

CFD Modeling Of Waste Heat Recovery On The Rotary Kiln System in the Cement Industry

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ABSTRACT

The cement production process is one of the most energy and cost intensive in the world. In order to produce clinker, a cement industry requires the substantial energy consumption. About 70% of energy consumption lies on the unit of rotary kiln system. The higher amount of energy consumption is due to the lack of work efficiency tools leading the waste heat. This reserach was focus on modeling of the waste heat recovery in the rotary kiln system using CFD. Analysis of mass and energy balance was used to determine the sources of heat loss from kiln system. The results showed that the distribution of the input heat to the system is a good agreement with the output energy and gave the significant insights oft the reasons for the low overall system efficiency. The system efficiency is obtained of 53 %. The major heat loss sources have been determined as kiln exhaust (21.88% of total input), cooler exhaust to stack (9.62 % of total input) and heat loss astemated as heat from kiln surface (13.54 % of total input). The amount of heat energy can be absorbed by air amounted to 163,080 Kcal / hour and can be used as air for combustion of fuel. Based on data calculation, the amount of coal can be saved amounted to 738 kg / day.

INTRODUCTION

Research on waste heat recovery has been mostly conducted in various fields. One of potential tools for implementing the waste of heat recoveryis kiln in the cement industry. Waste heat recovery research on the particular types of dry kilns has been conducted by several researchers. Enginand Vedat(2004) conducted a case study about energy auditing and recovery for dry type cement rotary kiln systems of a cement factory in Turkey. They calculated the amount of possible energy that can be recovered using the method of energy audits in a way

to make mass and energy balance of the kiln system. They discussed several systems to recover waste heat energy on the kiln system for the use of waste heat recovery steam generator (WHRS), pre-heating the raw materials, and heat recovery. These applications were calculated to produce how much energy and production cost savings that can be done. Kabiret.al.(2009) applied the basics theory of waste heat recovery on the existing cement industry in Nigeria. Their results showed that the electrical energy can be saved for 42.88 Mw / year and reduced the emissions of green house gasses of about 14.10%.

The cement industry absorbs the large amount of energy. The energy sources come from the fuel, electricity, explosives, *etc.* Heat energy derived from fuel combustion in the kiln is the largest energy demand which reach more than 75 % of the total energy requirements. Loss a number of energy consumption in the cement industry is usually caused by a lack of work efficiency. A number of energy produced from the fuel is not fully utilized in the process. There are a number of heats lost from the system through the hot exhaust gas, cooling stack and kiln wall surface. In this work, the heat recovery was emphasized on the kiln wall surface.

Kiln is a tube-shaped device where the burning process is occurred by fire. It is designed to maximize the efficiency of heat transfer from the combustion of fuel at the higher temperature. The high temperature leads the temperatures around the kiln is also further increased and dumped into the environment. Heat around the kiln temperature is called as a waste heat. Waste heat can be used as a source of energy. It can be recovered for saving of the production cost.

Mass and energy balance was made to calculate amount of heat lost from the kiln system and analyze the balance sheet to determine sources of heat loss from the system. Amount of heat was used as waste heat recovery from the system for several purposes such as pre-heating of fuel and raw materials, and the steam generator so that the total system energy consumption can be reduced.

The objective of this study is to investigate the waste heat recovery in a cement company. It provides a concept that can be useful for a cement company in conducting of energy savings for the production. It can also reduce greenhouse gas emissions generated at the same time reduce production costs. The advantage of the hot exhaust air flowing through the kiln wall is applied as a fuel in the pre-heater to burn coal.

UTILIZATION OF FLUE GAS FROM THE ROTARY KILN SYSTEM CONCEPT

Cement production process requires the substantial energy which reach 4 GJ per ton. In the theory, the production of one ton of clinker requires 1.6 GJ heat (Liu *et.al.*, 2004). However, the average energy consumption of cement production resulted by the kiln is about 2.95 GJ per ton, while the excess energy

consumption of other countries could reach 5 GJ/ton. For example, a manufacturer of clinker factory in China requires an average energy consumption of 5.4 GJ / ton (Khurana *et.al*, 2004). Based on these data, it can be concluded that there are a number of heats lost from the system. Amount of the excess energy is can be utilized potentially as a form of work efficiency tools.

Ideally, all of the heat injected into a kiln or furnace should be used entirely for heating the load or stack. However, in practice, the number of heat is lost in several ways such as loss of exhaust gas, loss of water content in the fuel, the loss due to hydrogen in the fuel, the loss through the opening in the furnace, the loss of the furnace wall / surface, and the other losses. The existence of the heat losses caused the lack of efficiency in the performance of the kiln. Therefore, it is important to optimize the thermal efficiency of the kiln so that the heat loss can be utilized as an energy source using Waste Heat Recovery (WHR).

