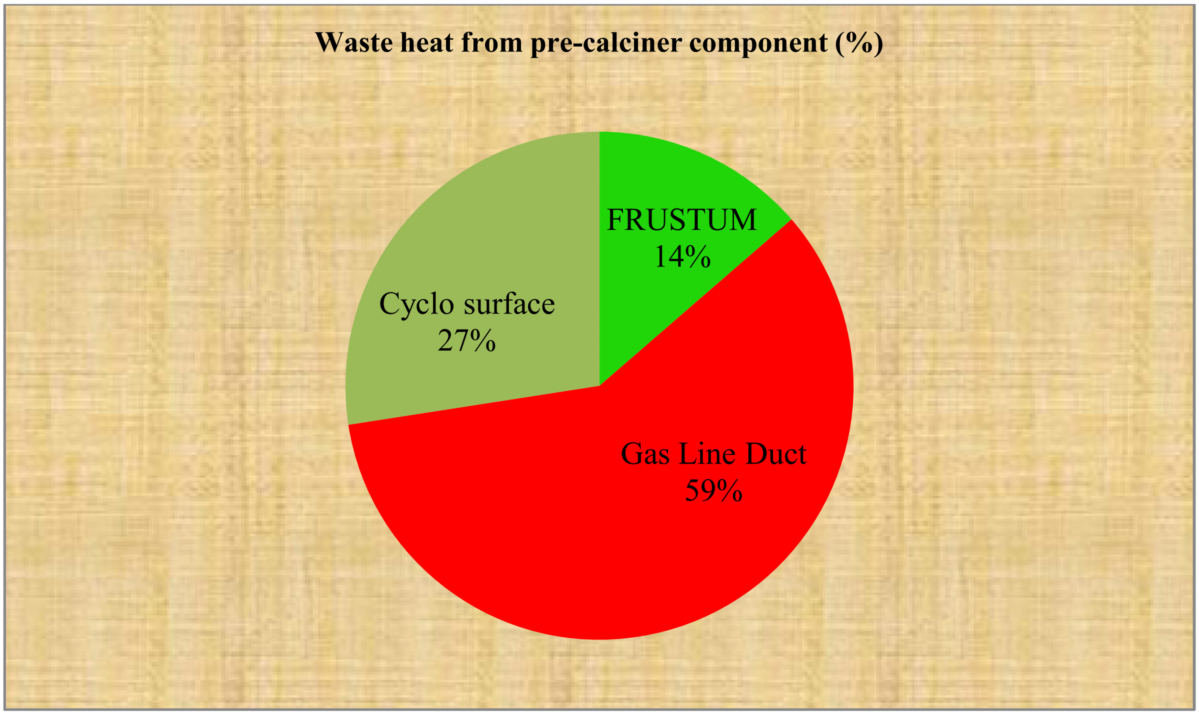


Figure 6.3 Pie chart of waste heat occurred on pre-calciner surface.

C) Heat lost from the surface of tertiary air duct

Hot gas recover heat from clinker cooler is flow to pre-calciner for complete combustion trough tertiary air duct (TAD). Internal temperature of hot gas flow through TAD is from the range of 800 to 1000 ^{0}C *(Philip, 2001).* The data take from CCR of the plant shows the temperature of tertiary air is 800 to 900 ^{0}C. External surface of TAD is higher temperature due to conductive heat transfer from internal hot gas to wall. External surface temperature of TAD wall is decrease from rotary kiln hood exhaust to pre-calciner. Table 6.11 shows external temperature of wall versus length.

Table 6.11 Temperature over tertiary air duct surface *(CCR)*

Surface temp at the inlet	***0 – 20m***	***20 – 40m***	***40 – 60m***	***60 – 68m***	***Surface Temp at outlet***
310^{0}C	299^{0}C	278^{0}C	256.5^{0}C	241^{0}C	237^{0}C

For a length 20 to 68 meters the shape of TAD is similar, so the same equation is used to calculate for each interval, but temperature distribution overall surface different. The equation to calculate waste heat from the surface of TAD is given by Table 3B of on page 89 and Table 1C of page 90. The general waste heat calculated over TAD is summarized in Table 6.12 and the waste heat is decreased from kiln outlet to precalciner inlet.

Table 6.12 Summary of waste heat from tertiary air duct (TAD)

TAD Zone	*TAD Length*	*Radiation (kW)*	*Free Convection (kW)*
ZONE 1	0-20m	419.99	402.53
ZONE 2	20-40m	383.61	342.15
ZONE 3	40-60m	348.58	287.08
ZONE 4	60-68m	128.42	100.53

The waste heat from the surface of TAD on each interval length is also shown by Figure 6.4. The waste heat is maximum at inlet and minimum at outlet therefore the system required high insulation at inlet.

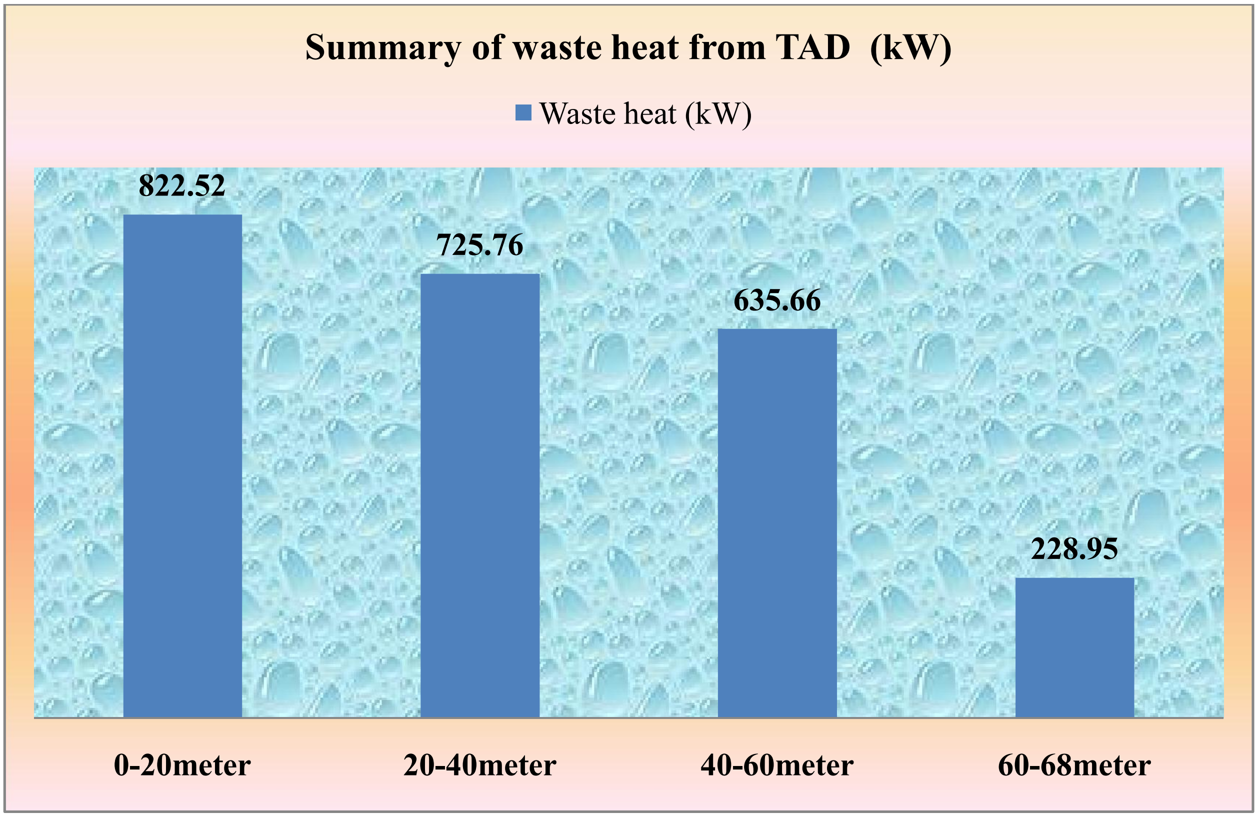


Figure 6.4 Summary of waste heat from each interval of TAD

D) Waste heat from rotary kiln shell

On external rotary kiln shell high temperature waste is occurred due to internal temperature of shell is up to 1500 ^{0}C. Maximum temperature on surface shell occurs at range of 15meter to 35meter. Table 6.13 is show temperature distribution on external shell measured through length.

