Energy and Exergy Analysis on the Rotary Kiln Unit of RKC-2 PT. Semen Gresik – Tuban Plant

Mala Hayati Nasution¹, Irwan Rasyid Syahputra¹, and Darul Rahman¹

¹Chemical Engineering Department
Universitas Internasional Semen Indonesia,
Kompleks PT. Semen Indonesia (Persero) Tbk, Jl. Veteran, Kebon Dalem, Sidomoro, Kebomas, Gresik, East Java 61122 Indonesia.

*Corresponding Author’s e-mail: mala.nasution@uisi.ac.id

Abstract. Cement industry is an industry that intensively uses energy in the process. One of the main units in a cement plant that consumes the most energy is the rotary kiln. Rotary kiln is used for calcination process of cement raw material into clinker. It operates at 900-1450°C. It obtains energy from coal combustion process. Energy conservation in rotary kiln can be used to optimize production costs. Energy conservation can be carried out through energy identification. One method of energy identification is through energy and exergy analysis. In this study, energy and exergy analysis was carried out at the rotary kiln unit of RKC-2 PT. Semen Gresik - Tuban Plant. The analysis was carried out based on the calculation of the mass balance, energy balance, enthalpy balance, entropy balance and exergy balance. These calculations are used to obtain energy efficiency, exergy efficiency and irreversibility. Based on the research results, the energy efficiency, exergy efficiency, and irreversibility were 69.2%; 50.48%; and 49.52% respectively.

Keywords: Rotary kiln; Energy; Exergy; Irreversibility

1. Introduction
The cement industry is one of the industries that is energy intensive, because it absorbs a large amount of energy. The costs incurred for energy consumption in a cement plant range between 20-30% of the total cement production cost (UNIDO, 1994). If the costs for energy consumption can be reduced, the company profits can be increased. Research conducted on several cement factories in Japan in 1992 showed that energy use for the clinker combustion process reached 91.90% of the total energy use in a cement factory, the remaining energy was used for electricity by 7.6%, drying fuel and coal, as well as other processes by 0.5% (UNIDO, 1994).

Theoretically, to produce one ton of clinker a minimum of 1.8 GJ of heat is required. Based on research in several cement factories with dry type cement production processes, the average energy consumption is 3.5 GJ to produce one ton of clinker. The kiln system efficiency is 50% and the rotary kiln efficiency is 96% (UNIDO, 1994). According to Engin and Tahsin, 2005, a cement factory in Turkey with a production capacity of 600 tons of clinker per day requires an energy consumption of 3.6 GJ to produce one ton of clinker products.

One of the units in the cement production process that has high energy requirements is a rotary kiln. Rotary kilns are the main equipment in cement manufacturing which requires combustion heat for the clinker formation process. The main source of combustion heat comes from coal. In the combustion process there is heat loss. Energy conservation in the rotary kiln will have a significant effect on reducing
the cost of energy requirements in the cement production process and increasing the performance of the rotary kiln.

One of the methods used in energy conservation is energy and exergy analysis. The analysis is carried out to (i) measure the minimum work required to produce a product; (ii) evaluate energy conversion; and (iii) identify energy and exergy losses. This analytical method not only shows the flow of energy in the process but also provides an overview of the decline in energy quality during the process due to the formation of entropy and irreversibility. The research "Energy Analysis and Exergy at Rotary Kiln Unit RKC-2 PT. Semen Gresik - Tuban Plant " was carried out through the process of calculating the energy balance, enthalpy balance, entropy balance, exergy balance, and process irreversibility.

2. Theoretical Analysis
The process is assumed to be at steady state conditions. The following balance equations are used to determine the energy and exergy efficiencies and the rate of irreversibility (Ari, 2011).