To determine how many heats can be recovered from the equipment or a system, the important thing to do is to make the analysis of mass balance and energy balance in the system. The objective is to calculate the amount of energy lost from the system and analyze the amount of energy that can be utilized. The energy lost from this system can be recovered as a source of energy for other processes. The manufacturing process in a Cement company produced large amounts of waste heat generated from the kiln or furnace. Waste heat is generated by fuel combustion or chemical reactions. It is then purged into the environment and not used any more for the purpose of economical.

At the beginning of the cement manufacturing process, the mixture of cement materials pass through the stages such as mining materials, weighing, drying. Then, it is accompanied by the destruction of materials, combustion, cooling, and grinding. Finally, it was stored in the reservoir which is called by Silo. These stages produce high quality cement with a high selling price. The process that can determine the outcome of a cement product is the burning process in the furnace turn which is called by a kiln. It is used to burn material that has been destroyed by heat in the raw mill kiln. The temperature reached 1400 °C – 1500 °C, so the material is crushed and melted.

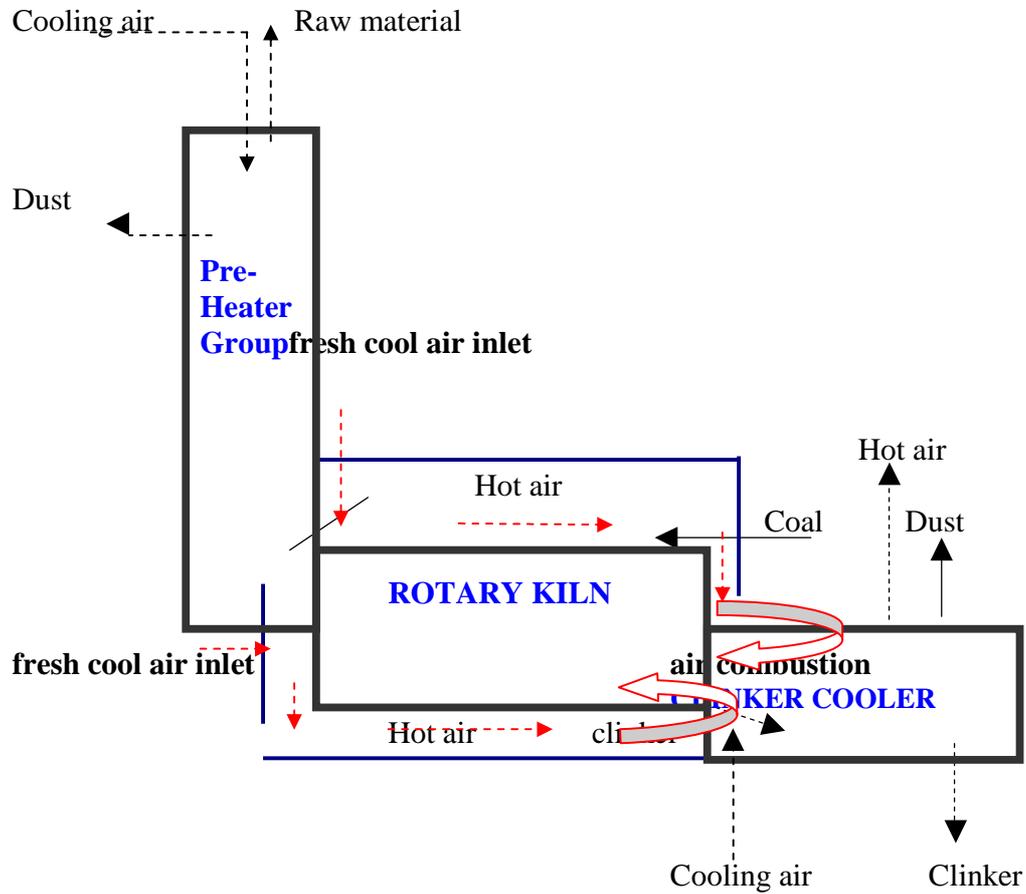


Figure 1 Utilization of Flue Gas from the rotary kiln system concept

Cold air flows through the secondary shell and intersects with the surface of the kiln directly. In this event there is a heat transfer from the wall of the kiln into the air so that air temperature increases. This hot air flows into the kiln as a secondary air for combustion. Exhaust gas from the system goes on the stream in conjunction with the air so that air temperature rises highly. This transformation needs the fuel combustion reaction heat economically because of the heat contained material be returned as a secondary combustion air.