Table 6.13 Temperature on rotary kiln surface zone

Length	*0 – 6.58 m*	*6.58 – 16.05 m*	*16.05 – 26.55*	*26.55 – 35.25*	*35.25 – 44.53*	*44.53 – 53.53*	*53.53 - 58.78*
Time							
9:20	319^{0}C	370 ^{0}C	384 ^{0}C	375 ^{0}C	308 ^{0}C	309 ^{0}C	259 ^{0}C
9:40	323^{0}C	374^{0}C	385^{0}C	382^{0}C	308^{0}C	302^{0}C	258^{0}C
10:00	321 ^{0}C	395 ^{0}C	391 ^{0}C	381 ^{0}C	309 ^{0}C	305 ^{0}C	258 ^{0}C
Average	***321^{0}C***	***380^{0}C***	***387^{0}C***	***379^{0}C***	***308^{0}C***	***305^{0}C***	***258^{0}C***
Overall average	***334^{0}C***						

For a length 0 to 58.78 m the shape of RK is similar to cylindrical, so the same equation is used to calculate for each interval, but temperature distribution overall surface different. The equation to calculate waste heat from the surface of rotary kiln is given on page 89 and 90. For the burner zone where the fan is removing heat from the shell forced convection *(From 16.05 to 35.25 meter)* is applied and the other region is free convection *(0 to 16.05 meter and 35.25 to 58.78 meter).*

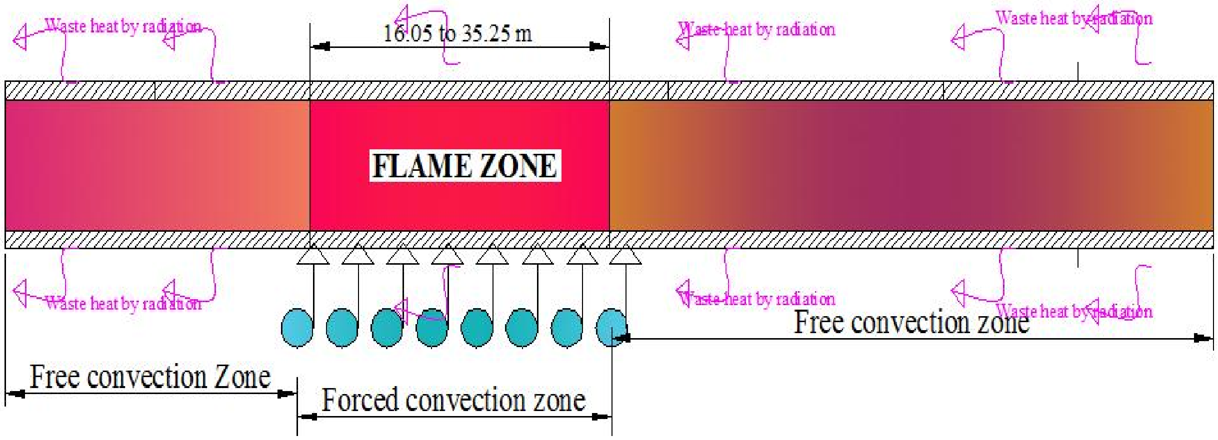


Figure 6.5 waste heat from rotary kiln shell

The general waste heat occurred over RK surface is summarized in Table 6.14

Table 6.14 Summary of Waste heat from Rotary Kiln Shell

Length (m)	0-6.58	6.58-16.05	16.05-26.55	26.55-35.35	35.25-44.53	44.53-53.53	53.53-58.78
Q_{RK}(KW)	714.816	1466.29	1692.03	1339.8	928.485	881.608	371.174

From summary of Table 6.14 and graph of Figure 6.6 maximum waste heat is occurred at kiln length of 16 to 25m. That indicate maximum shell tempearture is obseved. Inside a rotary kiln at the interval length of 16 to 25m is the region there is maximum flame temperature which cause increasing shell temperature.

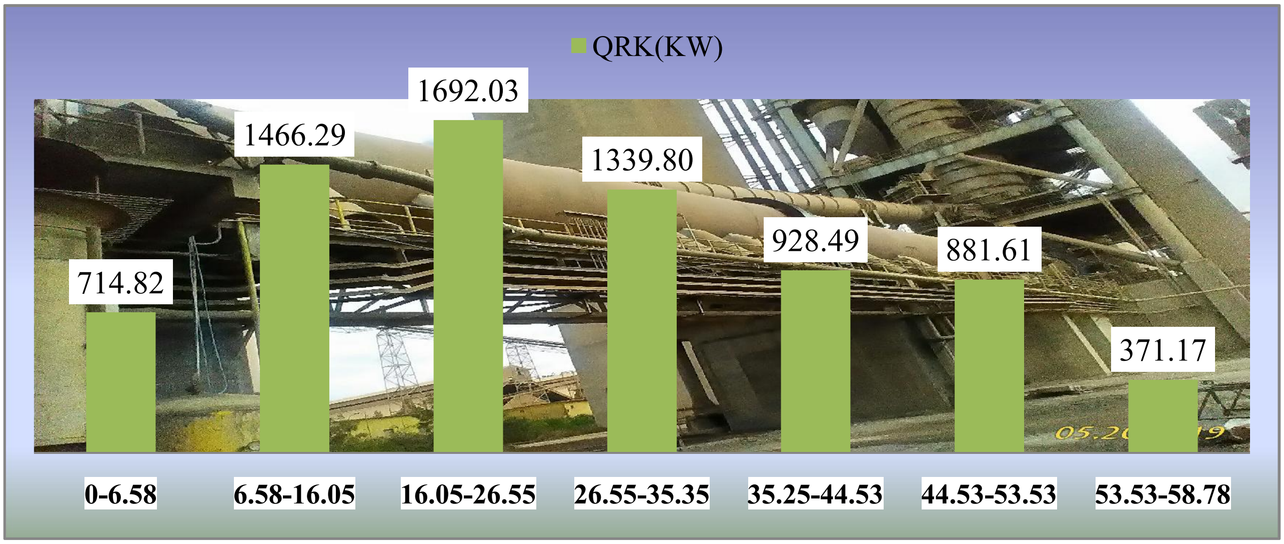


Figure 6.6 Graph of waste heat (kW) on rotary kiln shell vs it's length (m)

D) Waste heat from Grate cooler surface

Temperature of clinker exit from rotary kiln is up to 1400 ^{0}C and when exits from clinker cooler it's up to 120 ^{0}C. Since a clinker movement is translation motion by hydraulic lane the heat of clinker hot is transferred to cooler wall and cooling air. The heat transfer is by convection and conduction mode. As temperature measured on external wall of clinker cooler, the temperature on surface increased from cooler outlet to inlet of rotary kiln hood through its length.

Table 6.15 Temperature on Grate cooler surface

Length (m)	***0 – 6***	***6 - 12***	***12 – 18***	***18 – 24***	***24 – 30***	***30 – 35***
Time	*Temperature (measured),* ^{0}*C*					
8:20	120	150	220	250	270	*300*
8:40	125	146	204	237	280	296
9:15	143	170	198	217	253	287
Average	***129.33***	***155.33***	***207.33***	***234.67***	***267.67***	***294.33***
Overall average Temperature = 214.8 ^{0}**C**						

As temperature located on surface is increased it causes waste heat increments. The total waste heat is obtained from analytical calculation of convection and radiation is shown by Figure 6.7

through cooler length. From the figure waste heat is increased from clinker exit to inlet. Calculated waste heat depends upon equation of free convection.

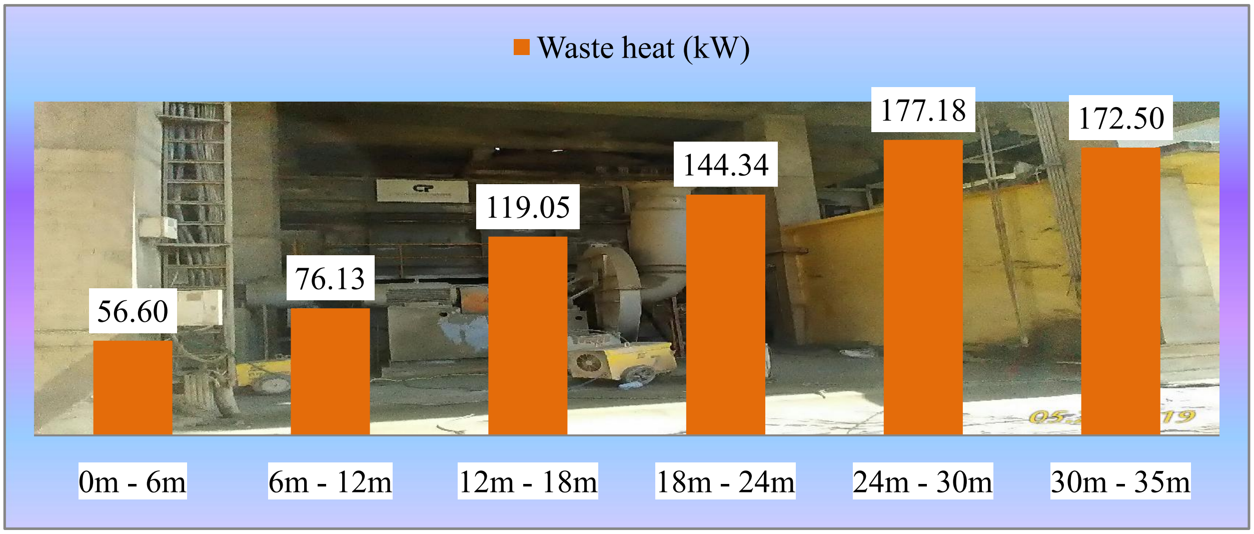


Figure 6.7 Bar chart of total waste heat from Grate cooler.