2.1. Mass Balance
The mass balance in the process is stated in equation (1). Based on the equation, the inlet mass entering is the same as the outlet mass. Mass balance data in the rotary kiln unit were obtained from operating data at the Tuban Cement Plant.

\[ \sum m_{in} = \sum m_{out} \]  \hspace{1cm} (1)

Mass balance calculations are based on the law of conservation of mass passing through a rotary kiln. These calculations are presented in equations (2) and (3) (Duda, 1985).

\[ \sum m_{in} = m_{coal} + m_{kiln\ feed} + m_{air} \]  \hspace{1cm} (2)

\[ \sum m_{out} = m_{clinker} + m_{exhaust\ gas} \]  \hspace{1cm} (3)

2.1.1. Determination of the residual mass of CaCO\textsubscript{3} and MgCO\textsubscript{3}
The inlet mass of CaCO\textsubscript{3} and MgCO\textsubscript{3} to the rotary kiln will undergo a 100% calcination reaction in the kiln. The calcination reaction is the reaction to release CO\textsubscript{2} from the compounds CaCO\textsubscript{3} and MgCO\textsubscript{3}, this reaction uses the most energy. Based on Duda, 1985, the equation for the calcination reaction are as follows:

\[ \text{CaCO}_3(s) \rightarrow \text{CaO}(s) + \text{CO}_2(g) \quad (179 \text{ kJ/mol}) \]  \hspace{1cm} (4)

\[ \text{MgCO}_3(s) \rightarrow \text{MgO}(s) + \text{CO}_2(g) \quad (118 \text{ kJ/mol}) \]  \hspace{1cm} (5)

To calculate the mass of CaCO\textsubscript{3} and MgCO\textsubscript{3} the results of calcination are presented as equations (6) and (7).

\[ m_{\text{CaCO}_3\ (calcined)} = \text{degree of calcination} \times m_{\text{CaCO}_3} \]  \hspace{1cm} (6)

\[ m_{\text{MgCO}_3\ (calcined)} = \text{degree of calcination} \times m_{\text{MgCO}_3} \]  \hspace{1cm} (7)

To determine the mass of CaO and MgO the results of calcination are presented as equations (8) and (9).

\[ m_{\text{CaO}} = m_{\text{CaCO}_3\ (calcined)} \times \frac{Mr \text{ CaO}}{Mr \text{ CaCO}_3} \]  \hspace{1cm} (8)

\[ m_{\text{MgO}} = m_{\text{MgCO}_3\ (calcined)} \times \frac{Mr \text{ MgO}}{Mr \text{ MgCO}_3} \]  \hspace{1cm} (9)

Meanwhile, to determine the mass of calcination CO\textsubscript{2} is presented in equation (10).

\[ m_{\text{CO}_2} = m_{\text{CaCO}_3\ (calcined)} \times \frac{Mr \text{ CO}_2}{Mr \text{ CaCO}_3} \]  \hspace{1cm} (10)
2.1.2. Determination of the coal mass. The amount of mass of coal entering the rotary kiln is obtained from the daily report of PT. Semen Gresik – Tuban Plant.

2.1.3. Determination of the mass of combustion air. Combustion air is the required air for the combustion process in a rotary kiln. The mass of combustion air can be determined by calculating the theoretical coal combustion. The chemical reactions that occur in the coal burning process are shown as follows:

\[
\begin{align*}
C_{(s)} + O_{2(g)} &\rightarrow CO_{2(g)} \quad (11) \\
2H + \frac{1}{2} O_{2(g)} &\rightarrow H_{2}O(i) \quad (12) \\
S_{(s)} + O_{2(g)} &\rightarrow SO_{2(g)} \quad (13)
\end{align*}
\]

The chemical reaction above can be written in the form of a general equation for the theoretical combustion reaction of coal as in equation (14) to (19).

\[
C_{xH_{y}N_{z}S_{p}O_{q}} + \alpha(O_{2} + 3.762 N_{2}) \rightarrow xCO_{2} + \frac{y}{2} H_{2}O + pSO_{2} + \left(3.762 \alpha + \frac{z}{2}\right) N_{2}
\]

\[x = \frac{\% C}{Ar C} \quad (15)\]
\[y = \frac{\% H}{Ar H} \quad (16)\]
\[z = \frac{\% Z}{Ar Z} \quad (17)\]
\[p = \frac{\% S}{Ar S} \quad (18)\]
\[q = \frac{\% O}{Ar O} \quad (19)\]