RESULTS AND DISCUSSIONS

A. Data Collected

The data was taken from the PT. X which is collected during six months within June to December 2010. The data applied in this study is the averaged values. The data collected in the forms of:

- data of production process,
- installed equipment design follows the pattern of operation,
- average production data for six months
- consumption of raw materials and products
- energy and fuel consumption

The data was analyzed in the form of mass and energy balance. Profiles of thermal energy use were made to obtain the thermal balance analysis of equipment such as the kiln combustion chamber and pre-heater / pre-calciner. For the calculation of mass and energy balance requiring data such as: fuel, raw materials and products, combustion air flow rate, wall temperatures, ambient temperatures and others.

The plant uses a dry process with a series of cyclone type pre-heater and an incline-kiln. The kiln is 4,5 diameter and 75 m long. The average daily production capacity is 4200 ton per day, and the specific energy consumption has been estimated to be 760 kcal/kg clinker. The compositions of raw material, clinker components and their percentages, and fuel were determined using standard procedures; the results are presented in Table 4.1 and Figure 4.2.

Tabel 4.1. Raw Material and Clinker Composition

Components	Raw Material (wt %)	Clinker (wt %)
CaO	42.43	63.86
MgO	0.72	1.87
SiO ₂	13.95	21.68
Al ₂ O ₃	3.69	5.76
Fe ₂ O ₃	2.23	3.60
K ₂ O	0.88	0.67
H ₂ O	0.24	-
SO ₃	0.43	0.79
Loss on ignition	35.43	1.77
Total	100	100

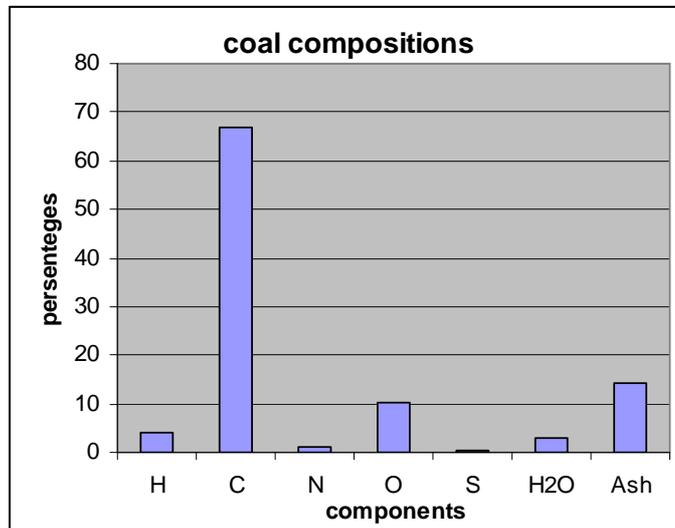


Figure 4.1 Coal Compositions

Based on the coal composition, the net heat consumption value is found of 890 kcal / kg clinker. The coal used in PT. X has a calorific value ranges between 5300 - 6400 kcal/kg as the primary fuel in the production process. The amount of coal required totally is about 25.5 tons per hour that consist of 10.3 tons per hour for kiln requirements and 15.2 tons per hour for the calciners. Data analysis technical for coal has been shown in table 4.2.

Table 4.2 **Technical Analysis Coal (%)**

Fixed Carbon	63.86
Volatile Matter	43.50
Ash	10.14
Sulfur	0.50
Moisture	12.00
Caloric Value Coal	6,200 kcal / kg
Pulverized Coal Fineness & Moisture:	
- Residue >90 U	17
- Residue >200 U	0.2
- Moisture	3

Combustion of coal provides the heat required for the reactions in the rotary kilns. Generally, it was operated on low fuel consumption without affect the quality of clinker produced. This could be achieved through an understanding on how the fuel is burnt and how efficient is utilised during burning. However,

energy audit is the technique used to evaluate the thermal energy performance of the kiln system (Kabir, et.al, 2009).

B. Analysis of Mass and Energy Balance

Mass and energy balance analysis is a technique used to evaluate the presence of heat energy from a process unit (rotary kiln system). This is a quantitative analysis of the overall calculation of a unit of all incoming materials, materials that come out; the material accumulated and discarded materials from the system. This calculation can show clearly the profile of mass and energy of a unit in an industrial process.