6.4 Total waste heat from the plant

The total waste heat from a plant is obtained by the difference of total input heat to a system and heat for clinker formation.

$Q_{waste} = Q_{In,total} - Q_{clinker\ formation}$………………………………………………..…………… (6.1)

Where Q_{waste} - Total waste heat

$Q_{In,total}$ - Total Input heat

$Q_{clinker\ formation}$ - Heat of clinker formation (Useful Heat)

- Total heat input to a system is include: heat generated by coal combustion, sensible heat of coal, primary air, linkage air, raw material, clinker cooling air and moisture of feed material.
- Waste heat includes: per-heater cyclone, pre-calciner, tertiary air duct, rotary kiln shell, and great cooler, heat with clinker outlet, gas flow through pre-heater and clinker cooler.
- Heat loss by cooler radiation for modern clinker cooler will be around 6kcal/kg-clinker (*Amole, 2018).*
- For a unit conversion of kW to kJ/kg-clinker, unit of heat kilowatt is divided for clinker production in kilogram per second.
- Unit of kJ/kg-clinker = $\frac{kW}{kg-clinker/s}$ ……waste heat per unit kilogram of clinker per second.

The summary of heat balance for Mugher cement factory is shown by Table 6.16.

Table 6.16 Summary of heat balance

S/No	***Input Heat***	***kW***	***kJ/Kg-clink***	***Shared %***
1	Heat generated by coal combustion (Q_1)	119308	3277.69	92.4
2	Sensible heat from the coal (Q_2)	389	10.69	0.3
3	Sensible heat of the raw meal feed (Q_3)	4902	134.68	3.8
4	Sensible heat of air from clinker cooler (Q_4)	3753.6	103.12	2.9
5	Sensible heat from primary air (Q_5)	320.32	8.8	0.25
6	Sensible heat from coal convening air (Q_6)	65.9	1.81	0.033
7	Sensible heat from moisture in the feed (Q_7)	392.4	10.78	0.302
Total (Q_{INPUT})		**129131.2**	**3547.57**	**100**
	Output Heat	***kW***	***kJ/kg-clink***	***Shared %***
8	Heat formation of clinker (Q_8)	64590.34	1774.46	50.02
9	Heat loss through by clinker outlet (Q_9)	6410	176.1	4.96
10	Heat loss through the dust in exhaust gas (Q_{10})	492.13	13.52	0.38
11	Heat loss by evaporation of moisture (Q_{11})	473.2	13	0.37
12	Heat of exhaust gas from pre-heater ($Q_{12PH,Ex}$)	24368.34	669.46	18.87
13	Heat of exhaust gas cooler stack ($Q_{12C,Ex}$)	10228.8	281.01	8.17
14	Pre-Heater surface (Q_{PH})	6207.84	170.55	4.56
15	Pre-Calciner surface(Q_{PC})	3691.26	101.41	2.86
16	TAD shell surface (Q_{TAD})	3257.9	89.50	2.52
17	Rotary Kiln shell surface (Q_{RK})	8615.6	236.69	6.67
18	Grate Cooler surface (Q_{GC})	800.8	21.99	0.62
	Total (Q_{OUTPUT})	**129131.9**	**3547.32**	**100**

6.5 Specific thermal energy consumption

Specific thermal energy consumption (STEC) is the most measures of cement plant performance. Is a ratio of thermal energy from coal per clinker produced. STEC for 6-stage pre-heater plus calciner plus high efficiency cooler is < 2.93 GJ/ton-clinker *(Philip, 2001).* A data from appendix of Table 1A, specific coal consumption is 0.121ton-coal/ton-clinker. From this data STEC at GCV of coal 27088.35kJ/kg can be founded 3.277GJ/ton. From result obtained the plant performance is low when it compared with world energy consumption by cement plant bench mark indicating that a strong potential for energy efficiency improvements. Due to less performance the plant coal consumption is higher.

6.6 Clinker cooler efficiency

The efficiency of a cooler is defined as the relationship between the recuperated heat to the kiln and the total heat transferred to the cooler.

$$\eta_{\text{cooler}} = \frac{Q_{In}-Q_{out}}{Q_{In}} \quad (6.2)$$

Where: η_{cooler} - Cooler Efficiency

Q_{In} - Heat Input of clinker

Q_{Out} – Heat Losses

Heat Input of clinker: is the heat content of clinker when entered into cooler.

Heat loss includes: heat waste from the surface of clinker cooler, heat waste by clinker exit and hot flue gas thorough cooler stack.

$Q_{\text{IN}} = M_{\text{CL}} * C_{\text{P,CL,}} * T_{\text{CL}}$

= 1065.4 kJ/kg-clinker

$Q_{\text{OUT}} = Q_{\text{cooler surface}} + Q_9 + Q_{\text{12C,Ex}}$

= 479.1 kJ/kg-clinker

$$\eta_{\text{cooler}} = \frac{1065.4-(479.1)}{1065.4}$$

= 55%

Typical efficiencies for a conventional grate cooler is 60 to70% *(Philip, 2001)*, but from performance evaluation of Mugher Cement clinker cooler the efficiency is a lowest which is 55%.

6.7 Thermal efficiency of a plant

$$\text{Thermal efficiency} = \frac{Total\ heat\ input - Total\ waste\ heat}{Total\ heat\ input}*100 \quad (6.3)$$

Total waste heat (Q_{WASTE}) = Total heat output ($Q_{\text{OUT, TOTAL}}$) – Heat for clinker formation (Q_8)

= (3547.57 – 1774.46) kJ/kg-clinker

= 1773.11kJ/kg-clinker

$$\eta_{\text{Thermal, plant}} = \frac{3547.57 - 1773.11}{3547.57} * 100$$

= 50.02%

6.8 Sankey diagrams

Sankey diagrams are specific type of flow energy diagram, in which the width of arrows is shown proportionally to the flow energy quantity. So the wide arrow to the system diagram represent large input energy and narrow arrow to a system diagram is represent small energy input. From Figure 6.8 of sankey diagram right side arrow is the energy input and the left hand side shows the energy output. Input energy *(Table 6.16, Input heat),* includes heat of coal combustion (92.4%), sensible heat of coal (0.3%), sensible heat of primary air (0.25%), sensible heat of material feed (3.8%) and moisture in material feed(0.303%). Output energy from the system *(Table 6.16, Output Heat),* includes energy for formation of clinker (50.02%), energy in exhaust gas from pre-heater and cooler stack, energy on surface of the system in form heat such as pre-heater cyclone, pre-calciner, tertiary, rotary cooler and clinker cooler surface. From sankey diagram the useful energy is represented by green straight arrow and the waste heat is represented by curved arrow line of up and down.

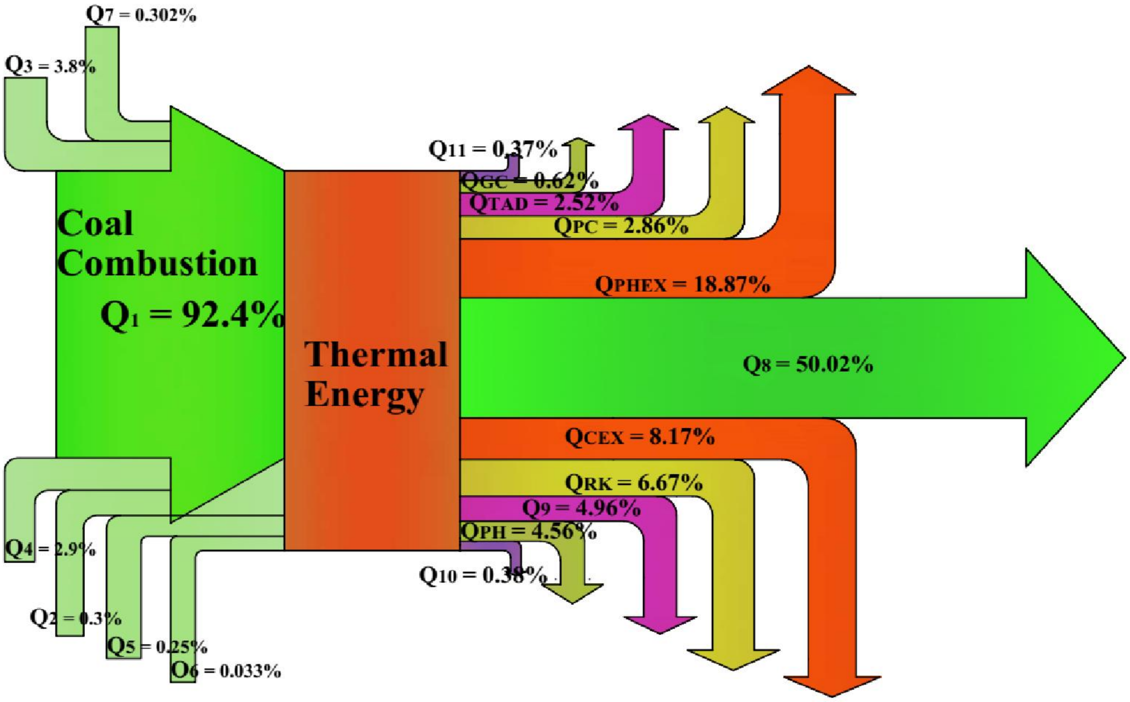


Figure 6.8 Sankey diagram of input and output heat of clinker production process

CHAPTER SEVEN

POTENTIAL WASTE ENERGY RECOVERY OPPORTUNITIES

7.1 Area of waste energy potential

The average energy consumption in Mugher cement factory is significantly higher than the best practice value, indicating that a strong potential for energy efficiency improvements. Thermal energy generated by rotary kiln and pre-calciner is used for clinker formation. From thermal energy generated about 50.02 % is useful for clinker production. The other is waste through different section of the plant. Most of waste heat in cement plant is unavoidable heat but can be reduced. Those types of thermal energy waste possible to reduce are:

- Waste heat with clinker exit
- Waste heat from a surface of rotary kiln shell, TAD, Pre-heater cyclone and grate cooler
- Waste heat by exhaust gas through pre-heater chimney
- Waste heat by exhaust gas through cooler chimney

7.2 Ways of Thermal Energy Waste Improvement

7.2.1 Waste heat with clinker exit

According to design of the plant clinker temperature is 65 ^{0}C plus ambient air when exit from clinker cooler. But the actual temperature of clinker is up 250 ^{0}C *(Figure 5.3 direct measured temperature).* As temperature of clinker exit is increased sensible heat waste to environment is increased. From average temperature measured of clinker outlet which is tabulated in Table 5.7 is 159.8 ^{0}C. At this temperature a clinker can hold thermal energy of 176.1kJ/kg-clinker, according to equation 5.22. But from design of system at a temperature of 65 ^{0}C the waste energy holding heat is 66.3 kJ/kg-clinker. By finding a difference between design and measured temperature around 110 kJ/kg-clinker heat is waste which equal to $4.1\text{x}10^{-3}$ kg-coal/kg-clinker. To improve at design temperature the cooling air supplied by Induced Draft Fan is properly flow inside the clinker cooler and heat is exchange properly during clinker is transported by lane.

7.2.2 Waste heat on Rotary Kiln Shell

Rotary kiln is a cylindrical shape where material burning and phase change is take place for clinker formation. Maximum temperature of the system is occurred in rotary kiln which is up to 1500 ^{0}C. To reduce maximum heat transfer from inside rotary kiln to environment the internal part is insulated by bricks. But due to maximum heat generation by coal combustion the external shell of rotary kiln is hot and temperature is reach up to 400 ^{0}C. From Table 6.13 the average measured temperatures on length of rotary kiln shell is 334 ^{0}C. The waste heat from rotary kiln by radiation and convection is 236.69 kJ/kg-clinker as chapter 6 result of heat output from kiln shell surface. This thermal energy is equals to 8.74x10^{-3} kg-coal/kg-clinker for a coal of gross calorific value 27088.35 kJ/kg. To reduce heat waste from rotary kiln shell using proper bricks material for insulating the internal shell and maintain by schedule. If the brick thickness is reduced by heat, coating accumulation is increase so the amount of heat transfer to environment through kiln shell is increased or insulation capacity of brick is decreased.

The other possibility of reducing waste heat from rotary kiln is recovering for pre-heating a primary air. A 50 °C rise in combustion air temperature provides a 3% energy saving (Monfort and Escrig, 2014). By construction of duct on surface, of a rotary kiln and the primary air is flow in the duct for pre-heating (Figure 7.1).

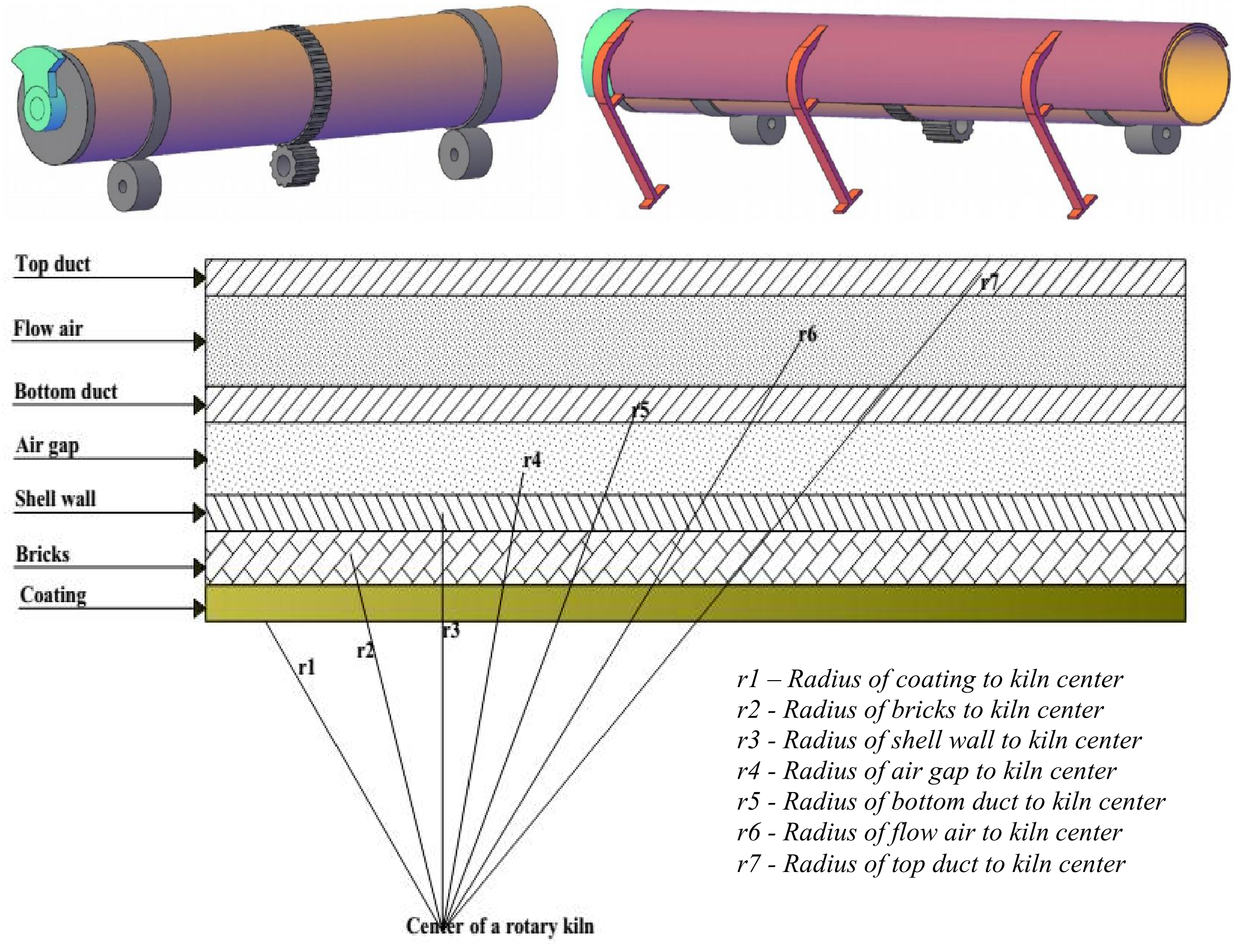


Figure 7.1 3D and sectional view of rotary kiln with primary air pre-heater duct

If temperature of primary air is increased it causes increasing sensible heat for heat input. From mass and energy balance of a plant a primary air requirement is around 25 %, the other 75 % using by secondary air and tertiary air for combustion.

Working principles of pre-heating primary air:

1. Ignition inside kiln and pre-calciner is started. At this time, mass flow rate of coal and primary air is constant. The temperature of coal and primary air is 70 and 25 ^{0}C respectively. Constant flame temperature is generated inside a rotary kiln.
2. The temperature inside rotary kiln is increase heat and cause for heat transfer from inside to outside shell. The shell temperature is increase as inside temperature is increase.
3. When the shell temperature is increased the heat is transfer from shell to duct bottom surface. The air flow inside a duct is going to heat up by heat exchange with duct. Convective heat transfer is take place. As temperature of primary air is increase the sensibility heat for input heat is increased. So if input heat is increased the mass flow rate of coal is decreased for flowing constant input heat.

Sensible heat of primary air at mass of 0.35kg/kg-clinker and temperature of 25^{0}C is 8.8kJ/kg-clinker. If primary air temperature increase to 150 ^{0}C by duct installed on rotary kiln, sensible heat is increased to 53.445kJ/kg-clinker. Then additional energy is 44.65kJ/kg-clinker which is equal with $1.65*10^{-3}$ kg-coal/kg-clinker.