The number of moles of air for theoretical combustion (\(\alpha\)) is obtained by equalizing the number of moles of chemical elements on the product and reactant sides as in equation (20).

\[\alpha = x + \frac{y}{4} + p - \frac{q}{2} \quad (20)\]

Meanwhile, the number of moles of coal for the total mass fed to the rotary kiln can be determined using equation (21).

\[Mole \ of \ coal = \frac{Mass \ of \ coal}{Mr \ coal} \quad (21)\]

The mass of flue gas formed for the total mass unit of coal fed to the rotary kiln can be determined by equation (22) to (25).

\[
\begin{align*}
mass \ of \ CO_{2} &= \text{mole } CO_{2} \times Mr \ CO_{2} \quad \text{ton/h} \quad (22) \\
mass \ of \ H_{2}O &= \text{mole } H_{2}O \times Mr \ H_{2}O \quad \text{ton/h} \quad (23) \\
mass \ of \ N_{2} &= \text{mole } N_{2} \times Mr \ N_{2} \quad \text{ton/h} \quad (24) \\
mass \ of \ i &\rightarrow (CaO)_{4}, Al_{2}O_{3}, Fe_{2}O_{3} \quad (29)
\end{align*}
\]

2.1.4. Determination of the mass of clinker. Combustion in a rotary kiln causes a chemical reaction, this reaction is also called the clinker formation reaction. The following are the reactions for clinker formation as follows:

\[
\begin{align*}
CaCO_{3} &\rightarrow CaO + CO_{2} \quad (26) \\
2CaO + SiO_{2} &\rightarrow (CaO)_{2}, SiO_{2} \quad (27) \\
CaO, Al_{2}O_{3} + 2CaO &\rightarrow (CaO)_{3}, Al_{2}O_{3} \quad (28) \\
CaO, Al_{2}O_{3} + 3CaO + Fe_{2}O_{3} &\rightarrow (CaO)_{4}, Al_{2}O_{3}, Fe_{2}O_{3}
\end{align*}
\]
\[(\text{CaO})_2\text{SiO}_2 + \text{CaO} \rightarrow (\text{CaO})_3\text{SiO}_2 \]  

(30)

The clinker-forming compounds have a special name which is used in the cement production process. These compounds are shown in Table 1.

| Chemical Formula | Compound Name          | Special Name |
|------------------|------------------------|--------------|
| 2CaO·SiO₂        | Dicalcium Silicate     | C₂S          |
| 3CaO·SiO₂        | Tricalcium Silicate    | C₃S          |
| 3CaO·Al₂O₃       | Tricalcium Aluminate   | C₃A          |
| 4CaO·Al₂O₃·Fe₂O₃ | Tricalcium Alumino Phase | C₄AF        |

|                  | Ferrite                |              |

The calculation of the clinker compounds formed is carried out using equations (31) to (35).

\[C_3S = 48\% \text{ CaO} + 17\% \text{ SiO}_2 + 0.7\% \text{ Al}_2\text{O}_3 + 0.5\% \text{ Fe}_2\text{O}_3 + 0.1\% \text{ SO}_3 + 0.1\% \text{ K}_2\text{O} + 0.1\% \text{ Na}_2\text{O} + 0.7\% \text{ MgO} \]  

(31)

\[C_2S = 5.1\% \text{ SiO}_2 + 0.1\% \text{ MgO} + 0.3\% \text{ Al}_2\text{O}_3 + 0.2\% \text{ K}_2\text{O} + 8.2\% \text{ CaO} + 0.1\% \text{ Fe}_2\text{O}_3 \]  