General process flow diagram used in all mass and energy balance analysis to facilitate this research, clearly described all the events that occurred in the process unit observed. The flow chart is a visual representation that shows all the flow of materials either enters or exit devices, along with composition data from a mixture of materials flow. The flow diagram of the kiln system is as following:

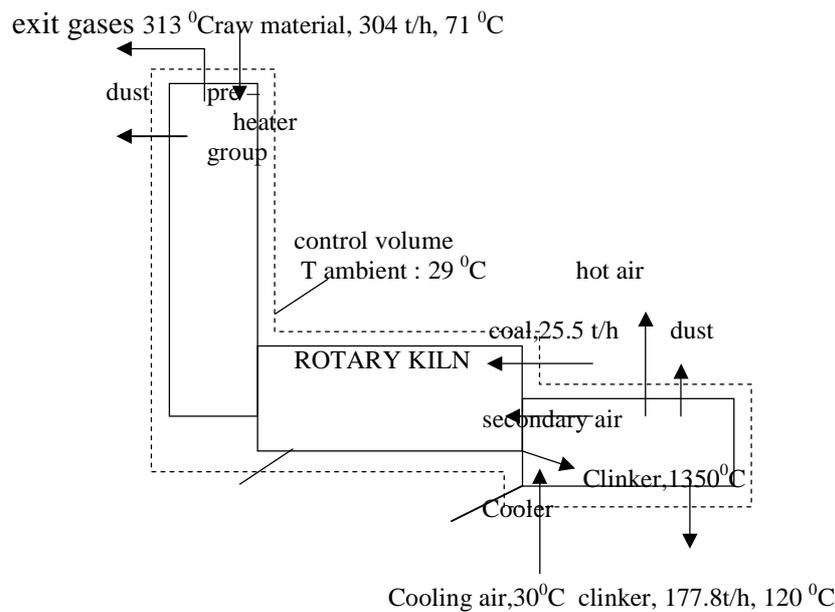


Figure 4.2 Flow diagram of rotary kiln system

The kiln systems energy performance can be determined from energy balance over the control volume shown in Figure 4.2. Heat energy for the control volume is similar to the using of simple steady state assumption. Therefore, relative distributions of outgoing materials and thermal energy can be computed accordingly, when internal heat transfer is neglected.

Material and heat balances around the control volume were performed on a basis of 1kg clinker. Datum temperatures of 0 °C was taken, the quantity of energy and sensible heat of the different streams into and from the control volume were calculated. For the balances, the following streams data were required:

- feed rate of raw material
- fuel and air entering the system
- clinker discharge rate
- Kiln exit gases leaving the system.

The data can be obtained from the plant records, while other relevant data for the analysis can be evaluated. The result of the material balance for the kiln system has been described in figure 4.3.

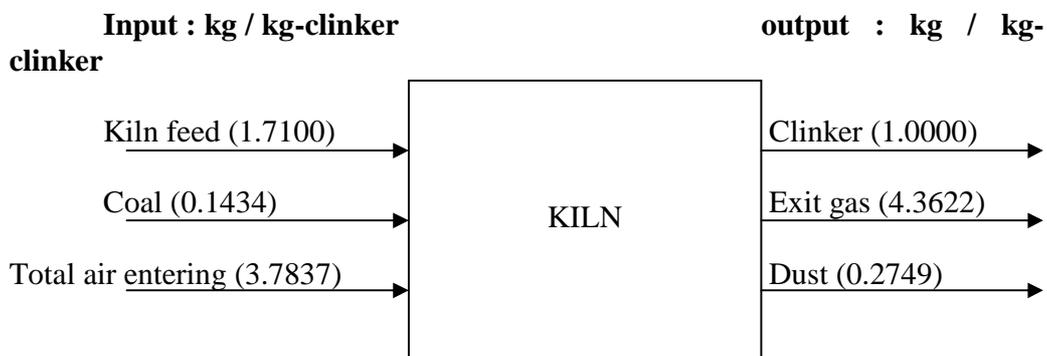


Figure 4.3 Material Balance of the Kiln system overall

Based on the results of the above material balance, we can see that 77% of the output mass is the mass of the exit gas. A large amount of mass has a large enough energy unused. The amount of energy contained in the mass we can see in the energy balance. The gas came out of the kiln system, the exhaust gases came out of the pre-heater and the gas also produced in the stack. The temperature of these gases were highly enough which is about 313 °C. This high temperature is highly potential as an energy source.

In order to analyze the kiln system thermodynamically, the following assumptions were made:

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

Table 4.3 Material Balance of the Kiln system

Components	Mass Input	Components	Mass Output
1. Raw Material :		1. Dust	0.2749
- SiO ₂	0.2385	2. clinker	
- Al ₂ O ₃	0.0631	- SiO ₂	0.2168
- Fe ₂ O ₃	0.0381	- Al ₂ O ₃	0.0576
- CaO	0.7256	- Fe ₂ O ₃	0.0360
- MgO	0.0123	- CaO	0.6386
- SO ₃	0.0079	- MgO	0.0187
- K ₂ O	0.0150	- SO ₃	0.0079
- Na ₂ O	-	- K ₂ O	0.0067
- H ₂ O	0.0041	- P ₂ O ₅	-
2. fuel (coal) :		- Mn ₂ O ₃	-
- O ₂	0.0198	- LOI	0.0177
- N ₂	0.0011	3. exit gas	
- H ₂	0.0086	- N ₂	1.2020
- H ₂ O	0.0108	- H ₂ O	0.0084
- S	0.0006	- CO ₂	0.8404
- Ash	0.0142	- SO ₂	0.0012
3. Transport kiln feed air :		- O ₂	0.0550
- O ₂	0.0212	4. Stack Gas	
- N ₂	0.0798	- O ₂	0.0589
4. Primary air		- N ₂	1.2866
- O ₂	0.0220	- H ₂ O	0.0080
- N ₂	0.0827	- CO ₂	0.8995
5. Cooling air fan		- SO ₂	5.6371
- O ₂	0.7507	5. Dust	0.2749
- N ₂	2.8243		
6. False air			
- O ₂	0.0006		
- N ₂	0.0024		
Total	5.6371	Total	5.6371

Base on the collected data, an energy balance is applied to the kiln system. The result of energy balance for the kiln system has been presented in table 4.4. The physical properties and equations can be found in Perry's Chemical Handbook. The complete energy balance for the system is shown in Table 4.4.

Table 4.4 Energy balance of the kiln system

Descriptions	Kcal / kg.clin	%
INPUT		
- Heat consumption of coal (Qa)	760.00	97.06
- Sensible Heat of coal (Qb)	0.6195	0.08
- Sensible Heat of Primary Air (Qc)	0.2759	0.04
- Sensible Heat of Air Transport Kiln Feed (Qd)	0.4360	0.06
- Sensible Heat of Raw Material (Qe)	18.6661	2.38
- Sensible Heat of Cooling Air Fan (Qf)	3.0069	0.38
	783.0044	100.00
Total Input		
OUTPUT		
- Heat reaction of clinker formation (Qg)	422.1037	53.90
- Vaporation Heat in raw material (Qh)	2.4137	0.31
- Sensibel heat of Klinker Outlet Cooler (Qi)	0.5865	0.08
- Sensible Heat of Exhaust Gas (Qj)	171.3334	21.88
- Sensible heat of clinker cooler's air to stack (Qk)	75.3428	9.62
- Sensible heat of dust (Ql)	5.212	0.67
- Heat loss	106.0123	13.54
	783.0044	100.00
Total Output		

Table 4.4 showed that the coal combustion as a fuel generated of 97.06% (760 Kcal / Kg clinker) of the total heat input to the unit. It can be seen from the table that the total energy used in the process is about 783.0044 Kcal / kg clinker. The sensible heats with the raw material, fuel, air entering the coolers, and organic carbon (feed component) heat contents are relatively small. The total sensible heats with the streams are about 2.94% of material streams. The energy balance given in table indicates the relatively good consistency between the total heat input and total heat output. The distribution of heat losses to the individual components exhibits reasonably good agreement between some other key plants reported to the previous study.

Thermal energy recovery and saving technologies reported by Engin(1997), and Kabir et.al (2009) demonstrates how the heat losses can be recovered. Based on the energy balance amount lost from the kiln system amounted to 106.0123 kcal/kg clinker, about 13.539% of the total output energy.

C. Energy Saving Opportunities for Dry Kiln System Baturaja Cement Plant

The low energy efficiency established the potential energy saving opportunities in the unit. Relevant thermal energy recovery and conservation concept for the kiln system are proposed and studied. Successes for using the concepts are expressed in terms of financial and environmental benefits. Some application that can used as recovery and conservation measures such as: raw material drying at the raw mill; waste heat recovery from kilns exit gases using steam generator; and kiln shell heat losses reduction.

1. Heat Recovery from The Kiln System

The overall system efficiency can be defined by $\eta = Q_g / Q_{\text{total input}} = 422.103 / 783.0044 = 0.53$ (53%). This efficiency is relatively low. Some kiln systems that operate at full capacity also has an efficiency of 55% based on the current dry process methodology. The overall efficiency of the kiln system can be improved by recovering some of heat losses. There are a few major heat loss sources that would be considered for heat recovery. Heat losses produced by kiln consist of the exhaust gas (21.88%), hot air from cooler stack (9.62%), heat loss that estimated as heat of kiln surface (13.54%).

2. Waste Heat Recovery Concept

The hot kiln surface is another significant heat loss source, and the heat loss through convection and radiation dictates as waste energy 96.41 Kcal. On the other hand, the use of a secondary shell on the kiln surface can significantly reduce this heat loss. For the current rotary kiln, $R_{\text{kiln}} = 2.25$ m, and a radius of $R_{\text{shell}} = 2.65$ m can be considered. Since the distance between the two surface is relatively small (40cm), a realistic estimation for the temperature of the secondary shell can be made.