$Q = M_{air} * C_{p,air} * \Delta T_{air}$………………..……………………………………………… (7.1)

Where: Q – Sensible heat of air

From equation 7.1, if temperature is increased specific heat capacity will increased, that means at constant mass flow rate sensible heat (Q) is increased.

To find mass of coal saved from input heat:

$Q_C = Q_1 + Q_2 + Q_5$ ………………………………………..…………………………….. (7.2)

Where: Q_C - Heat generated *(Depend on primary air temperature)*

Q_1 - Heat generated by coal combustion *(Equation 5.14)*

Q_2 - Sensible heat of coal *(Equation 5.15)*

Q_5 = Sensible heat of primary heat *(Equation 5.18)*

Q_C = 3297.2kJ/kg-clinker

By rearranging equation 7.2, then the mass of coal saved can be obtained:

$M_{Saved} = (Q_c - M_{P,air} * C_{p,p,air} * T_{p,air}) / (GCV + C_{p,coal} * T_{coal})$…………………………...….. (7.3)

Where: M_{Saved} – Mass of coal saved per clinker *(kg-coal/kg-clinker)*

7.2.3 Waste heat by hot exhaust gas through pre-heater and cooler

Exhaust gas is the mixture of different combustion and calcinations product such as CO_2, SO_2, NO_2 and H_2O as vapor. Temperature of exhaust gas is reach up to 350 ^{0}C from both pre-heater and cooler exhaust. From energy balance the waste heat by exhaust gas through pre-heater at 290 ^{0}C is 669.46kJ/kg-clinker and for cooler at 280 ^{0}C the waste heat is 281.01kJ/kg-clinker. The total waste heat by exhaust gas is 950.47kJ/kg-clinker which is equal to 0.035kg-coal/kg-clinker. The purpose of exhaust gas from pre-heater is in partially used for raw mill and coal mill for moisture remove before grinding process is starting. The rest of hot flue gas is waste to environment. But it is possible to reduce hot gas temperature waste to environment by using waste heat recovery system.

Waste heat recovery system is a technology used to generate electricity from waste heat by using boiler and steam turbine *(Stanley et al., 2017).* To improve electrical energy consumption of the plant it's possible to generate electricity by using waste heat recovery system (WHRS) from exhaust gas. To generate steam hot flow gas from pre-heater or cooler is entered to WHRS Boiler, and then heat exchange is take place between hot gas and water in the boiler. The steam generated from the boiler is flow to steam turbine to rotate turbine and generating electricity. Figure 7.2 shows waste heat recovery cycle system from hot flue gas of pre-heater and clinker cooler.

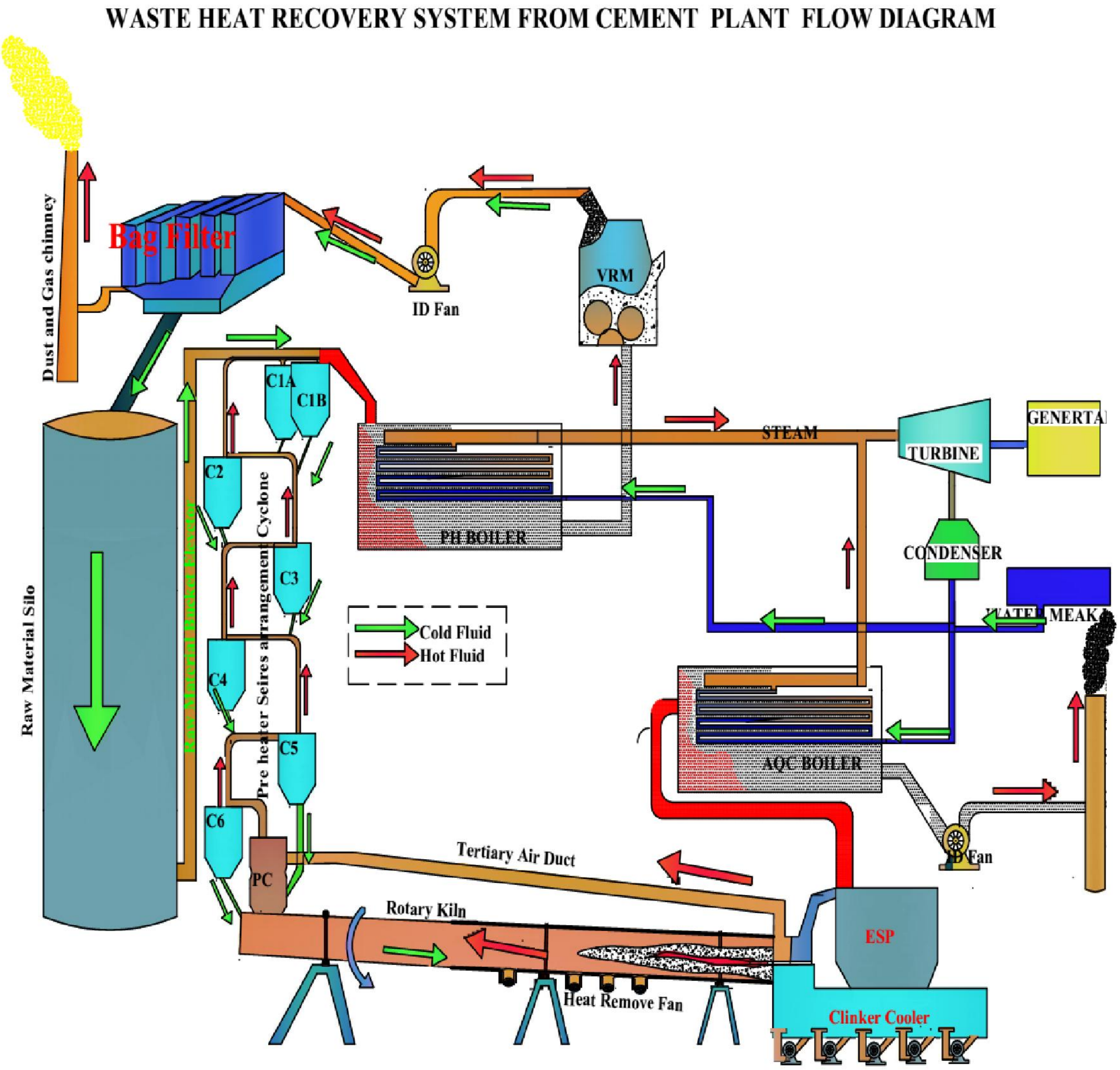


Figure 7.2 Waste heat recovery systems from cement plant

7.2.3.1 Waste heat design parameters

A waste heat recovery system is complex system with multiple interrelated sub-systems *(Holcim, 2013).* The WHR system consists of Suspension pre-heater boiler, Air Quenching Chamber boiler, steam turbine generator, water-circulation system and dust-removal system. A thermodynamic cycle used for WHRS Rankine Cycle. Rankine cycle is converts heat into work *(Cengel and Boles, 2005).* For install of WHRS the factors to be considerable is 1) moisture content of raw material and coal, 2) capacity of plant and 3) water availability. In Table 7.1 general parameters to design power generation by waste heat recovery system is given.

Table 7.1 Waste heat recovery system design specification

Item	***Symbol***	***Specification***
Pre heater type	-	CNCS3016 Pre-heater
Type of Pre-calciner	-	CDC301 Pre-calciner
Applicable fuel	-	Heavy oil, Coal and Natural gas
Applied to kiln	-	Φ4.4×66m
Production capacity	-	3144.73TPD
System pressure loss	-	<5500Pa
System dust collection efficiency	-	≥93%
Number of stages in the pre-heater	-	6
Pre-heater exit gas details:	-	
a. Mass of gas	$M_{PH,Ex}$	2.802kg /kg clinker
b. Specific heat capacity	$C_{P\ PH,Ex}$	1.508 kJ / kg / ^{0}C
c. Temperature	$T_{PH,Ex1}$	290 ^{0}C
Cooler exit gas details:		
a. Mass of gas	$M_{C,Ex}$	1.901kg /kg clinker
b. Specific heat capacity	$C_{PC,Ex}$	1.328 kJ / kg / ^{0}C
c. Temperature	$T_{C,Ex1}$	280 ^{0}C
Limestone moisture content	-	2%
Raw mill running hrs	-	22HPD (Average opr.hr.)
Kiln running days per annum	-	300 days
Heat transfer efficiency of Waste Heat Recovery (WHR) boiler for pre-heater	$\eta_{WHR,PH}$	85 %
Heat transfer efficiency of Air Quenching Chamber (AQC) boiler	$\eta_{AQC,C}$	85 %
Turbine Generator (TG) efficiency	η_{TG}	33 %
Total heat consumption	SHC	*3547.57 kJ/kg-clinker*
Raw coal moisture	-	15 %
Raw meal to clinker factor	RMF	1.57
Heat requirement for moisture in raw mill and Coal mill	-	3980.5kJ /kg water (*Assumption)*
Calorific value of fine coal used	GCV	270888.35kJ/ kg coal
Coal mill running	HPD	20hrs per day
PH gas temperature at WHRB outlet	$T_{PH,EX2}$	240 ^{0}C (*Assumption)*
Cooler exit temperature at AQC boiler outlet	$T_{C,EX2}$	180 ^{0}C (*Assumption)*