(32)

\[C_3A = 0.1\% \text{ Na}_2\text{O} + 0.1\% \text{ MgO} + 3.2\% \text{ Al}_2\text{O}_3 + 0.3\% \text{ SiO}_2 + 4\% \text{ CaO} + 0.3\% \text{ Fe}_2\text{O}_3 \]  

(33)

\[C_4AF = 0.2\% \text{ MgO} + 2.2\% \text{ Al}_2\text{O}_3 + 0.4\% \text{ SiO}_2 + 5\% \text{ CaO} + 2.1\% \text{ Fe}_2\text{O}_3 \]  

(34)

*Free lime = 0.9% CaO*

2.2. Energy Balance

The energy balance is a basic method of investigating a process. Through the energy balance it can be seen the requirement of the development in the process. In general, the energy balance equation is expressed in equations (36) and (37).

\[\sum E_{\text{in}} = \sum E_{\text{out}} \]  

(36)

\[Q + \sum m_{\text{in}}h_{\text{in}} = W + \sum m_{\text{out}}h_{\text{out}} \]  

(37)

The assumption in the energy balance calculation is that there is no change in kinetic and potential energy during heat transfer or work so that the energy balance equation is as presented in equation (38).

\[\sum m_{\text{in}}h_{\text{in}} = W + \sum m_{\text{out}}h_{\text{out}} \]  

(38)

2.2.1. Determination of the coal thermal energy. The calculation of thermal energy that can be produced by coal is presented in equation (39) to (41).

\[Q_{\text{coal}} = (H_{\text{coal}} \times m) \]  

(39)

\[HHV = 33950C + 144200 \left( H_2 - \frac{O_2}{8} \right) + 9400S \]  

(40)

\[LHV = HHV - 2400 \left( M + H_2 \right) \]  

(41)

2.2.2. Determination of the sensible heat of the coal. The calculation of the sensible heat of the coal is presented in equation 42.

\[Q_c = c_c \times m_c \times T_c \]  

(42)

2.2.3. Determination of the kiln feed heat. The kiln feed heat calculation is presented in equation 43.
\[ Q_{kf} = m_{kf} \times c_{kf} \times T_{kf} \] (43)

2.2.4. Determination of the heat of CaO. The calculation of the heat of CaO is presented in equation 44.
\[ Q_{CaO} = m_{CaO} \times c_{CaO} \times T_{CaO} \] (44)

2.2.5. Determination of the heat of MgO. The calculation of the heat of MgO is presented in equation 45.
\[ Q_{MgO} = m_{MgO} \times c_{MgO} \times T_{MgO} \] (45)

2.2.6. Determination of the heat of combustion air. The calculation of the heat of combustion air is presented in equation 46.
\[ Q_{\text{air}} = m_{\text{air}} \times c_{\text{air}} \times T_{\text{air}} \] (46)

2.2.7. Determination of the heat of clinker. The calculation of the heat of clinker is presented in equation 47.
\[ Q_{\text{clinker}} = m_{\text{clinker}} \times c_{\text{clinker}} \times T_{\text{clinker}} \] (47)

2.2.8. Determination of the heat of kiln exhaust gas. The calculation of the heat of kiln exhaust gas is presented in equation 48.
\[ Q = m \int_{T_{\text{ref}}}^{T} C_p \left( T \right) dT \] (48)

2.2.9. Determination of the heat loss. The heat loss that occurs in the kiln shell walls is caused by two factors, namely radiation and convection with the formulas presented in equations (49) to (51).
\[ Q_{\text{radiation}} = \sigma \varepsilon A_{\text{kin shell}} (T^4_s - T^4_\infty) \] (49)
\[ Q_{\text{convection}} = h_{\text{con}} A_{\text{pk}} (T_s - T_\infty) \] (50)
\[ h_c = \frac{k \ Nu}{D} \] (51)