Cold air will stream through the secondary shell and will intersect with the surface of the kiln directly. In this event there will be heat transfer from the wall of the kiln into the air so that air temperature will rise. This hot air will flow into the kiln for combustion air. Through this transformation needs the fuel combustion reaction heat to be economically since the heat contained material must be returned as the combustion air.

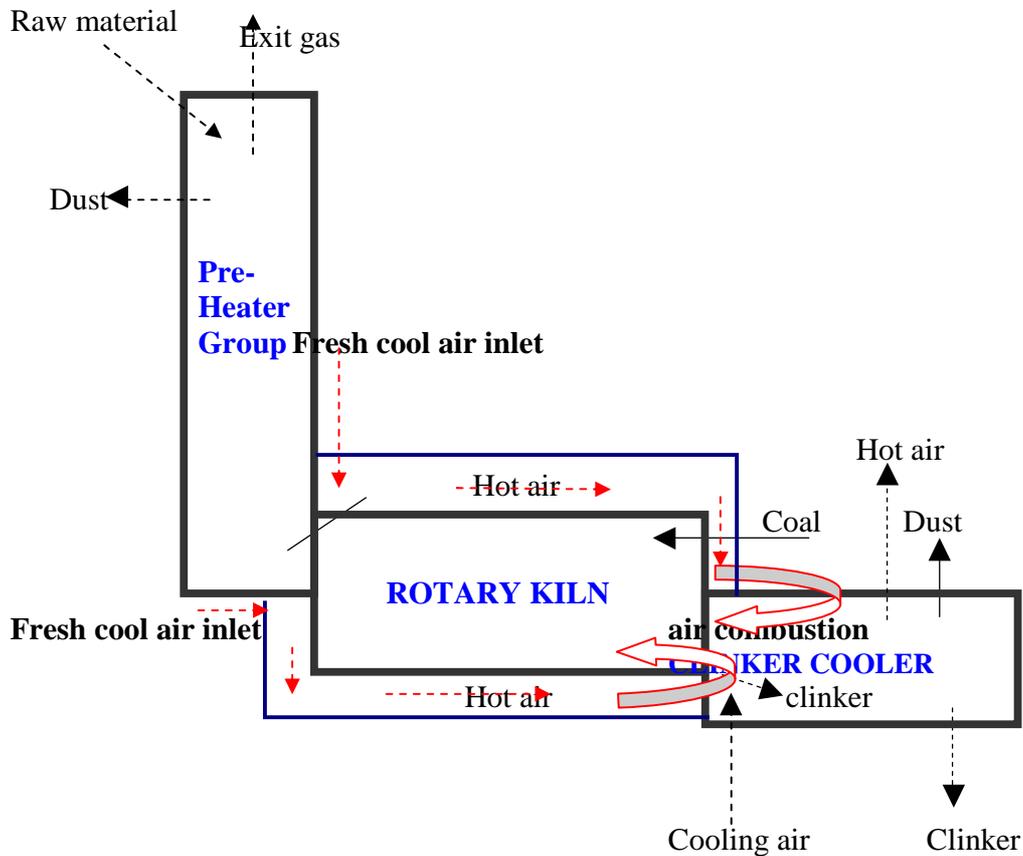


Figure 4.4 Utilization of Flue Gas from the rotary kiln system concept

Based on the data obtained, the amount of energy that can be absorbed by air amounted to 163,080 Kcal / hour. This energy is obtained from the results of heat transfer that occurs from the surface of the kiln into the air. Air containing the amount of energy was used as combustion air for fuel. Based on data calculation, the amount of coal can be saved of about 738 kg / day.

D. CFD Analysis

CFD is a simulation of fluid flow system using a modeling/ formulation of physical problems which are solved mathematically and a numerical method of formation of numerical parameters, grid, and the solver. CFD uses several multiple solvers in the problem solving. One of the solvers used is Fluent 6.3. This software is one of the computer programs that can be used in modeling fluid flow, heat transfer, mass transfer in a complex geometry.

This study has used CFD analysis to show the flow of heat absorbed by air from the surface of the kiln wall. In addition, by using a fluent we can simulate several conditions that occur in the kiln. Kiln has a diameter of 4.5 m by 75 m long. It can generate heat around the kiln wall around 600 °K. The geometry of kiln was made by Gambit processor, and then the data was exported into solver.

The description of process as following: air flows at the inlet of the shell and absorbs the heat along the kiln wall. While the kiln wall is in contact with the surface of the heat, the air comes out of the shell outlet for the higher temperature. Velocity of air was varied of 3 m/s, 6 m/s, 9 m/s and 15 m/s. Figure 4.5 and figure 4.6 describe the distribution of air temperature on the inlet and outlet of the shell. From these figures we can see that the air temperature changes in the kiln shell. The highest temperature was obtained at the kiln wall. This is due to the heat absorbed at this condition.