Waste heat recovery and power generation calculations:

1. Heat available in the pre-heater gas:

$Q_{PH,Ex} = M_{PH,EX} * C_{PPH,EX} * T_{PH,EX1}$……………....…………………………………..……..... (7.4)

Where: $Q_{PH,Ex}$ – Heat content of hot gas from pre-heater

$Q_{PH,Ex}$ = 669.08kJ/ kg clinker

2. Heat requirement for raw mill: Vertical roller mill is requires 900 to 1100 kcal of heat per kg of moisture (Bruce, 2014). Heat required is calculated by eqn 7.7

A) Vertical raw mill capacity = $TPD_{Clinker}$ * RMF * 24/operation hour of raw mill…….... (7.5)

Where: $TPD_{clinker}$ – Mass of clinker production per day

Raw mill capacity = 3144.73 * 1.57 * 24 / 22

= 5386 TPD

= 1.712kg/kg clinker

B) Moisture in raw mill = $\frac{\text{Raw mill TPH}* \text{ (weight of raw meal)\%}}{(weight\ of\ raw\ meal - weight\ of\ moisture)\%}$ - Raw mill TPH……….. (7.6)

= [224.4 * 100 / (100 - 2)] – 224.4

= 4.6 TPH

= $0.035T_{moisture}/T_{clinker}$

= 35 kg-moisture /ton- clinker

C. Heat requirement for raw mill = moisture in raw mill * heat of moisture removes…….. (7.7)

= (35kg of moisture/ton-clinker) * (3980.5kJ/kg-moisture)/1000

≈ 139kJ/ kg clinker

3. Heat requirement for coal mill:

A) Coal mill capacity = SCC * $TPH_{Clinker\ production}$ * coal meal operation hour per a day…….. (7.8)

= 19.03TPH

B) Moisture evaporation in coal mill = $\frac{\text{coal mill TPH}* \text{ (weight ofcoal)\%}}{(weight\ of\ coal - weight\ of\ moisture)\%}$ - coal capacity TPH

= [19.03 * 100 / (100 – 15)] – 19.03

= 25.6kg /Ton of clinker

C) Heat requirement for raw coal mill = moisture in coal * heat of moisture remove

= 25.6 * 3980.5/1000

≈ 102kJ/ kg clinker

Excess heat available in the pre-heater ($Q_{PH,ex}$):

$Q_{PH,ex}$ = Heat available in the pre-heater gas minus heat required for coal mill and raw mill

= [669.49 – (139 + 102)] kJ/kg-clinker

= 428.49kJ/ kg clinker

Heat available in the Cooler exit gas ($Q_{12C,EX}$):

($Q_{12C,EX}$) = 281.01kJ/kg-clinker

Total excess or waste heat available = $Q_{PH,ex}$ + **($Q_{12C,EX}$)**

$= (428.49 + 281.01)$ kJ/kg-clinker

$= 709.5$kJ/ kg clinker

4. Heat recoverable in Pre-heater side Boiler

$Q_{WHRB,PH} = M_{PH,EX} * C_{P\ PH} * (T_{PH,EX1} - T_{PH,EX2})$……………..……………………….…... (7.9)

Where: $Q_{WHRB,PH}$ – Heat recovered from pre-heater boiler

$Q_{WHRB,PH} = 2.802$kg/kg-clinker * 1.508kJ/kg/^{0}C * $(290 – 220)^0$C

$= 296.8$kJ/ kg clinker

5. Heat recoverable in Cooler side Boiler

$Q_{AQC} = M_{C,EX} \times C_{PC} * (T_{C,EX1} - T_{C,EX2})$……………………………………….…… (7.10)

Where: $Q_{AQC,C}$ – Heat recovered from Cooler boiler

$Q_{AQC} = 1.901$kg/kg-clinker * 1.328kJ/kg/^{0}C * $(280 – 180)^0$C

$= 252$kJ/ kg clinker

6. Heat available to steam for power generation

$= Q_{WHRB,PH} * \eta_{WHR,PH} + Q_{AQC,C} * \eta_{AQC,C}$……….………………...…… (7.11)

$= 169$kJ/kg-clinker x 0.85 + 219kJ/kg-clinker x 0.85

$= 466$kJ/ kg clinker

7. Power generation possible

= Heat available in the steam x η_{TG}…………………………….….. (7.12)

$= 466$kJ/kg-clinker x 0.33

$= 154$kJ/ kg clinker

To convert the power generated into standard power unit = $\frac{\text{Power generation possible}}{3600/hour}$

$$= \frac{154kJ/kg-clinker}{3600/hour}$$

$= 0.0428$ kWh /kg-clinker

$= 42.8$kWh /ton of clinker * 131TPH (*Table 1A in Appendix*)

$= 5608$kW

8. Water requirement for Water cooled condenser:

Heat to be removed in the condenser:

$= 466$kJ/kg-clinker * (100 – 33)/(0.85 x 100), *(for 0.85 and 0.33, boiler and turbine efficiency)*

$= 367$kJ/kg clinker

Makeup Water: is necessary to offset cycle water losses, the most significant of which is boiler blow down. Values between 0 and 3% are typical needed for each circulation *(Black and Veatch, 1996)*. The makeup water flows through the condensate and feed water systems, increasing the total flow through the heaters and pumps.

$$\text{Make up Water requirement} = \frac{367 \text{ kJ/kg−clinker}}{2262.6 \text{ kJ/kg−water}}$$

Theoretically about 540 kcal (2262.6kJ/kg-clinker) is required to evaporate or remove one kg of moisture from raw meal per limestone *(Philip, 2001).*

$$= 0.162 \text{kg water/kg clinker}$$

$$= 0.162 * 131 \text{TPH}$$

$$= 21.3 \text{ TPH}$$

$$\text{Water requirement per power generated} = \frac{\text{Make up Water}}{\text{Power generated}}$$

$$= \frac{21.3\text{TPH}}{5.608 MW}$$

$$= 3.8 \text{ MT/MW}$$

From the exhaust gas of pre-heater and grate cooler steam combination 5.608 MW of electricity can be generated. If amount of this power is recovered, the plant can save the price to pay for 5.608 MW. Assuming if the factory operates continues for 10 month, the operation hour is 7200. So the energy saved per year is calculated by *equation 7.13.*

Gross Annual Power Generation = Power generated * hours of usage ……………………. (7.13)

$$= 5608\text{kW} * 7200 \text{ hour}$$

$$= 40.4 * 10^6 \text{kWh/yr}$$

Thermal efficiency of factory if the waste heat is improved:

$$\text{Thermal efficiency (new)} = \frac{Total\ heat\ input - Total\ waste\ heat}{Total\ heat\ input} * 100 \quad \text{(7.14)}$$

Q_{WASTE} = Total heat output ($Q_{OUT,\ TOTAL}$) – Heat for clinker formation (Q_8) - Heat recovered

Heat recovered = heat from (clinker exit + pre-heater + clinker cooler + rotary kiln)

$$= 297.9 \text{kJ/kg-clinker}$$

$$= (3547.57 – 1774.46 – 297.1) \text{ kJ/kg-clinker}$$

$$= 1475.21 \text{kJ/kg-clinker}$$

$$\eta_{\text{Thermal,new}} = \frac{3547.57 - 1475.21}{3547.57} * 100$$

$$= 58.42\%$$

CHAPTER EIGHT

ECONOMIC EVALUATION OF MUGHER CEMENT FACTORY

8.1 Economic evaluation of thermal energy waste

Cement industry is one among the most energy intensive industries. From the result of energy balance summary around 49.98 % heat is waste from the system by unavoidable way. Around 50.02 % of heat generated from the combustion process is used for clinker formation. The plant has consumed 3547.57 kJ/kg-clinker of total thermal energy. Coal consumption by plant is around 380.34 TPD as a data collected from plant on a fully operation per a day *(Table 1A in Appendix),* from September 5/2018 to January 20/2019 and specific coal consumption of 0.121kg-coal/kg-clinker. When the waste heat from a plant is in terms of specific mass of coal consumption the plant lost around 0.065 kg-coal/kg-clinker which is 301,099,500 Birr per annual for a price of coal in Ethiopia today is 5147 Birr per ton and plant design capacity. But the plant have a chance to save a coal by improving clinker cooler, modification system on rotary kiln for primary air pre-heating and generating electric power from waste heat of flue gas from pre-heater and cooler. The coal captured from each system is:

1. From clinker cooler = 110 kJ/kg-clinker = $4.06*10^{-3}$ kg-coal/kg-clinker
2. From rotary kiln shell = 44.65 kJ/kg-clinker = $1.65*10^{-3}$ kg-coal/kg-clinker
3. From waste gas of pre-heater and cooler = 154 kJ/kg-clinker (Net heat)
   = $5.69*10^{-3}$ kg-coal/kg-clinker

Total mass of coal possible to save = $1.1*10^{-2}$ kg-coal/kg-clinker

Total thermal energy possible to save = 297.9 kJ/kg-clinker

Price per mass of clinker = 56.62 Birr/ton-clinker

8.2 Cost of waste heat recovery and annual saving.

8.2.1 Primary air pre-heater construction cost evaluation and annual saving

According to design of primary air pre-heater, the cost of material and installation is estimated to 1,300,000 Birr. This price includes material cost and installation. By increasing temperature of a primary air to 150 ^{0}C through a duct, which is a result of sensible heat increment is by 53.445kJ/kg-clinker; the amount of coal saved is $1.65*10^{-3}$kg-coal/kg-clinker. A price of coal saved is 4,336,037 Birr per year. The time to recovery cost of project can be calculated by simple payback period, which is:

Payback Period = $\frac{Initial\ investment}{Cash\ inflow\ per\ period}$……………………………………………………8.1

Payback period = $\frac{1{,}300{,}000}{4{,}336{,}037}$

= 4 month.

Therefore the payback period is short and the factory can profitable after four month.

8.2.2 Waste heat recovery system installation cost and Payback period

The total capital cost of waste heat recovery system which includes equipment and installation is a strong function of a project size. The global waste heat recovery supplier a total installed costs for WHRS can range from US$7,000/kW for 2 MW systems to US$2,000/kW for 25 MW systems (Holcim, 2013). If the investment cost is US$2000/kW, then the project investment cost and payback period is summarized in Table 8.1. The cost expressed in a Table is a direct converted from US dollar to Ethiopian Birr by currency conversion of 30 Birr per dollar.

Total project cost = US$2,000/kW*5608 kW = US$11,216,000.

Table 8.1 Waste heat recovery installation cost and payback period

Item	***Value***
Clinker Production	3,000 TPD *(As factory design)*
Installed WHR Capacity	5608 kW
Annual Operating Hours (AOH)	300 day/year = 7200 hours
Gross Annual Power Generation (GAPG)	$40.4*10^6$ kWh *(Equation 7.13)*
Displaced Electricity Price	2.1240 Birr/kWh *(As industry tariff)*
Annual Electricity Savings (AES)	GAPG * 2.1240 Birr/kWh = 85,682,160 Birr
Annual operating and maintains costs (2.5)% (AO&MC)	AES *2.5/100 = 2,142,054 Birr
Net Annual Savings (NAS)	AES - AO&MC = 83,540,106 Birr
Total Investment (TI)	2000$/kWh * 5608kWh* 30 Birr/$ = 336,480,000 Birr
Simple Payback period	TI/NAS = 4 years

8.3 Benefit of the plant

If the plant recover a waste thermal energy from clinker exit, rotary kiln shell and hot flue gas of pre-heater and clinker cooler the thermal efficiency of a plant is increased by 8.4%. Also it improve coal consumption is by 9.1%.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The purpose of this study to analyzing performance of Mugher cement factory on thermal system. Mugher cement factory is consuming large amount of thermal energy for clinker production. Bituminous coal is used as source of thermal energy in pre-calciner and rotary kiln by combustion process. The thermal energy required for clinker formation is 1774.46kJ/kg-clinker, but due to unavoidable way huge waste heat is occurred in this plant. Form energy balance of the system the highest thermal energy source is from coal combustion and other is from sensible heat of material flow to kiln.

A thermal performance of a plant is evaluated from energy balance that can be in form of input and output heat. The waste heat occurred on surface of plant is obtained by convection and radiation heat which is calculated from measured temperature on each surface. The thermodynamic property of air is obtained from appendix Table 2A to 6A. Thermal efficiency of the plant obtained by study is 50.02% and the specific energy consumption is 3.277GJ/ton-clinker. The result found from waste heat on all surface of the plant is expressed in chapter six by Figures and Table. Therefore by study, discovered Mugher Cement Factory has a massive waste of thermal energy and less efficiency.

In the plant there is area where the waste heat can reduce and recovered. If the waste heat from clinker cooler, waste heat gas from pre- heater and rotary kiln shell is recovered there is a thermal energy saving up to 297.9kJ/kg-clinker. Also thermal efficiency of a plant can improve by 8.4%. Generally if the plant possible to recover a 44.65kJ/kg-clinker thermal energy lost from kiln shell and generate 40.4 $*10^6$kWh/year electric power from hot flue gas exhaust from pre-heater & cooler, it would be possible to save currency about 87,876,143 Birr in annual.

9.2 Recommendations to a factory

After further detail work and feasibility study, there is a possible need of complete modification to improve thermal efficiency.

- Internal kiln maintenance should be by designed schedule.
- Pre-heater, pre-calciner and tertiary air duct can be reduced by insulating them.
- In addition to the plan of reducing of energy consumption in cement production process, the recovery waste heats can be achieved in order to produce the electrical energy by utilization cogeneration power plant. As indicated above, the plant alone can provide about 5608 kW.
- If the plant recover waste heat on rotary kiln shell for the use of pre-heating primary air it can increasing thermal efficiency of a plant.

9.3 Recommendations to future work

- Detail study on clinker cooler for heat recover to reduce red river at kiln outlet
- Overall insulating of pre-claciner, pre-heater and tertiary air duct to improve rather thermal performance.
- Performance of thermal system improvement and Green gas house emission relation in cement plant.
- Using of alternative fuel for thermal energy consumption improvement.

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APPENDIX A

CLINKER PRODUCTION AND THERMODYNAMIC PROPERTIES OF AIR AT AVERAGE TEMPERATURE

Table 1A: Clinker production data sheet of Mugher Cement Factory by Coal (24 op.hr)

Date of data Recorded	*Material feed to kiln (TPD)*	*Clinker production (TPD)*	*Coal Consumed (TPD)*			*SCC (ton-coal/ton-clinker)*
			Kiln	*CDC*	*Total*	
5/9/2018	5046	3214	142.5	244.4	386.9	0.12
8/9/2018	4499	2866	145	222	367	0.128
17/9/2018	5092	3243	136.3	249.5	385.8	0.119
18/9/2018	5143	3276	138.4	241.3	379.7	0.116
19/9/2018	5153	3282	135.9	251.9	387.8	0.118
7/10/2018	5141	3275	143	243.5	386.5	0.118
9/10/2018	5239	3337	151.2	248.6	399.8	0.12
10/10/2018	5297	3374	154.9	250.8	405.7	0.12
11/10/2018	5140	3274	152	245.7	397.7	0.12
27/10/2018	5051	3217	149.3	251	400.3	0.124
11/11/2018	4194	2671	144.5	211.7	356.2	0.133
12/11/2018	4476	2851	145.4	220.9	366.3	0.128
11/1/2019	4698	2992	152.5	238.5	391	0.131
17/1/2019	4889	3114	148.4	207.4	355.8	0.114
20/1/2019	5601	3185	139.6	199	338.6	0.106
Average	**4977.27**	**3144.73**	**145.26**	**235.08**	**380.34**	**0.121**

CDC: Pre-Palciner burner, SCC: Specific coal consumption

Table 2A: Air Property at average temperature of pre-heater cyclone and ambient air

	Air properties	T. ave (^0C)	Density (kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)	Dynamic viscosity (Kg/ms)	Prandtl number
	Symbol	T_{ave}	ρ_a	C_{pa}	K	μ	Pr
Cyclone 1	Frustum	60	1.0468	1008.8	0.02859	$2.01x10^{-5}$	0.71
	Material duct	65	1.0312	10092	0.0281	$2.04x10^{-5}$	0.7096
	Cyclone surface	44	1.0996	1007.76	0.02744	$1.94x10^{-5}$	0.712
Cyclone 2	Frustum	71	1.0123	10097	0.0294	$2.06x10^{-5}$	0.71
	Gas duct	50.5	1.0764	1008	0.02792	$1.97x10^{-5}$	0.711
	Material duct	66	1.0281	1009	0.02902	$2.04x10^{-5}$	0.7095
	Cyclone surface	65	1.0312	1009	0.02895	$2.04x10^{-5}$	0.71
Cyclone 3	Frustum	74.5	1.00156	1010	0.0296	$2.08x10^{-5}$	0.71
	Gas duct	62.5	1.053	1009	0.0288	$2.02x10^{-5}$	0.71
	Material duct	107.5	0.932	1013	0.0315	$2.23x10^{-5}$	0.71
	Cyclone surface	103	0.94	1012	0.0316	$2.21x10^{-5}$	0.71
Cyclone 4	Frustum	102.3	0.94	1012	0.0316	$2.21x10^{-5}$	0.71
	Gas duct	82.5	0.993	1011	0.0302	$2.12x10^{-5}$	0.71
	Material duct	132.5	0.873	1016	0.0336	$2.33x10^{-5}$	0.71
	Cyclone surface	52.5	1.084	1008	0.02806	$1.98x10^{-5}$	0.71
Cyclone 5	Frustum	100	0.945	1012	0.0314	$2.19x10^{-5}$	0.71
	Gas duct	72.5	1.021	1010	0.0295	$2.07x10^{-5}$	0.71
	Material duct	162.5	0.811	1020	0.0355	$2.46x10^{-5}$	0.705
	Cyclone surface	112.5	0.917	1014	0.0322	$2.25x10^{-5}$	0.71
Cyclone 6	Frustum	152.5	0.8291	1018.4	0.0349	$2.42x10^{-5}$	0.705
	Gas duct	72.5	1.021	1010	0.0295	$2.07x10^{-5}$	0.71
	Material duct	187.5	0.7674	1024	0.0371	$2.56x10^{-5}$	0.705
	Cyclone surface	130	0.8782	1016	0.0334	$2.32x10^{-5}$	0.706