2.3. Exergy Balance
The exergy balance are presented in equations (52) to (54).
\[ \sum E_{x_{\text{in}}} - \sum E_{x_{\text{out}}} = \sum E_{x_{\text{dest}}} \] (52)
\[ \sum E_{x_{\text{dest}}} = \sum (1 - \frac{T_o}{T_k}) Q_k - W + \sum m_{\text{in}} \Psi_{\text{in}} - \sum m_{\text{out}} \Psi_{\text{out}} \] (53)
\[ \Psi = (h - h_0) - T_o (s - s_0) \] (54)

2.3.1. Determination of the physical exergy. Physical exergy is exergy related to changes in pressure and temperature in the flow. According to Bejan, 1996, physical exergy can be calculated using the following equation
\[ E_{\text{ph}} = m (h - h_0) - T_o (s - s_0) \] (55)

2.3.2. Determination of the chemical exergy. Chemical exergy is exergy related to changes in chemical compounds. According to Bejan 1996, chemical exergy can be calculated using the following equation:
\[ E_{\text{ch}} = m x e^{ch} \] (56)
3. Energy Analysis

The results of the calculation of the heat energy balance in the rotary kiln are shown in table 2. Based on the table 2, there is a difference between the amount of inlet and outlet energy. The inlet energy is much greater than the outlet energy. The difference between the amount of inlet and outlet energy shows that there is heat energy loss or heat loss of 375,644,605.4 kJ / hour.

| Components         | Flow (kJ/h) | Components       | Flow (kJ/h) |
|--------------------|-------------|------------------|-------------|
| Kiln feed          | 364,584,546.3 | Exhaust gas      | 150,527,377.0 |
| Secondary air      | 119,761,060.3 | Clinker          | 694,572,383.2 |
| Primary air        | 48,758.5    | Heat loss        | 375,644,605.4 |
| Coal               | 1,101,593.1 |                  |              |
| Clinker reaction   | 417,030,673.3 |                  |              |
| Sensible heat of coal | 318,217,734.0 |                  |              |
| Total              | 1,220,744,365.6 | Total            | 1,220,744,365.6 |

Based on research, heat loss occurs due to three factors, namely radiation, convection and conduction. The amount of heat lost due to radiation, convection and conduction are 9,894,424.44 kJ/hour; 326,429,550.96 kJ/hour and 39,320,629.98 kJ/hour respectively. These three factors are largely determined by the type of the material in the rotary kiln. The conduction factor usually occurs on the inner and outer wall surfaces of the rotary kiln which is limited by refractory materials (refractory bricks) and steel due to the difference in temperature inside and outside the rotary kiln. The convection factor is due to heat transfer through an intermediate substance in the form of fluid, namely liquid and gas, in this case there is direct contact between the combustion hot air and the kiln feed material in the rotary kiln. This causes an increase in temperature at each point (zone) in the rotary kiln. The radiation factor is caused by the heat emitted from an open furnace or fireplace, so that the heat energy escapes to the environment. The percentage of heat loss due to radiation, convection and conduction factors are 0.81%; 26.74% and 3.22% respectively. Based on these results, it is known that the heat loss factor by convection is more significant than by radiation and conduction.

A Sankey diagram showing the energy flow in a rotary kiln is shown in figure 1. Based on this figure, it can be seen that the greatest inlet heat energy comes from the energy resulting from the clinker process of forming C4AF, C3A, C2S and C3S compounds in the clinker, which is 34.16%. The energy generated is quite large compared to the others because the reaction is exothermic so it releases large amounts of heat. The most widely used thermal energy is the energy for clinker formation, which is 56.90% of the total heat energy that enters the rotary kiln. Based on the research results, the energy efficiency value of the rotary kiln was 69.2% when the coal flow rate was 16.875 tons / hour and the mass flow rate of clinker products that came out of the rotary kiln was 351.919 tons / hour. Based on research by Engin, 2002, the optimal kiln system efficiency is 50%. The results of energy efficiency calculations in this study are higher than those of Engin and Vedat, 2005 by ignoring the excess heat which is fed back to the raw mill and coal mill.
4. Exergy Analysis