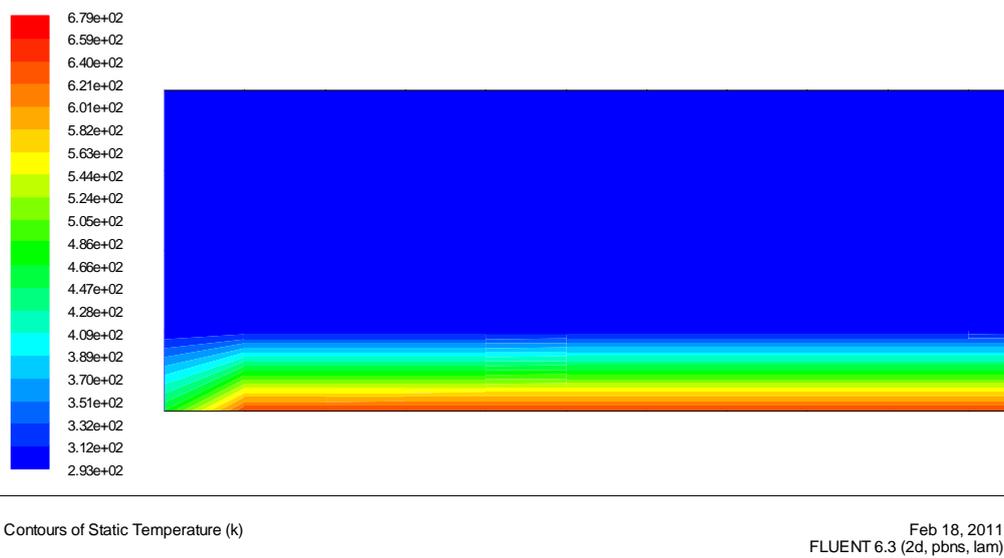


Figure 4.5 air inlet temperature profile

In figure 4.5 we can see that the initial temperature of air is equal to the ambient temperature of 293 °K. The blue color in the figure shows the lowest temperature which is at the shell wall and the red color shows the highest one which is at the kiln wall. At the beginning, when the air is discharged into the kiln shell, temperature was not significantly changed.

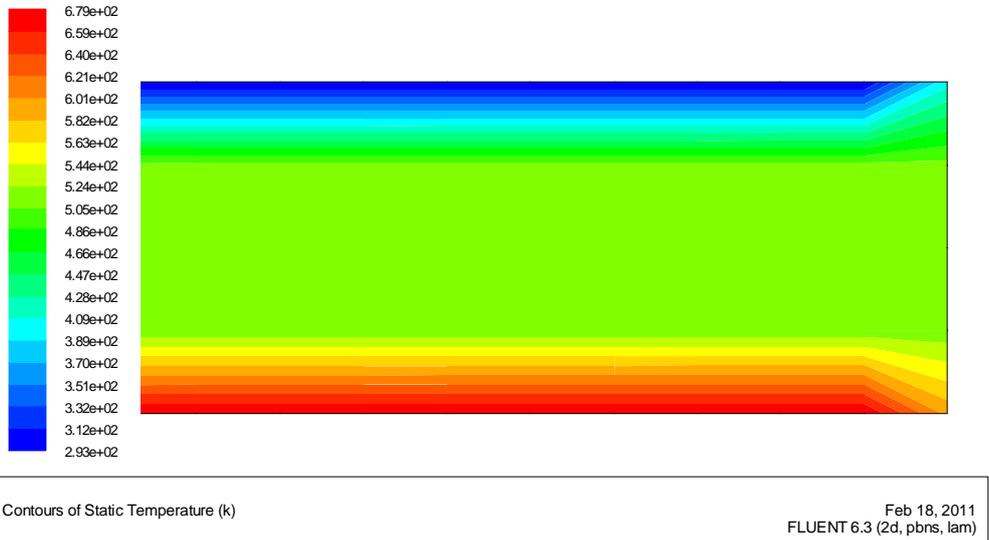
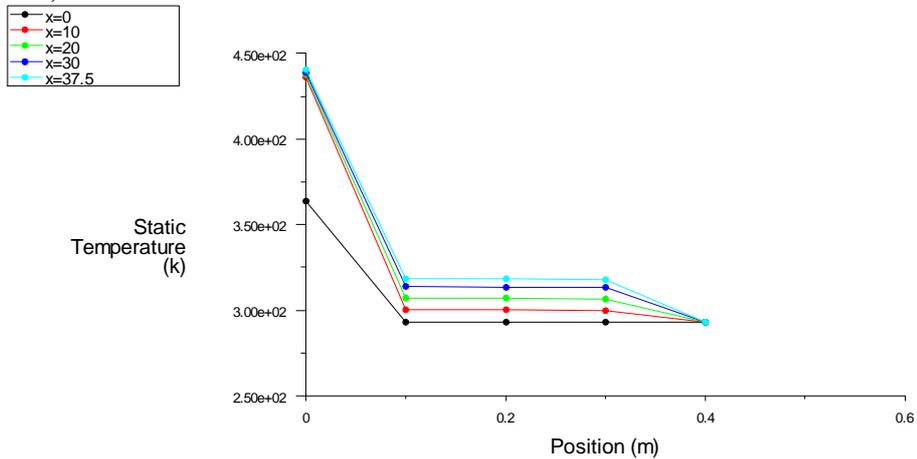