Table 3A: Air Property on Pre-calciner surface and ambient air (Average)

Air properties		T. Ave (^{0}C)	Density (kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)	Dynamic viscosity (Kg/ms)	Prandtl number
		T_{ave}	ρ	Cp	K	µ	Pr
Pre-Calciner	Frustum	80	0.9997	1010	0.03	2.10x10^{-5}	0.7084
	Gas line duct	107.5	0.9285	1013	0.0319	2.23x10^{-5}	0.707
	Cyclone surface	82.5	0.993	1011	0.0302	2.12x10^{-5}	0.71

.

Table 4A: Air Property on tertiary air duct surface and ambient air (Average)

	Length (m)	Density (kg/m^3)	Specific heat (J/kg^{0}C)	Thermal conductivity (W/mK)	Dynamic viscosity (Kg/ms)	Prandtl number
Average Temperature (^{0}C)	**L**	P	Cp	K	µ	Pr
167.5	Inlet	0.8026	1021	0.036	2.48x10^{-5}	0.705
162	0 – 20	0.8123	1020	0.0355	2.46x10^{-5}	0.705
151.5	20 – 40	0.831	1018	0.0348	2.41x10^{-5}	0.705
141	40 – 60	0.854	1017	0.0341	2..37x10^{-5}	0.705
133	60 – 68	0.871	1016	0.0336	2.33x10^{-5}	0.706
131	68	0.8026	1021	0.036	2.33x10^{-5}	0.706

.

Table 5A: Air Property on Rotary kiln shell and ambient air (Average)

Average Temp (^{0}C)	**Length (m)**	Density (kg/m^3)	Specific heat (J/kg^{0}C)	Thermal conductivity (W/mK)	Dynamic viscosity (Kg/ms)	Prandtl number
	L	P	Cp	K	µ	Pr
173	0 - 6.58	0.793	1022	0.0362	2.5x10^{-5}	0.705
202.5	6.58 - 16.05	0.742	1027	0.0381	2.62x10^{-5}	0.7052
206	16.05 - 26.55	0.74	1027	0.0383	2.63x10^{-5}	0.705
202	26.55 - 35.25	0.7427	1026	0.0381	2.62x10^{-5}	0.7052
166.5	35.25 - 44.53	0.8044	1021	0.036	2.47x10^{-5}	0.705
165	44.53 - 53.53	0.807	1020	0.0357	2.451x10^{-5}	0.705
141.5	53.53 - 58.78	0.853	1017	0.0342	2.37x10^{-5}	0.7054

Table 6A: Air Property on Grate cooler surface and ambient air (Average)

Average Temp (^{0}C)	**Length (m)**	Density (kg/m^3)	Specific heat (J/kg^{0}C)	Thermal conductivity (W/mK)	Dynamic viscosity (Kg/ms)	Prandtl number
	L	P	Cp	K	M	Pr
77.2	0.0 -6.0	1.007	1010	0.02981	2.1×10^{-5}	0.71
90.2	6.0 - 12.0	0.972	1011	0.0307	2.15×10^{-5}	0.708
116.2	12.0 - 18.0	0.909	1014	0.0325	2.26×10^{-5}	0.706
129.8	18.0 - 24.0	0.879	1016	0.0334	2.32×10^{-5}	0.706
146.3	24.0 - 30.0	0.842	1018	0.0345	2.39×10^{-5}	0.705
159.67	30.0 - 35.0	0.816	1020	0.0354	2.45×10^{-5}	0.705

APPENDIX B

WASTE HEAT EQUATION FROM SURFACE OF PLANT

Table 1B. Summary of waste heat equation for pre-heater cyclone.

$Q_{PHS} = \sum_{i=1}^{6} Q_{PH,Ti}$	Q_{PHS} – Waste heat from pre-heater surface i – Represent number of cyclone $Q_{PH,T}$ – Waste heat from on cyclone
$Q_{PH,Ti} = Q_{RTi} + Q_{CVi}$	Q_{RTi} – Total radiation from each cyclone Q_{CVi} – Total convection heat from each cyclone
$Q_{RTi} = Q_{F,Ri} + Q_{G,Ri} + Q_{M,Ri} + Q_{CS,Ri}$	Total waste heat by radiation from each *frustum, gas duct, material duct and cyclone surface*
$Q_{CVTi} = Q_{F,CVi} + Q_{G,CVi} + Q_{M,CVi} + Q_{CS,CVi}$ $Q_{CV} = h * A_S * \Delta T$	Total waste heat by convection from each *frustum, gas duct, material duct and cyclone surface*
$Q_{CV} = \frac{\mathrm{Nu \times K \times A \times \Delta T}}{L_c}$	Free and forced convection waste heat
Q_{FRi}, Q_{GRi}, Q_{MRi}, $Q_{CSRi} = \sigma * \varepsilon * A_S * (T_{Sh}^4 - T_A^4)$	Waste heat by radiation from each cyclone component

Table 2B. Summary of waste heat equation for pre-calciner.	
$Q_{PC} = Q_{F,T} + Q_{GL,T} + Q_{CS,T}$	Q_{PC} – Total waste from pre-calciner $Q_{F,T}$, $Q_{GL,T}$, $Q_{CS,T}$ – Waste heat from pre-calciner frustum, gas line and cyclone surface
$Q_{F,T}$, $Q_{GL,T}$, $Q_{MD,T}$, $Q_{CS,T} = Q_R + Q_{CV}$	Heat waste by radiation and convection from each component of pre-calciner
$Q_R = Q_{F,R} + Q_{GL,R} + Q_{CS,R}$	Waste heat by radiation from each component
$Q_R = Q_{F,CV} + Q_{GL,CV} + Q_{CS,CV}$	Waste heat by convection from each pre-calciner component.

Table 3B. Summary of waste heat equation for TAD	
$Q_{TAD} = \sum_{i=1}^{4} Q_{TAD,Ti}$	Q_{TAD} – Total waste heat from tertiary air duct i – Interval (division of the system)
$Q_{TAD,Ti} = Q_{TAD,Ri} + Q_{TAD,CVi}$	Total waste by radiation and convection on TAD surface

Table 4B. Summary of waste heat equation for rotary kiln	
$Q_{RK} = \sum_{i=1}^{7} Q_{RK,Ti}$	Q_{RK} – Total waste heat from rotary kiln shell i – Interval (division of the system)
$Q_{RK,Ti} = Q_{RK,Ri} + Q_{RK,CVi}$	Total waste by radiation and convection on RK surface

Table 5B. Summary of waste heat equation for clinker cooler (GC)	
$Q_{GC} = \sum_{i=1}^{6} Q_{GC,Ti}$	Q_{GC} – Total waste heat from clinker cooler shell i – Interval (division of the system)
$Q_{GC,Ti} = Q_{GC,Ri} + Q_{GC,CVi}$	Total waste by radiation and convection on GC surface

APPENDIX C

AREA AND CHERCTRISTICE EQUATION OF SOME COMPONENT

Table 1C. Area and cherctristice equation of some component		
Shape	Area (A_S)	Cherctristics length (L_C)
Frustum	$\pi*(r + R) * (\sqrt{((R - r)^2 + h^2}\ )$	$\frac{\frac{\pi}{3}*h(R^2+r^2+R*r)}{\pi(R+r)*\sqrt{(R-r)^2+h^2}}$
Material duct	$2(W*L + W*h + L*h)$	$L_C = \frac{4*W*L}{8*(W+L)}$
Gas line duct	$\pi * D * L$	L
Cyclone surface	$\pi * D * L + \frac{\pi* D^2}{4} - \pi\frac{\pi * {D_{GD}}^2}{4}$	D
TAD	$\pi * D * L$	D
Rotary kiln	$\pi * D * L$	D
Clinker cooler	$\pi * D * L$	L