The results of exergy calculations which include physical and chemical exergy are shown in table 3.

| Components     | Flow (kJ/h) | Components     | Flow (kJ/h) |
|----------------|-------------|----------------|-------------|
| Kiln feed      | 746,835,463.7 | Exhaust gas   | 114,196,099.9 |
| Secondary air  | 73,862,852.0  | Clinker        | 602,651,832.1 |
| Primary air    | 467,300.0     | Destructed Exergy | 703,086,805.1 |
| Coal           | 598,769,121.3 |                |             |
| **Total**      | **1,419,934,737.1** | **Total**      | **1,419,934,737.1** |

A Sankey diagram showing the exergy flow in a rotary kiln is shown in figure 2. Based on figure 2, the largest inlet exergy comes from the kiln feed exergy namely 52.60\% from total inlet exergy. This value is the largest when compared to other inlet flows. This is because the kiln feed plays an important role as the main raw material in the clinker formation process in the rotary kiln. The most widely used exergy is exergy for clinker formation, which is 42.44\% of the total physical and chemical heat exergy that goes into the rotary kiln. Based on the results of the calculation of the value of exergy efficiency in the rotary kiln is 50.48\%. The value of exergy efficiency is smaller than the value of energy efficiency. Energy efficiency shows the quantity of energy while exergy shows the quality of energy. Based on the results of the research, the amount of energy that can be utilized in a rotary kiln is 50.48\%.

**Figure 1.** Sankey diagram of energy balance.
5. Conclusion

In the rotary kiln RKC-2 PT. Semen Gresik (Persero), Tbk Tuban plant, the total inlet energy is 1,220,744,365.6 kJ / hour. The total outlet energy output is 845,099,760.22 kJ / hour and the heat loss is 375,644,605.4 kJ / hour. Heat loss due to conduction factor is 39,320,629.98 kJ / hour or equivalent to 3.22% of inlet energy. Heat loss due to convection factor is 326,429,550.96 kJ / hour or equivalent to 26.74% of inlet energy. Heat loss due to radiation factor is 9,894,424.44 kJ / hour or equal to 0.81% of inlet energy. Energy and exergy efficiency of the rotary kiln RKC-2 PT. Semen Gresik (Persero), Tbk Tuban plant are 69.2% and 50.48% with excess hot air that is fed back to the rawmill and coal mill is assumed to be negligible.

Symbols : A, surface area; c, specific heat; Cp, heat capacity; D, characteristic length; E, energy; Ex, exergy; Ψ, exergy; h, specific enthalpy; hc, convection heat transfer coefficient; HHV, higher heating value; LHV, lower heating value; m, mass; Mr, molecular weight; Nu, Nusselt number; Q, thermal energy; s, entropy; T, temperature; σ, Stefan-Boltzmann constant; W, power;

Subscription : c, coal; ch, chemical; dest, destruction; e, molar exergy; gen, generated; in, inlet; kf, kiln feed; o, reference; out, outlet; ph, physical; ref, reference; s, surface;

6. References

[1] United Nations Industrial Development Organization (UNIDO) 1994 Output of a Seminar on Energy Conservation in Cement Industry.
[2] Engin T and Vedat A 2005 Energy Auditing and Recovery for Dry Type Cement Rotary Kiln Systems – A Case Study Energy Conversion and Management 46, Issue 4 551-562.
[3] Ari V 2011 Energetic and exergetic assessments of a cement rotary kiln system Scientific Research and Essays 6(6) 1428-1438.
[4] Duda WH 1985 Cement Data Book (London : Macdonald & Even).
[5] Bejan A 1996 Advanced Engineering Thermodynamics (New York : Wiley)

7. Acknowledgments

We wish express appreciation to Mr. Adam Wijatmiko, Head of RKC – 2 PT. Semen Gresik (Persero), Tbk Tuban plant for his permission and support to carry out the research.