Figure 4.6 air outlet temperature Profil in outlet shell

Figure 4.6 illustrates the condition of the air temperature at the shell kiln outlet. It is shown that the temperature decreased from the kiln wall to the shell wall that is indicated by the changing of colors. This figure describes the temperature changing occurs from the red color to become the blue one. Any color changes that occur identified that there was a change in temperature. We also can see that the air temperature at the inlet shell of 293^0K (blue color) to 518^0K (red color).

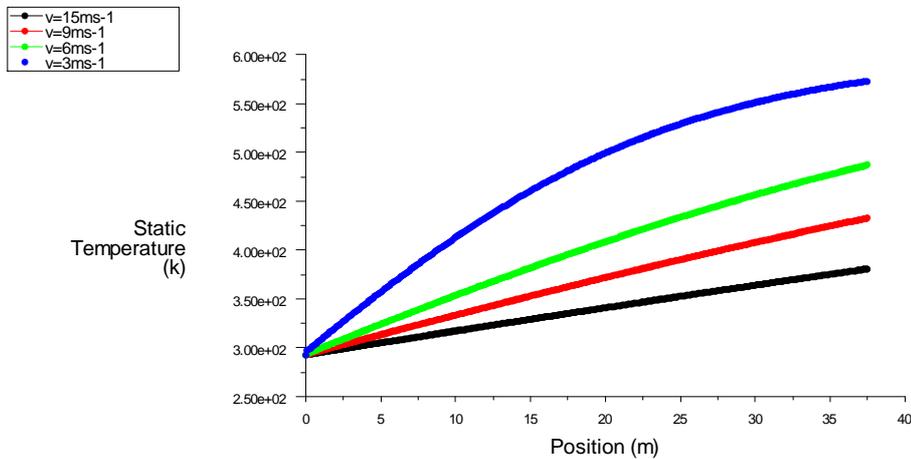


Static Temperature

Feb 05, 2011
FLUENT 6.3 (2d, pbns, lam)

Figure 4.7 Temperature distributions at each position on the kiln shell width

The distribution of air temperature inside of the kiln shell can be seen in the chart above. Y-axis represents the position of air flow at some point on the radius of shell wall. X-axis represents the air temperature at the length of the kiln shell. For $x=0$ (inlet), the temperature near the kiln wall is about 365°K , then the temperature decreased constantly of about 293°K with the position of 0.1 till 0.4 (the kiln wall). For $x=10\text{m}$, 20m , 30m and 37.5m (distance from the inlet) the air temperature of about 435°K and the decreasing of temperature is similar at the position of $y=0.1\text{m}$ to $y=0.3\text{m}$. Finally, at the position of $y=0.4\text{m}$ and the temperature decreased to become 293°K . Under these conditions we can see that the most effective heat absorption is located at position $y=0$ to $y=0.1$.



Static Temperature Feb 08, 2011
FLUENT 6.3 (2d, pbns, lam)

Figure 4.8 Distribution of temperature along the kiln shell in $v = 3\text{m/s}$, 6m/s , 9m/s , 15m/s

Figure 4.8 indicates that at various of air velocities, the profile of temperatures are similar. Therefore one of the analyzed data is expected as a representative of the overall operating conditions. It can be seen that the reducing of air velocity caused the temperature increasing. Based on the data results obtained in figure 4.8, the smaller of the air velocity which is used, the higher of heat can be absorbed by air.

CONCLUSION

The distribution of the input heat energy to the system components showed good agreement between the total input and output energy and gave significant insights about the reasons for the low overall system efficiency. According to the results obtained, the system efficiency is 53 %. The major heat loss sources have been determined as kiln exhaust (21.88% of total input), cooler exhaust to stack (9.62 % of total input) and heat loss estimated as heat from kiln surface (13.54 % of total input). The amount of heat energy can be absorbed by air amounted to 163,080 Kcal / hour and can be used as air for combustion of fuel. Based on data calculation, the amount of coal can be saved amounted to 738 kg / day.

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